greentex

SUSTAINABLE DESIGN AND PROCESS IN TEXTILES FOR HIGHER EDUCATION

Edited by:
Monika Malinowska-Olszowy
Anna Laska-Leśniewicz

The book was prepared as a part of the **GreenTEX project**.

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Lodz University of Technology
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Technical University of Liberec
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Content

1. Introduction

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The E-Book on Sustainable Design and Process in Textiles is one of the several types of educational activities undertaken in the GreenTEX project. To the best authors‘ knowledge, it is necessary to change the awareness and approach to sustainability in the broad textile industry (and related ones). Future textile designers who in the future will create new products and solutions not only for the textile and clothing industry but also for others that use textile products (such as medicine, transport, hygiene industry and protective equipment) must have full knowledge and awareness of how to create new solutions in line with the goals of sustainable development.

The textile and clothing industry is responsible for the emission of around 2 to 3 billion tonnes of carbon dioxide annually. It's about 10 percent. Global CO_2 emissions from fossil fuels. The industry is therefore on the same list of the largest global emitters of greenhouse gases as energy, transport and food manufacturing. At the same time, the production of textiles and footwear consumes a great deal of water, and the cultivation of cotton used in the garment industry requires intensive pesticide use and degrades soil. In addition, due to the poor recycling infrastructure, the vast majority of, for example, clothes end up in landfills. Currently, the textile and clothing industry is the second largest industry burdening the environment (right after the fuel industry). Only better knowledge about the design and production processes of textile products and the awareness of the negative effects on the environment will make both, businesses and consumers, begin to see the real costs of this industry and look for possible solutions.

At the end of 2018, the leaders of the global fashion sector adopted the Fashion Industry Action Charter for Climate, in which they committed to reducing greenhouse gas emissions by 30% by 2030 and by 2050 – to achieve climate neutrality. Over the last 2 years, the signatories of the Charter have developed a strategy to achieve these goals by jointly identifying the most ecologically problematic areas of the fashion sector, finding effective tools for verification and reporting on environmental degradation at each stage of the production chain, identifying the possibilities of reducing pollution, with particular emphasis on the use of renewable energy sources, energy-efficient logistics and transport, and the transition to a circular economy model. Also in March 2020, the European

Commission adopted a new Circular Economy Action Plan, along with the EU's Textile Industry Strategy, to foster innovation and encourage re-use in the sector. However, in order to achieve these goals, it becomes crucial to recruit specialists in the field of materials science and designers who can take into account environmental aspects when creating new products. The market needs specialists who face a number of challenges, including the following tasks: introducing circular economy standards, measuring and reducing the negative impact on the environment, ensuring appropriate working conditions, as well as implementing transparent rules for communicating changes to the environment and consumers.

The E-Book on Sustainable Design and Process in Textiles is a compendium of knowledge in a nutshell. It covers various aspects to provide a wide perspective on how principles of sustainable development and circular economy can be implemented in the broadly understood '*design of textiles*'. The proposed GreenTEX approach is presented in a form of a diagram – see Figure 1.1 and it includes the following issues:

- starting from sustainable raw materials (various types of materials suitable for use);
- Green Design (different ecological design strategies, such as: dematerialization, modularity, longevity, recyclability, re-manufacture etc.);
- sustainable textile processes (various processes with analysis of SD aspects, such process as textile manufacturing process, pre-treatment process, coloration process, special finishing process etc.);
- textile products (diverse types of sustainable products);
- distribution (transportation aspects, carbon footprint);
- consumption and market (analysis of the market and customers' demand, awareness of the end consumer and its influence on the whole industry);
- financial and marketing analysis of textile industry;
- reusing and recycling (possibilities for textile industry).

Figure 1.1. The complex approach on 'designing' developed as the GreenTEX diagram – implementation of Sustainable Design and Process in Textiles
Source: authors' own work.

Extra readings

1. GreenTEX project website [online], www.greentex.p.lodz.pl
2. GreenTEX platform [online], www.greentex.p.lodz.pl/platform

2. Sustainable development and circular economy

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2.1. Sustainable Development

Sustainability has become a popular term in recent years. It can be understand as meeting our own needs but with respect of future generations that should be able to meet their needs as well. According to the UCLA Sustainability Committee, sustainability is defined as:

> the integration of environmental health, social equity and economic vitality in order to create thriving, healthy, diverse and resilient communities for this generation and generations to come. The practice of sustainability recognizes how these issues are interconnected and requires a systems approach and an acknowledgement of complexity [1].

The issue connected with sustainability was mentioned some decades ago – for example in the National Environmental Policy Act of 1969 from the United States sustainability was declared a national policy:

> to create and maintain conditions under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic and other requirements of present and future generations. [2].

Nowadays, the global and urgent aim is to provide sustainability and sustainable development. Sustainable Development can be defined as 'development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs' (definition published in the Brundtland Report, also known as Our Common Future, in 1987 by the United Nations) [3].

There are three pillars of sustainable development:

- Environment (environmental sustainability),
- Economy (Economic sustainability),
- Society (Social sustainability).

In order to know the directions and act in sustainable way, sustainable development goals (SDGs) were designed and intented to be achieved by 2030.

2.2. Sustainable Development goals

The Sustainable Development Goals (SDGs, known also as Global Goals) are athe plan to achieve a better and sustainable future for all people. SDGs were created and accepted in 2015 by the United Nations. At the UN summit in New York, the document entitled 'We are transforming our world: Agenda for Sustainable Development – 2030' was signed [4]. It contains 17 goals of sustainable development which are to guide both governments and various types of organizations (international and non-governmental), universities, science, business and citizens. All SDGs address the global challenges we face, including poverty, inequality, climate change, environmental degradation, peace and justice. Sustainable Development is primarily aimed at equalizing the standard of people's lives, so that every person has a chance for a dignified and safe life.

The SD goals set are focused on 5 areas: people, planet, prosperity, peace, partnership. The goals are presented in Figure 2.1. and they include such aspects as: (1) poverty in all its forms, (2) hunger, food security, nutrition and promotion of sustainable agriculture; (3) healthy lives and promotion of well-being for all; (4) inclusive and equitable quality education; (5) gender equality; (6) availability and sustainable management of water and sanitation; (7) access to affordable, reliable, sustainable and modern energy; (8) inclusive and sustainable economic growth; (9) sustainable industrialization and innovation; (10) reduction of inequality; (11) sustainable cities and communities; (12) responsible consumption and production; (13) actions combating climate change; (14) sustainable use of the oceans, seas and marine resources; (15) sustainable use of terrestrial ecosystems; (16) peaceful and inclusive societies for sustainable development, access to justice and inclusive institutions at all levels; (17) global partnerships for sustainable development.

Check *GreenTEX Handout – Sustainable Development Goals (https://greentex.p.lodz.pl/)*

Figure 2.1. Sustainable Develepment Goals

Source: United Nations, The 17 goals, online https://sdgs.un.org/goals (access: 30.09.2022).

2.3. The essence of circular economy

The concept of a circular economy refers to a system whose main purpose is to minimize the consumption of raw materials, the amount of waste and the consumption and loss of energy. This can be achieved by creating process loops, i.e. waste from one process is treated as valuable raw material for other processes. As a result, this leads to a reduction in the overall amount of waste and emissions that have an impact on the environment. Circular system is a closed loop, where one aspect flows smoothly into the next. The individual items should be broken down as follows [5]:

- Raw material – raw materials and design;
- Product – production, distribution, consumption;
- Waste – consumption and collection.

There is still recycling, which we will not include in any category, because it is an activity that is a superior function in circular economy.

Check *GreenTEX Handout – Circular Economy Model (https://greentex.p.lodz.pl/)*

2.4. Circular economy model

The most popular model of circular economy is the so-called ReSOLVE approach developed by the Ellen MacArthur foundation. It is a concept that presents six business lines of action for companies that strive to implement the principles of the circular economy. The term ReSOLVE was created as an abbreviation of the following words: Regenerate, Share, Optimize, Loop, Virtualise and Exchange. According to him, activities under business models can be classified in the following areas [6]:

- Regenerate – all activities aimed at restoring, preserving and repairing the quality of ecosystems, as well as returning recovered biological resources to the biosphere;

- Share – sharing resources between different users, e.g. in the form of sharing private products by multiple co-owners or public use of a certain group of products, by reusing them during their entire technical lifetime and by extending their lifetime by maintaining, repairing and designing for durability;

- Optimize – increasing the performance of a given product, eliminating waste in the production and supply chain at all stages of the cycle;

- Loop – Keeping ingredients and materials in closed loops and giving priority to inner loops means reusing products or ingredients in manufacturing and recycling materials;

- Virtualize – dematerialization of resource use by providing a given functionality in a virtual way: directly or indirectly;

- Exchange – replacing old non-renewable materials with advanced materials, using new technologies or new forms of services.

2.4. Sustainable Development and Circular Economy in Textiles

One of the basic elements of the concept of sustainability is a circular economy with a closed cycle for textiles, apparel, footwear and accessories. To be considered sustainable, brands must improve every aspect of the products' life cycle [7]:

- Production (use of new manufacturing technologies and alternative materials to reduce water and energy consumption);

- Logistics (increasing the reusability/recyclability/composability of packaging);

- Sales and marketing (introducing clear labelling describing product composition and origin);

- Product use (looking for green material technologies to increase durability and usability, resistance to external factors);

- Elimination of textile waste;

- Design (incorporating sustainable fashion principles into the design process of innovative products that minimize environmental and social impact);

- Procurement of raw materials (sourcing eco-friendly raw materials – raw materials, dyes, finishing elements for production).

Another mean of completing sustainability tasks and validating actual practices is to obtain specialized certifications that validate company's overall social and environmental performance. The main challenges facing companies are the investment required to develop new business models, the impact of change on business profitability, employee education and culture change in organizations, maintaining credibility, consistency of brand image and reputation. These necessary changes are contained in the EU Strategy for Sustainable and Circular Textiles, announced by the European Commission on March 30, 2022. The document states that by 2030, textile products placed on the EU market must be sustainable and recyclable, mostly made of recycled fibers, free of hazardous substances, and produced with respect for social and environmental rights.

The strategy includes a broad spectrum of actions necessary to adapt the textile ecosystem to achieve sustainable production and consumption. Simultaneously, these actions will ensure that the industry will remain competitive, innovative, and resilient to crises. The aim is to reform the EU textile sector in a short period of time while ensuring that it becomes a global pioneer in transforming the sector's value chains into circular, innovative, transparent and environmentally friendly ones. The strategy also draws attention to the deliberate destruction of unsold products. To discourage such practices a:

> transparency obligation is to be introduced, under which large companies will have to publicly disclose the number of products they discard and destroy, including textiles, and their subsequent treatment in preparation for reuse, recycling, incineration or landfill [8].

The legislation is also expected to oblige manufacturers to provide reliable information on textile products sold on the EU market. Amongst others, the Digital Product Passport will be introduced to support this goal.

Extra readings

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3. Sustainable materials

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3.1. Natural Fibres

Natural fibre is any raw material, similar to hair, directly derived from an animal, vegetable or mineral source and converted into non-woven fabrics such as felt or, when spun into yarn, into cloth. Natural fibres include those produced by plants, animals and geological processes. They are biodegradable over time. They can be classified according to their origin. The classification of natural fibres is presented in Figure 3.1. Traditionally, natural fibres sources are broken down into animal, plant or mineral [1, 2].

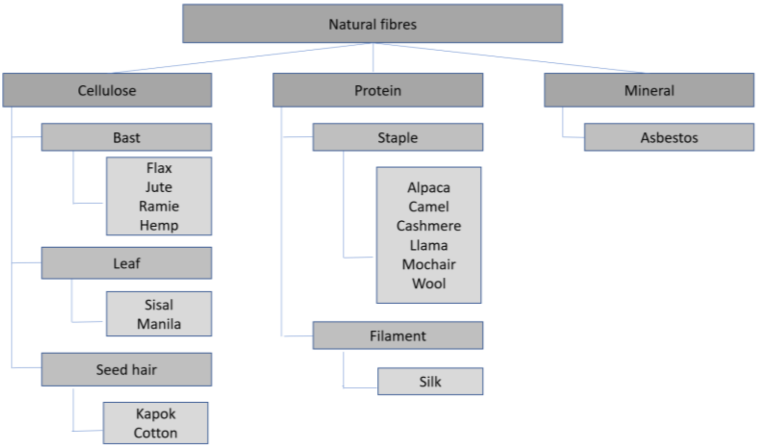

Figure 3.1. Classifications of Natural Fibres
Source: authors' own work.

Plant or cellulose fibres Plant or cellulose fibres come from different parts of the plant and from different sources [1, 2, 3, 4]:

- Bast fibres of the dogwood come from the crown surrounding the base of the plant. These fibres have a very high tensile strength and are often used in industry. The most widely used bark fibres are flax (from the flax plant), jute, industrial hemp and ramie [1, 3, 4];

- Leaf fibres are collected from the leaves of the plant. Sisal and manila are the most common leaf fibres [3, 4];

- Seed fibres are collected from the plant's seeds or seed boxes. Cotton and kapok fibres are the most commonly used here [3, 4].

Bast fibres

Fibrous material harvested from the stem of the flax plant and used to make linen - a breathable, soft, versatile and hypoallergenic fabric [1]. Due to their cultivation method, appearance, resistance and thermal properties, flax has been widely used in many industries. Flax is a plant known for its properties throughout its life cycle [3]. Jute fibres extracted from the extra-long stems of jute plants are generally strong but coarse. They are ideal for textiles requiring high durability, where the feel of the fabric is unimportant – as jute fabric is not soft. Jute is environmentally friendly as well as being one of the most affordable fibres.

Native to East Asia, ramie is a plant in the nettle family used to create strong, stiff fabrics similar to linen [4]. However, the low elasticity and brittleness of ramie fibres means that the fabrics improve when ramie is mixed with other fibres such as wool. China is the major producer of ramie, producing more than 95% of the world's ramie for fibre. Ramie is one of the strongest natural fibres.

Hemp fibres

Organic fabrics made from hemp fibres are durable, versatile and weather-resistant. China is the largest producer of hemp, accounting for 20-30% of the world's hemp crop. Its main properties are: Sustainable and environmentally friendly fibre; One of the strongest and most durable natural textile fibres; Absorbs moisture, prevents bacteria formation; Blocks ultraviolet rays; Superior durability; Easily recyclable [2, 3].

Leaf fibre

It is obtained from the leaves of the sisal plant, is a type of agave. Sisal fibres have a high strength and abrasion resistance. They are white in colour, easy to dye and have good resistance to sea water. Manila fibre have stronger resistance than sisal. Manila is used for teabags, banknotes and reinforced plastics, for marine cables and other ropes, also for nets and matting [2, 3].

Seed fibres

Cotton fibre is a soft staple fibre that is grown around the seeds of the cotton plant, called the boll. Each cotton fibre is made up of concentric layers with a hollow central core called the lumen. The outer layer, known as the cuticle, is a thin layer of fat, protein and wax. Beneath the cuticle is a primary wall, mainly composed of cellulose, in which the fibrils are arranged in a crisscross pattern. Further towards the center is a secondary wall composed of cellulose, which comprises the bulk of the fibres. Kapok fibre cannot be spun into yarns because they are very weak. Their density is only 0.35 [g/cm3], due to the large air-filled lumen. The fibres are water repellent, fine, soft and lustrous [2, 3].

Protein, or animal fibre, comes from different parts of an animal [1-2]:

- Animal hair or wool can be taken from hairy animals and the most widely used hair would be sheep wool;

- Silk – here the fibre is collected from the dried cocoons of cocoon-making insects or from the saliva of insects. The most commonly known silk is from silkworms.

Wool is a fine hair fiber from sheep. In labeling, the term ‘wool’ also may be used to identify fibers from other fleece animals, such as the Angora goat, Cashmere goat, Camel, Alpaca, Lama. Alpaca wool is obtained from the annual shearing of the alpaca. We only get 12 to 32 microns fibres. It is the most prestigious natural fibre in the world because it has many unique virtues [2]. Insulating power of alpaca wool is 7 times higher than sheep's wool and an unrivalled softness similar to cashmere wool. For this reason, it offers much better protection against the cold, is soft and does not allow sweating thanks to its thermoregulatory properties.

Camel fibre or camel hair is a special hair fibre derived from camels and belongs to a group known as special hair fibres. So, in order to learn about camel hair, we should know, first of all, what a special fibre actually is [1]. Any textile fibre derived from certain animals like the goat and camel families is rarer than the most commonly used fibres and is valued for its desirable properties such as fine diameter, natural luster, warmth and its ability to have a pleasant touch (properties perceived in handling). Cashmere is the fine, fluffy, downy silk produced by the cashmere goat and is by definition an undulating, opaque fibre that is 11-18 microns thick and 10 times lighter and warmer than wool. Cashmere fibre is fine, light, soft and warm. Cashmere is the best and lightest of all animal fibres. It has a high degree of natural curl and is able to handle and hold firmly during spinning. Due to its high cohesion, cashmere has excellent warmth, almost one and a half to two times better than wool. Llama hair fibers are shorn from the animal once a year. They are similar to alpaca fibers, but weaker.

Llama fibre is one of the best natural fibres in the world. Llama fibre is almost completely lanolin-free and is actually a hollow hair compared to ‘wool’. It is lightweight and very strong, with amazing thermal properties [1, 2]. Mohair is raised by Angora goats and has several valuable characteristics. Mohair is as warm as wool, although much lighter, making it ideal for travelling. Mohair is also coveted for its warmth, durability and beauty. Mohair is similar to wool, although it has other unique properties not found in any other type of fibre.

Wool is the fibrous covering of sheep and is the most important animal fibre used in textiles. Sheep's wool is one of the most hygroscopic (water-repellent) natural fibres, although its surface has hydrophobic (water-repellent) properties. Sheep's wool can absorb 33% of its own weight in moisture, bind it within the fibre and release it again when needed. The insulating properties of sheep's wool are maintained even when wet, thanks to the high air lock in the wool [1, 2].

Check *GreenTEX Handout – Wool Circularity (https://greentex.p.lodz.pl/)*

Silk is the only continuous yarn, a natural fibre and, like wool, a protein-based fibre. Silk is a yarn spun by the caterpillars of various butterflies. Silk is a natural protein fibre. It has a filament density of 1,34 g/cm^3, making it a medium weight fibre. Very lightweight silk textiles can be made from silk filaments [1].

Mineral natural fibre: Asbestos is a naturally occurring mineral made up of flexible fibres that resist heat, electricity and corrosion. Asbestos fibres were once woven into fabric to make textiles that resist heat and corrosion. These properties make the mineral useful but they also make asbestos highly toxic [2].

3.2. Man-made Fibres

Chemical fibres can be divided into two main groups:

Fibres **from synthetic polymers:**

- compounds with a heterochain (polyamides, polyesters, polyurethanes);
- compounds with a carbon chain (polyolefins, polyethylenes, polypropylenes, polystyrenes, polyvinyl chlorides, polytetrafluoroethylenes, polyacrylonitriles, polyvinyl alcohols);

Fibres **from natural polymers:**

- from cellulose:
    a. regenerated cellulose (viscose, copper fibres, modifications – the most important are lyocell fibres);
    b. cellulose derivatives (acetate, triacetate, semidiacetate).
- from algae (alginate);
- from vegetable proteins (soy, zein, peanut);
- from animal proteins (casein, keratin, fibroin, collagen);
- from polyisoprene (natural rubber – rubber);

Other natural polymers:

- alginate fibres;
- chitin fibres.

There are two different descriptions of man-made fibres. According one of them which was widely used earlier, man-made fibres are fibres which are made from natural polymers only. Fibres which are made from new sinthesized polymers are synthetic fibres. By other description all chemical fibres are man-made and can be divided into man-made fibres from natural polymers and man-made fibres from sinthesized polymers. Both descriptions are used and both have some advantages as well as disatvantages. Here we will not discuss which description is better.

Viscose fibres (created in 1892) make up 80% of chemical fibres from natural polymers. They are cheap, from renewable sources but their main disadvantage is the ecologically unsustainable method of production. In order to produce viscose fibres, we need a source of relatively pure α-cellulose (min. 88%) which can be easily separated from the plant in question. For example, wood or bamboo is a suitable source of cellulose, bark is not, as it contains only a small (50-70) % of pure α cellulose. Of natural cellulosic fibres, only cotton (92%), linen (81%) and other cellulosic fibres meet this % [5].

The further development of viscose fibres is primarily aimed at eliminating the disadvantages of this fibre, such as non-ecological solvents in the production of the spinning solution, as well as negative properties: a rapid decrease in strength at increased humidity, fibrillation of lyocell fibres, etc. Last but not least, there is an effort to use alternative sources of cellulose, for example: wheat chaff, citrus peel, etc. These fibres are usually called bio-based fibres [6, 7].

However, it is necessary to consider whether the separation of a relatively small amount of cellulose and its purity is not too demanding in terms of energy and ecology [8, 9]. Viscose fibres can be used for the production of clothing textiles (they have good properties in terms of physiological comfort – they are absorbent), but also for technical purposes such as reinforcing cords for tires.

The possibility of moisture access to the fibre and the mechanical properties will remain. Other fibres made from natural polymers, especially fibres from natural proteins, must be cross-linked with formaldehyde to obtain better mechanical properties. Fibres made from natural polymers have properties close to natural fibres and are largely degradable in nature, but usually do not achieve as good mechanical properties as synthetic fibres.

Fibres from synthetic polymers. Synthetic fibres or fibres from synthetic polymers - their basis is a monomer (preferably linear). The reactions by which the monomer and then the polymer are formed can be: polycondensation, polyaddition and polymerization). The advantage of synthetic fibres is that we can make them custom-made: we determine the fineness, cross-section, length and to a certain extent the strength and elasticity of the resulting fibres can be influenced by the production method.

Mostly used are the polyester (created in 1941), the polyamides (created in 1935), the acrylic (created in 1941) and the polypropilene (created in 1954). They widely are using for clothing as well as for technical textile. Usually they have a very good mechanical properties. On the other hand, they are not sustainable. A major disadvantage of synthetic fibres is the release of microparticles during their use, but especially after the end of their useful life.

Check *GreenTEX Handout – How long do materials decompose? (https://greentex.p.lodz.pl/)*

Recycling of synthetic fibres is a way to increase sustainability. Recycling begins with the collection of the fabric, followed by sorting and preparation for fibre reunification. Sorting is a challenging part of the process, as we sort by material and by colour (if not sorted by colour, the recycled product will be dyed black). Mixtures of fibres are a problem in sorting. Another possibility to reuse the polymer is complete recycling, especially dissolution, but this route is demanding from an economic point of view, the resulting fibres are more expensive than the original fibres and do not even reach the original properties. Furthermore, it is a process in which many other chemicals are used and it is an environmentally demanding technology.

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4. Green design

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4.1. Introduction

Green Design is a broad term that can be applied in many different contexts and refers to a variety of phenomena within contemporary product production. More specifically green product design can be also labelled as design for eco-efficiency, design for environment (DfE) or sustainable product design. The most general definition of green design describes it as a production model that integrates environmental protection criteria into every phase of product development – from conception to recycling – and makes optimal use of resources and energy. It has been argued however, that green design as ecologically sustainable design should be used together with economically sustainable design and socially sustainable design, so it takes into account a larger system. In a narrow sense green design is often associated with green architecture, so it might be better to use Ecological Design as a more suitable term in a broader context of product design.

4.2. History

Ecologically conscious resource management and design practices have been employed for centuries by local cultures around the globe. However the term ecological design was first used in a 1996 book by Sim van der Ryn and Stewart Cowan in which they defined it as seamless integration of human activities with natural processes to minimize destructive environmental impact [1]. Their arguments were followed in 2002 by the milestone book by William McDonough and Michael Braungart entitled ‘From Cradle to Cradle‘, which proposed a circular economy model to replace the traditional linear one of ‘cradle to grave‘ [2].

***Read more** – R1 in Extra Readings*

4.3. Related terms

Social design: Focused on the needs of various groups of recipients, on defining and solving real problems. Formal and aesthetic concerns are secondary to the functionality and social impact of these projects. The initiator and advocate of such an approach was Victor Papanek in his seminal book ‘Design for the Real World: Human Ecology and Social Change‘ (1971) [3].

Critical design: This term was introduced by Anthony Dunne in his book ‘Hertzian Tales‘ (1999), describing an attitude toward design or a philosophical mindset rather than a method. It reminds of other practices like Radical Design in Italy and avant-garde British architecture of the late 1960s – 1970s that have regarded design as a way to challenge the status quo, and to make viewers/users to consider the possible consequences of present choices and taken for granted solutions [4].

***Read more** – R2 in Extra Readings*

4.4. Green Design Strategies

– **Biomimicry:** (biomimetic design) looking for nature and natural systems for inspiration; emulating best biological ideas and solutions to improve design,

***Read more** – R3 in Extra Readings*

– **Dematerialization:** reducing the overall size, weight and number of materials incorporated into a design in order to reduce costs of transportation, reduce waste and improve product‘s longevity;

– **Design for disassembly:** designing products that can be easily taken apart for recycling, repair or remanufacturing. Designers shuld carefully examine types of materials that are used and the connection methods;

– **Influence:** all objects in our surroundings have impact on our behaviour and further consumer choices – they in turn ‘design us‘. Designers carry the responsibility for creating products, services, and systems that influence society in more positive ways. (see also: critical design, speculative design);

– **Longevity:** products should be aesthetically timeless (immune to seasonal trends), durable, made with quality materials and will retain their value over time so people can pass them on or resell;

– **Modularity:** products consisting of modules, separate but complementary pieces, that can be reconfigured in various ways to adapt to different spaces ad individual needs. Modularity increase recycling and repairability by offering replacement parts;

– **Product Service Systems (PSS) Models:** business models and tactics, offering alternatives to purchasable products. Leasing a product out, rather than selling it, allows the company to manage the product across its life cycle, so it can be designed to fit back into a pre-designed recycling or re-manufacture system;

– **Product stewardship and extended producer responsibility:** a take-back program, when the producers offer to take back, repair, remanufacture or recycle the products. This motivates them to design products to be easily fixed, upgraded or disassemled for high-value material recycling;

– **Recyclability:** product designed in such way that they are likely to be recaptured and recycled;

– **Repairability:** this is the key aspect in the circular economy. Things wear out and break, so need to be designed to allow for easy, preferably diy repair;

– **Reusability:** designing so that the product can be reused in a different way from its intended original purpose, re-made to gain new function and to follow changing consumer‘s needs, without much extra material or energy inputs;

– **Re-manufacture:** designing to ease refurbishing: renovating and reassembling product‘s components to manufacture a new product;

– **Systems Change:** designing interventions that can shift the status quo of an unsustainable or inequitable system by changing its particular elements or procedures [5].

4.5. Waste prevention strategies in product design

A comprehensive design strategy is needed for preventing the generation of waste.

- use materials that minimize waste and are nontoxic and biodegradable;
- design for easy separation of different materials so they can be reused or recycled;
- zero waste approach in product design.

***Read more** - R5 in Extra Readings*

4.6. Zero waste in fashion design and clothing production

Zero waste refers to various waste reduction activities, both by producers, designers and consumers, undertaken in order to care for the environment and responsible use of raw materials. One of the first people to apply this method was chemist Paul Palmer, founder of Zero Waste Systems Inc. The first comprehensive book on zero-waste fashion design was written by Timo Rissanen and Holly McQuillan [6] in 2018 (Zero Waste Fashion Design).

Problem: Textile waste in clothing production

- waste in the clothing production process accounts 10 – 30 [%] of the textile material [7].

Solutions:

- CAD system in ‘zero waste’ resolution (e.g. Assyst, Gerber, InvenTex, Lectra, Optitex);
- automatic layout of clothing patterns;
- clothing visualization on avatar without production;
- production of seamless clothing on a knitting machine (e.g. Shima Seiki);
- use the textile waste in other textile production (e.g. carpet, other cloths.

Recycling in fashion design

Use of recycled textiles – obtained from textile waste:

- Mechanical recovery of fibers from old textiles [8];
- Reclaiming raw materials from waste (e.g. plastic bottle PET [9]);
- Project from bottle raw materials – fashion designers: Iris von Herpen [10];
- In Research: chemical recycling of cotton fibers [9].

Production of clothing that can be recycled:

- In Research: life cycle assessment, LCA of textiles and cloth, e.g. 100% PET, 100% cotton and nearly 100% wool [11];
- Some clothing brands offer the option of leaving designer clothes for recycling [12];
- Problem with raw material mixtures e.g. cotton+ Elastane – only for downcycling for insulation [9].

Patchwork in fashion design:

- Definition: Patchwork – sewing together many smaller pieces of textile materials (often with simple geometric shapes) to create a new design [13];

- Historical genesis:
  - patchwork in Egyptian clothing and walls around 980 BC [13];
  - Chinese patchwork, from the Liu Song dynasty (420–479) [14];
  - Japanese patchwork, 19th and 20th century, boro – from cotton fabric dying by indigo [15];
  - patchwork fashion the 1960s [16];
- Fashion designers using patchwork, e.g.:
  - hippie style dress made with patchwork technique of patterned and multicolored triangles from 1969 Yves Saint Laurent [ill.1];
  - fashion collection from 2018, designed by Daniel Silvestein [ill.2], made from scraps from the production of his previous collections.

Pattern 'zero waste' – use of the entire surface of the fabric:

- Historical no-waste solutions where the entire garment drapping on to the body from a single piece of fabric: Greek Chilton [ill.3], Roman Toga [ill.4], Indian Sari [ill.5], Japanese kimono [ill.6];
- Fashion designers projects without waste, e.g.:
  - 'A-POC' collection from 1997 designed by Issey Miyake [ill.7] – items of clothing cut from one piece of fabric;
  - 'Kimono doorway' capsule collection from 2015 designed by Elena Ryleeva [ill.8] – straight-line-cut and elements refers to Japanese kimono;
- Problems: different width of the textiles, different selvedges in textiles e.g. glue in knit or hole in fabric, problem with errors in textiles e.g. holes, textile structure compaction [17].

Check *GreenTEX Handout – Designer's checklist (https://greentex.p.lodz.pl/)*

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5. Sustainable textile processes

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5.1. Eco-friendlier Textile Pretreatment and Modification Processes – Enzyme technology

Textile pretreatment and modification processes can be more eco-friendly. Using biotechnology, i.e. enzymes in textile processing has environmental benefits. Compared to conventional processes, enzyme processes are more environmentally, economically and energetically favorable. Advantages of enzymes to conventional chemicals are: biodegradable and non toxic, degrades certain substance so does not damage the fiber, replace aggressive chemicals, reduce processing time and save energy, improve material color, reusable until terminated reaction [1-5].

Enzyme technology in textile pretreatment includes: amylases in desizing process; pectinases, for the degradation of pectin in bio-scouring and the bast fibres retting process; proteases, for the protein degradation in the wool scouring and degumming of silk; lipases, for the degradation of lipide in wool scouring and laundering; cellulases, for the degradation of cellulose in the bio-polishing, defibrillation, and stone-washing of denim; hemi-cellulases for the degrading hemi-cellulose in bast fibre retting; xylanase for the degrading lignocellulose in bast fiber; catalases and laccase for the degrading hydrogen peroxide applied in bleaching, dye discolouration and effluent treatment; glucose oxidase for attacking glucose, acting as a bleaching agent. Laccase can be used for denim finishing, wool dyeing and anti-shrink process, and contribute to the synthesis of dyes. There is a possibility of cotton eco-friendly pretreatment using one-bath enzyme technology: amylase desizing - pectinase scouring - glucose oxidase bleaching.

Check *GreenTEX Handout – Enzymatic Pretreatment of Cotton (https://greentex.p.lodz.pl/)*

Enzyme technology can be applied in surface modification processes of synthetic fibers. Hydrolisis of synthetic fibers is mot common modification technique of surface modification or full degradation. It can be done usling alkali or the enzymes. Enzymes for surface modification can be: cutinase, lipase, esterase for polyester and PLA, amidase, protease and cutinase for

PA, nitrilase, cutinase, lipase for PAN, etc. The best example is hydrolisis of polyethylene terephtalate (PET). Alkaline hydrolysis is a conventional process usually performed at a temperature higher than 100°C for more than 1 hour. However, the use of strong alkali and high processing temperatures (>100°C) can lead to fabric damage and a negative impact on the environment. There is the possibility of hydrolysis of the PET fibers in the fabric in a sustainable, energy-efficient process at low temperature using an accelerator, a cationic surfactant HDTMAC, to achieve desired weight loss, and fiber morphology.

Enzymatic hydrolysis of polyester with emphasis on improving hydrophilicity and other properties using environmentally and economically advantageous means and processes. Defining process and technical-technological solutions, and improving existing and developing new technological procedures in the refining and dyeing of synthetic textiles, primarily PET, which would be industrially applicable; with a reduction in the emission of toxic chemicals, water and energy consumption; reuse of bath after wet processes, etc.

5.2. Sustainable dyeing and printing processes

As other textile process, new ways of sustainable dyeing and printing have been researched. In dyeing processes non-toxic natural dyes gets more interest, and in printing conventional techniques give way to new digital printing.

Environmentally acceptable technologies and sustainable materials in the field of textile dyeing are strongly related to the application of natural dyes with main goal humane-ecological approach. The raw materials for natural dyes comes form the nature (flora nad fauna), but also from the waste of other industries: food, agricultural, pharmaceutical, and other. Dye extraction is performend by selection of environmentally friendly solvents, ie avoidance of organic solvents as well as contribution of modern methods as ultrasound, microwaves, etc. Special attention is given to the pre-treatment of materials by selection of bio-mordants; optimizing the concentration of metal salts as well as material modification that pre-mordanting is not necessary.

Check *GreenTEX Handout – Natural Dyes (https://greentex.p.lodz.pl/)*

In dyeing process, process parameters should be optimized and the bath reusable. For that purpose the analysis of materials and wastewater should be performed and monitored. The use of natural dyes, that have antibacterial, antifungal, antioxidant and antitumor properties on textile materials, is due to a growth of consumer awareness of the environmental impact of synthetic dyes causing water pollution, waste disposal problems and impossibility of biodegradability. Colored materials, products that, based on the processes performed and the analyzes, justifiably bear the label ‘eco‘ should be used. The ‘eco‘ label will have influence on the wider community in order to raise awareness of the impact of modern fashion on the environment [6-8].

Textile printing technology is one of the major wastewater pollutants. Wastewater, after textile printing, contains agglomerates of dyes and thickeners that represent a compact, often water-insoluble, structure and cause clogging of drains, ie much more robust structures than pumps. It contains printing pastes and/or photoemulsions as well. For this reason, water-based printing pastes are increasingly used, but it is not always possible to realize for printing all the effects required by the market (swelling printing, metallic pigments, fluorescent pigments, etc.).

Due to their properties, the rheological and physico-chemical properties of post-press wastewater are most often treated using coagulants/flocculants, which, as mentioned above, can be an additional problem in wastewater loading. Considering conventional screen printing phases: graphic design, colour separation, screen preparation, exposure, drying and washing, print-paste preparation, printing, drying and finishing it is evident that in between each phase one or more washing processes occurs.

Therefore, the textile printing technology is given the imperative of a closed water circuit, i.e. the reuse of water in washing processes, or to change technology to digital printing. Digital printing phases: graphic design, printing, heat fixation, finishing have only one washing cycle at the end. However, all materials due to the different fibre composition, cannot be digitally printed [9-11].

5.3. Environmental Textile Finishing

It is known that conventional textile finishing processes require huge amounts of energy and water with the frequent use of agents that have a detrimental effect on the environment. Over the last decade, stricter requirements have been imposed on environmental protection and human health which have greatly influenced the restructuring of existing and the introduction of new technological finishing processes in the textile industry by carefully selected dry and wet finishing processes. New finishing processes are developed using a limited amount or without water, with the choice of more environmentally friendly agents and reduction of energy consumption. Due to the complexity of harmonizing requirements at the technological level, the implementation of eco-friendlier textile finishing processes using microwave, ultrasonic, UV and other advanced technologies are still mostly in the development phase at the laboratory and industrial levels [12-14].

The more environmentally friendly treatments to achieve targeted and/or multifunctional properties of textiles such as flame and heat resistance, oil and water repellence, wrinkle resistance, antimicrobial efficacy, wellness treatments, etc. can be realized by proper selection of chemical agents and optimization of technological processes following the principles of green chemistry; reduction of the number and quantity of agents, use and selection of catalysts, monitoring the environmental impact of degradable products; selection of dry and wet finishing operations with reference to environmental and economic performance (water, chemicals and energy); key technologies for the sustainable development of multifunctional textiles for use in the daily living, working and hospital environment with the aim of saving water, chemicals, and energy (application of ultrasound, microwaves, UV, and other advanced technologies in finishing processes); material analysis and evaluation of obtained properties.

Check *GreenTEX Handout – Environmental Impact of Textile Chemicals (https://greentex.p.lodz.pl/)*

5.4. Eco-friendly textile care processes

Guidelines for sustainable development ask for measures to reduce energy consumption and waste, the application of chemicals that present lower hazard, the use of efficient and biodegradable detergent, lower bath ratios and reduced waste water loads. Textile care processes in general can be devided into washing (laundry), dry cleaning or wet cleaning processes.

Check *GreenTEX Handout – Care Labeling (https://greentex.p.lodz.pl/)*

Typical washing detergent consist of a large number of components (13 and more), i.e. anionic and non-ionic surfactants, builders (zeolite, phosphate), chemical bleaches (peroxyde, percarbonate, perborate, peracetic acid), alkali, optical brigthener, enzymes, odours, anti-foaming agent, anti-redeposition agent, additives, etc. of which each component has its own task in the washing process. Unreacted components from the detergent, as well as suspended and dispersed impurities, are discharged directly into the sewage system, which, cumulatively, pollutes the environment. Detergent composition varies on fiber composition, washing medium, and laundry system. The continuous and discontinuous laundry systems indicate which detergents will be used.

In the continuous washing process, the so-called tunnels, and detergents are dosed as components in accordance to expected results. In a discontinuous washing system, the machines have a higher capacity, using powdered detergents with specific additives. The development and receipt formulation for new detergents as well as optimisation of the existing washing procedures, keeping the textile properties, hygiene and aesthetic aspect, lead to more sustainable industrial process of textile care [15-17].

Dry cleaning is sustainable process since the organic solvent is fully recovered, redestiled and can be reused. However, application of toxic organic solvents led to developement of a new principle of washing, so-called wet cleaning. The advantages are multiple: it is a mild washing process where mild detergents are used, machines have the ability to regulate and adjust all process parameters, and other. In all washing processes, wastewater from machines is discharged into the sewer system, needing purification.

5.5. Energy and Water

Types of environmental pollution and sources in textile proceses in general can be devided to textile waste, wastewater and air pollution.

Wastewater represents huge problem in wet textile processing and textile care processes. The water issues in the textile industry can be more sustainable if the water purification and reusing is considered. Water from sizing processes, from scouring and bleaching processes, from dyeing and printing processes, from laundrying process can be purifiead and reused up to some amount. Wastewater from the textile industry is extremely burdened with waste fibers (fibrils), dyes, surfactants, salts, softeners and other means and preparations. The prominent composition of wastewater makes it difficult to treat it with existing technologies that, due to the heterogeneity of water, cannot meet the set requirements for treatment and recovery. All methods for wastewater treatment of the textile industry, especially dyeing, finishing and care (laundry) have their advantages and disadvantages. For economic, technological and environmental reasons, it is important to combine methods because the water purification guidelines indicate that it is necessary to purify to the level of return to the process [9, 18, 19].

Microplastics: Textile care processes, i.e. washing and wet cleaning processes, as well as drying process, contributes to water and air polution. During textile care processes microplastics (synthetics) and microparticles (natural fibers) are released to the water and to the air [20].

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6. Textile products – composites

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6.1. The use of composites and the currently amount of production

The world is currently facing the risk of a climate catastrophe. The constantly growing amount of waste force companies to look for a new production solutions that allows to minimize post-production waste. World economies are increasingly turning to the idea of sustainable development.

Textile product means any raw, semi-manufactured or manufactured product, either factory or handmade, which is composed of textile fibres, regardless of the manufacturing process employed, any of the products, materials or items: woven textiles, non-woven textiles, knitted textiles, pre-formed loose fibers, filaments or yarns and textile reinforcement composites.

In 2021 the size of the global composite market was estimated at USD 88 billion. It is forecasted that this value will increase by 7.5% annually, reaching USD 126.3 billion in 2026. On the other hand, the value of the European composite market in 2018 was USD 16.6 billion. It is predicted to grow at a pace equal to the world value. The main sectors driving growth are the automotive and aviation industries which were hit by a temporary stagnation in the second half of 2020, caused by the Covid-19 pandemic. Demand for composites will also increase in the wind energy and defense sectors [1].

The type and constituents of the composites, i.e. the proportions of resin, reinforcement and filler, are tailored to the specific end use of the composites which means that there are many types of composites. Composites can, therefore, be classified based on structure or application. Carbon and glass fibers account for the main share in the production of composites. It is predicted that the share of carbon fibers in the production of composites will continue to increase.

The properties of these fibers, such as high temperature resistance, high stiffness, low thermal expansion, low weight and high chemical resistance, make them very popular in industrial applications [2]. Glass fibers had the largest share in the production of composites in 2018. They are light and durable. However, they have lower stiffness compared to carbon fiber. Their properties, on the other hand, are extremely favorable compared to metals. The development of the automotive and wind energy industries in Germany is expected to drive the entire European composite production market [3].

Composite materials are widely used in the automotive, aerospace and renewable energy industries because they are characterized by high strength, low weight and low maintenance. A car made of composites is lighter than that made of metals which translates into lower fuel consumption while driving and this, in turn, has a smaller impact on environmental pollution by exhaust fumes.

Technological innovations aimed at minimizing production cycle times are expected to stimulate demand for composites in the automotive sector. The presence of strict environmental regulations in Europe has forced car manufacturers to include composites in car production. All over the world, especially in Europe, regulations are forcing OEMs (Original Equipment Manufacture) to significantly reduce the carbon dioxide emissions of vehicles. The proposed regulations in the countries are expected to further fuel demand for products from this sector.

The same is true of aeronautics. It is one of the fastest growing sectors on the European market. The consumption of products in this industry is increasing due to their lightness and high stiffness. The primary purpose of using composite materials in these solutions is to reduce the weight of the aircraft and introduce machines with improved performance. Europe is one of the key markets in the aviation and defense sector and demand is driven by aircraft manufacturers such as Airbus and Dassault Aviation. Composites are also used in the production of sports articles and in the marine and oil industry.

6.2. Recycled composites

A very important aspect of the economy based on the idea of Sustainable Development is the principle of reduce – reuse – recycle, i.e. limiting production and waste generation, using already manufactured goods for as long as possible and recycling those items that are no longer usable. It is important to take into account the principles of Sustainable Development already at the product design stage, i.e. designing recycling-oriented products. The preferred form of waste management is material recycling, which reduces the demand for the production of new raw materials through the re-circulation of recycled materials.

There are solutions for recycling composites containing carbon fibers in order to use them for further production of composites that can be used in the automotive and aviation industries. Carbon fiber regeneration initially involves cleaning the composite from metals and cutting large composite structures to a size suitable for further processing. The capacity of this process is 4 tons per hour. The recovery of the carbon fibers takes place by a pyrolysis process in which the resin is burnt off. The furnace is capable of producing 1500 tons per year.

The carbon fiber is then further processed to form a non-woven mat or pellet. The use of recycled carbon fiber can reduce the cost of fiber reinforcement by about 40%. Another advantage is that recycled carbon has over 10% less global warming potential than virgin fiber. The recycled composite has the same production capacity as the 6 mm long virgin fiber composite. Moreover, the recycled composite retains 90% of its original tensile strength without changing its Young's modulus [4].

In the case of construction and demolition waste, wood, paper and plastics, these raw materials are mainly used to obtain energy through incineration. The use of them in a closed loop for the production of recycled composites is still rare. Mixing and possible contamination of materials are challenges that limit recycling. The recycling of metals, glass, paper, cardboard and plaster requires specialized technologies.

The degradation and contamination of materials often affect the properties of composites made of recycled materials. Processed materials often cause discontinuities in the composite if not processed properly. The possible use of such materials should be considered individually. Also, the environmental benefits that can be obtained depend on the composition of the composite material. Estimating the true potential of recycled composites remains difficult as studies on processing quality, economics, carbon footprint, health and safety are scarce and composition specific [5].

6.3. Eco products used in the production of composites

Natural fibers play an important role in the development of high-performance, fully biodegradable ‘green’ composites that will be key materials in solving current environmental problems. Compared to 2012, in 2017, three times more composites containing natural fibers were produced and used. This shows that the demand for composites reinforced with natural resources is growing. According to Nova Institute and FNR, since 2012 there has been a sharp increase in the use of flax as a reinforcement of composites in technical applications, furniture, automotive, construction, aviation, car parts, fire extinguishers, ballistic laminates, or biomedical applications. Composites containing natural fibers are lighter, and therefore a car made of such material consumes less energy while driving, while emitting less pollutants [6].

Moreover, natural fibers are preferred over synthetic fibers because they are renewable and biodegradable, which cannot be said about synthetic fibers. Natural fibers can be used as green substitutes due to their advantages such as light weight, good mechanical properties and low density with good strength.

Other natural fibers used in the production of composites are, among others jute, kapok, cotton, coconut, kenaf, kudzu, linden, sisal, hemp, alpaca, wool, angora. The term ‘green composites’ can be defined as those composites in which both the resin and the reinforcement are fully biodegradable and made of renewable raw materials. Biodegradable resins are obtained from plants, animals or bacteria. These are i.e. natural rubbers, soy protein, chitin and chitosan, starch, gelatin, PLA, PHBV, PCL, PVA, PBAT, PHB.

6.4. Waste composites and recycled composites

The vast majority of the market are composites made of glass and carbon fibers. Due to their properties, such as high strength in relation to low weight, high stiffness, high damping capacity, long service life, high resistance to wear, corrosion and fire, they are used in aviation, wind turbines or the automotive industry [7, 8]. The constant demand for green energy sources increases the production of composites used in the construction of wind turbines. Along with the increase in this demand, the turbines themselves are also constantly improved and expanded, increasing their weight and size.

Current wind turbines will last approximately 20–25 years. It is predicted that in the years 2020–34, over 200,000 tons of waste from used wind turbines will be generated [9]. Environmental legislation (including the Circular Economy Package of the European Commission) obliges to increase the recycling of waste. While composite products are typically strong and can be used for a long time, the first generation of composite products, such as windmills, is nearing the end of the product life cycle. This creates a new problem, namely the need to recycle the composites. This material is constructed to be strong and durable, and despite being firmly bonded, it is still heterogeneous, making recycling very difficult. Additionally, composites are often used in combination with other materials, such as foam fillings, for example, leading to mixed waste streams.

The largest part of the market are thermosetting polymer composites, reinforced with glass fibers. In Europe alone, over a million tons of such composites are placed on the market each year. Due to the construction of the composite itself, i.e. its heterogeneous structure, recycling is very complicated. Such composites cannot be remelted to obtain a new element. These materials are recycled in two ways:

– mechanical recycling, which is relatively simple, inexpensive and the most common. Used materials are subjected to comminution, grinding and classification. As a result of these processes, a recyclate is obtained that can be reused;

– thermal recycling – use of high temperature (300-1000°C) for resin pyrolysis and separation of fibers and fillers. Pure fibers can then be used for further production (however, they have worse properties than virgin fibers), while the remaining material is used as fuel.

When it comes to carbon fiber reinforced composites, depending on the composite production technology, the amount of carbon fiber waste is 30-40%, globally it is currently about 24 kt and it is forecast that in 2021 the amount of carbon fiber waste will be 32 kt. Currently, less than 1 kt is recycled. About 2/3 of all fiber waste is production waste and 1/3 is fiber from used parts fiber-reinforced composite (FRC) materials account for a significant proportion of plastic waste because they have a wide range of applications, including in construction, aeronautics, aerospace, sporting goods, renewable energy industry.

FRC materials are characterized by high strength, high durability, low weight and high flexibility of shapes which makes them a good alternative to steel and other materials. The development of the FRC industry has not only increased production and consumption, but also leads to the creation of a large amount of End of Life Products (EOL). The maintenance and recycling of used FRC scrap has become an important challenge for a sustainable and circular economy.

In 2015, almost 300,000 tons of composites waste were produced in the European Union alone of which 250,000 tons were EOL products.

Currently, the majority of composite waste (almost 98 %) is landfilled, and those that undergo further processing are most often used as fuel. As the use of composite materials continues to increase, it is essential to develop solutions to reduce the waste generated [10].

Check *GreenTEX Handout: Waste generated during the production of textiles (https://greentex.p.lodz.pl/)*

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7. Distribution

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7.1. Introduction

Distribution can be understood as the whole process of sending goods from one party to another. The goods are transfered between producers and customers. To destibute goods distribution channels are used. A distribution channel is a chain of businesses through which a good passes till it gets to the end consumer. Distribution channels are part of the process that answers the question 'How do we get our product to the customer'. It should not be confused with supply chains which are the part of the process answering the question 'Who are our suppliers?'. Distribution channels may include wholesalers, retailers, distributors and the internet.

The main components of distributions are:

- storage and warehousing (storage of finished goods or materials for manufacturing/ production);
- packaging;
- labeling (information about the product and its package);
- (physical) transportation.

There can be distinguished several types of distributions [1]:

- direct distribution – a strategy where a producer delivers products diretly to a customer;
- indirect distribution – a strategy where there are additional party/ parties that distribute produts to a customer;
- selective distribution – a strategy where company's products are sold in a few exclusively chosen places (by selected distributors) in a selected region;

- exclusive distribution – a strategy where there is just one distributor is authorized to sell products within a define region;

- intensive distribution – a strategy based on the idea of making company‘s products availavble for customers in as many places as possible.

The comparison of 5 types of distribution is shown in Figure 7.1.

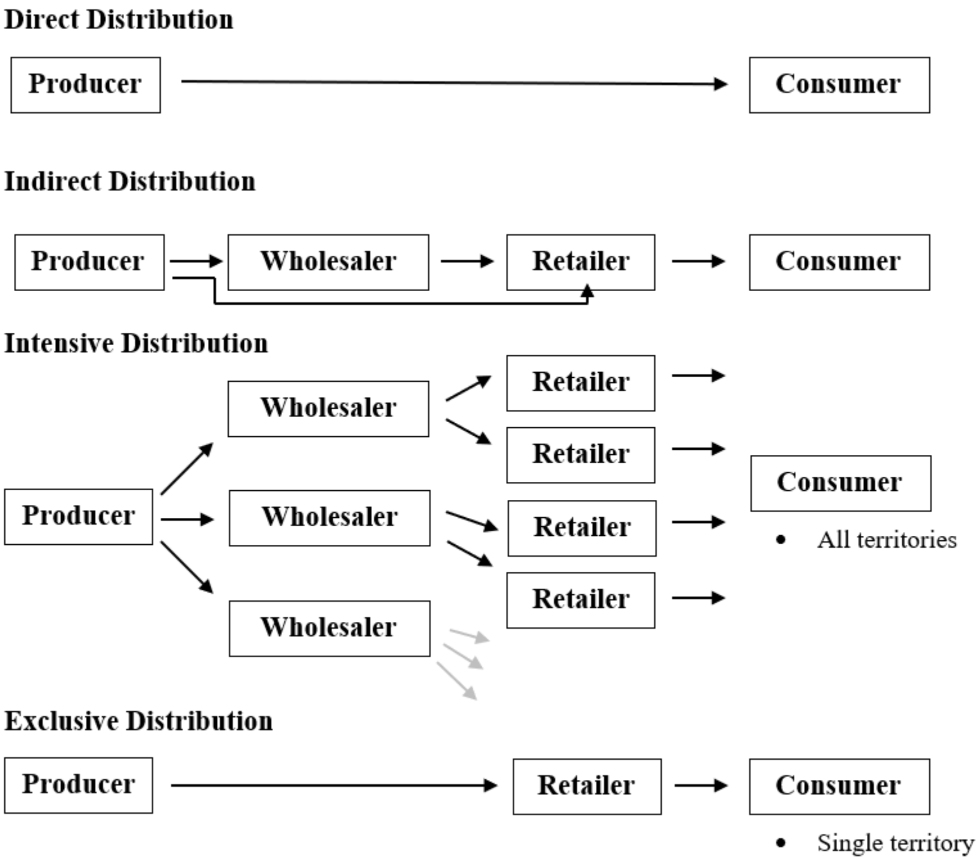

Figure 7.1. Different types of distribution
Source: authors' own work.

Packaging is the process of designing and producting packages. The whole package life cycle should be taken into consideration. The Sustainable Packaging Coalition® (a project of GreenBlue®) has proposed the definition of sustainable packaging. Sustianable packaging means that [2]:

- it is beneficial, safe & healthy for individuals and communities throughout its life cycle;
- it meets market criteria for performance and cost;
- it is sourced, manufactured, transported, and recycled using renewable energy;
- it optimizes the use of renewable or recycled source materials;
- it is manufactured using clean production technologies and best practices;
- it is made from materials healthy throughout the life cycle;
- it is physically designed to optimize materials and energy;
- and it is effectively recovered and utilized in biological and/or industrial closed loop cycles.

7.2. Transportation and carbon footprint

Physical transportation is about the movement of products (or materials) from one place to another. Transportation has a big impact on environment. The factors that affect the environmental impact are, among other, a distance between a producer and a customer, the quality of transportation infrastructure, the amount and locations of depots.

Transport infrastructure should be optimised – products need to travel as much reduced distance as possible. The recommended actions include [3]:

- choose local manufacturing and distribution;
- shift from roads to rail, and from air to sea;
- implement intelligent transportation management systems with the newest technologies (such as 5G or 6G);
- use electric cars, trucks (with lower emission), drones and autonomous cars.

Transport accounts for around one-fifth of global carbon dioxide (CO_2) emissions [4]. The World Resource Institute's Climate Data Explorer provides data that in 2016, global CO_2 emissions were 36.7 billion tonnes CO_2; emissions from transport were 7.9 billion tonnes CO_2. Transport therefore accounted for 21% of global emissions. The total amount of greenhouse gases (including carbon dioxide and methane) that are generated by our actions can be defined as a carbon footprint. According to the Nature Conservancy organization [5], globally the average carbon footprint for a person is closer to 4 tons, whereas in the United States – 16 tons. In order to avoid a 2°C rise in global temperatures, the average global carbon footprint per year needs to drop to under 2 tons by 2050. Every single action matters. There are many carbon footprint calculators available online.

Check *GreenTEX Handout – Carbon Footprint (https://greentex.p.lodz.pl/)*

7.3. Sustainable distribution

The companies present divers strategies to obtain more greener distribution. Let‘s familiarize with some of them:

1. Using as much as possible natural light and energy-efficient lightening in warehouses (and all other buildings/ offices);

2. Investing in insulation for warehouses (and all other buildings/ offices);

3. Using renuable energy resources;

4. Appling biodegradable or recycled packaging materials;

5. Choosing local suppliers which supports local economy as well;

6. Investing in electric trucks or clean idle trucks;

7. Consolidtaing shipments – sending full truckloads;

8. Using eco-friendly tires;

9. Becoming a part of supporting programs, e.g. SmartWay Partners (offered by Environmental ProtectionAgency) that provides tracking tools for control of company‘s emissons.

Check *GreenTEX Handout – Sustainable Distribution (https://greentex.p.lodz.pl/)*

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8. Consumption and market in the textiles industry

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Demographic and economic growth in recent decades have resulted in a substantial increase and in a mass production of garments and textiles. The concept of 'fast fashion' arises, in which the articles produced are sold and discarded very quickly, which produces a huge amount of waste in clothing and other textiles (see Figure 8.1). The significant changes that have taken place in the competitive scenario in which fashion companies operate, combined with the profound transformation in the lifestyles of end consumers, translate into the need to redefine business models [1].

The textile and fashion industry are among the most polluting and resource intensive industries due to the large consumption of water, energy and chemicals, affecting the environment [2]. In the case of European countries, they consume large amounts of clothing and textiles as a result of the current 'buy and throw away' culture [2]. This linear system leaves economic opportunities untapped, puts pressure on resources, pollutes and degrades the natural environment and its ecosystems, and creates significant negative social impacts at local, regional and global scales. For instance, the total emission of greenhouse gases from textile production, at 1.2 billion tons annually, is more than all international and maritime flights combined [3].

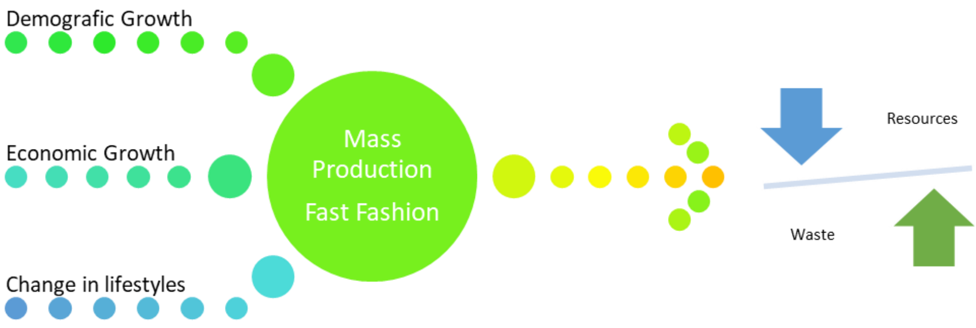

Figure 8.1. Environmental impact of recent textile industry developments
Source: authors' own work.

The shift from a linear to a circular model requires knowledge, awareness and engagement of all market participants: manufacturers, technology designers, policymakers and consumers. The speed and success of these changes will largely depend on consumer choices, the quantity and quality of the products they buy, openness to new business models and the way in which used products are handled. But it is essential to know the motivations and behavior of consumers in order to inform and make recommendations to policy makers and managers in these industries (see Figure 8.2).

Changing consumer attitudes towards clothing consumption, linked to low-cost production and sourcing materials from industrial markets abroad, has led to a culture of impulse buying in the fashion industry, where new styles of clothing are available for the average consumer each week [7, 8].

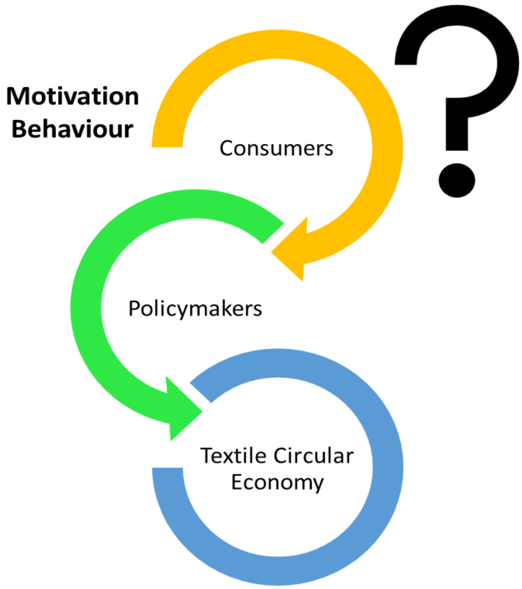

Figure 8.2. Relevance of consumers in Textile Circular Economy
Source: authors' own work.

The trends have implied an increase in demand for cheap textiles and clothing and conventional fibers, as well as contributing to an increase in the amount of low-quality textile waste, lack of landfill capacity and higher disposal costs [6]. In this way, due to the high volume of textile waste that is produced worldwide, textile reuse and recycling can be a sustainable solution for the reduction of solid waste in landfills, reducing the production of 'pure' materials and energy consumption and, in this way, producing a lower impact on the environmental footprint [11].

It is becoming increasingly evident that the current linear economic model (take-make dispose) has little possibility of effectively adopting the principles of sustainable development [6]. The Textile Industry has a high demand for energy and natural resources, which contributes to the rapid generation of the post-consumer waste stream [11]. According to the principles for a circular textile industry, consumers should wash, change and reuse clothes, as well as put quality ahead of quantity [11]. Thus, CE's objective is to provide maximum utility and value from products, components and materials [2].

The textile and apparel industry, as well as consumers, have been given a significant share of responsibility for textile sustainability, and consumer demand for ethical and sustainable textiles and apparel is perceived as a crucial driver of business initiatives as the Corporate Social Responsibility (CSR) [12]. Recycling textile waste can serve as a possible solution to many financial and environmental problems, such as high cost of waste disposal and depletion of natural resources [13].

Nowadays, many consumers tend to buy more than what they really need, treating the cheapest garments as disposable [6]. The discard nature of fast fashion and the throwaway culture is resulting in a serious environmental, social and economic problem [11]. Consumers seem to have little information and to be less aware of the need and ways to deal with clothing and textiles at 'end of life' compared to glass, paper or plastic [6]. However, Lehner et al. [5] state that the population is widely aware of the environmental consequences of household textile waste [5, 13].

However, many people are not aware or aware of the impact of their behavior on the act of purchase [13]. Still, although consumers are aware of the environmental challenges related to the textile and clothing industry, they may not act accordingly [12]. Bhatt et al. [14] mention that consumer fashion awareness, creativity and environmental concern, positively influence purchase intentions of recycled clothing and show more interest in learning upcycling techniques for clothing. However, the study by Yoo et al. [15] noted the perceived importance of conscientious behavior by consumers positively affects the intention to purchase recycled fashion products, but environmental concerns did not affect the intention to purchase recycled fashion products.

McNeill & Moore [7] argue that a persistent threat to sustainable consumption was the lack of understanding of sustainable or ethical fashion production. Therefore, lack of knowledge on the part of customers can act as a barrier to fostering a positive attitude towards sustainable fashion consumption [7]. The high-performance risk perceived by consumers can also lead to hesitation in buying recycled fashion products [16]. The study by Yoo et al. [15] assumes that there are negative effects of social, financial and performance risks on consumers' purchase intention in relation to recycled fashion products.

The importance of consumers in the textile industry is greater in developed countries compared to developing countries, since in developed countries fast fashion is more common, while developing countries already buy second-hand products from developed countries [13]. Therefore, the discourse of attributing environmental responsibility to the individual consumer has become part of the mainstream of policy making, and the distribution of (environmental) information, as well as the facilitation of consumer empowerment, is considered an important policy tool in several western countries [12].

Consumers who see fashion as vital to their own identity and the 'novelty' in fashion as a promoter of it, have little market prospects for sustainable fashion, as well as their priorities in fashion are in another position [7]. According to Rehman [17] personal factors and sales promotion have positive effects on purchasing behavior of consumers in the fashion clothing industry.

The value perceived by the consumer plays a role in consumer behavior [16, 13]. According to Weewer et al. [13] the perceived value is dependent on internal factors (personal preference, brand loyalty, knowledge, feeling of obligation and feeling of individual power) and external factors (price, institutional factors and social environment) [13]. Internally, the importance of consumer knowledge is highlighted, as well as consumer awareness [13].

On the other hand, one of the most relevant external factors is the price of the product, this factor is also considered a conditional value because it concerns how much a consumer has for being able to spend [13]. Emotional value (such as feeling joy and pleasure) is a unique subjective emotion that consumers feel towards the product in the process of buying and using it, which in turn has a significant impact on purchasing behavior [16].

According to Gazzola et al. [1] there are gender differences, with women being more informed and aware than men regarding the application of sustainability principles to the textile sector. This is also confirmed by Baier et al. [18], showing that women are more likely to engage in pro-environmental behavior than men.

Recently, younger consumers are becoming highly sensitive to social and environmental issues and their shopping habits are influenced by these principles [1, 5, 13, 14]. However, according to Martinez and Wiederhold [19] younger people tend to be more concerned with their image and new trends, which sometimes plays a more significant role than choosing the item with the best environmental benefits.

Education is an important factor in creating a truly sustainable fashion industry, teaching young designers to design with low waste and with consideration for the product life cycle [20]. However, Austgulen [12] states that education is not considered a statistically significant factor influencing political consumerism. Figure 8.3 summarizes the most relevant internal and external factors.

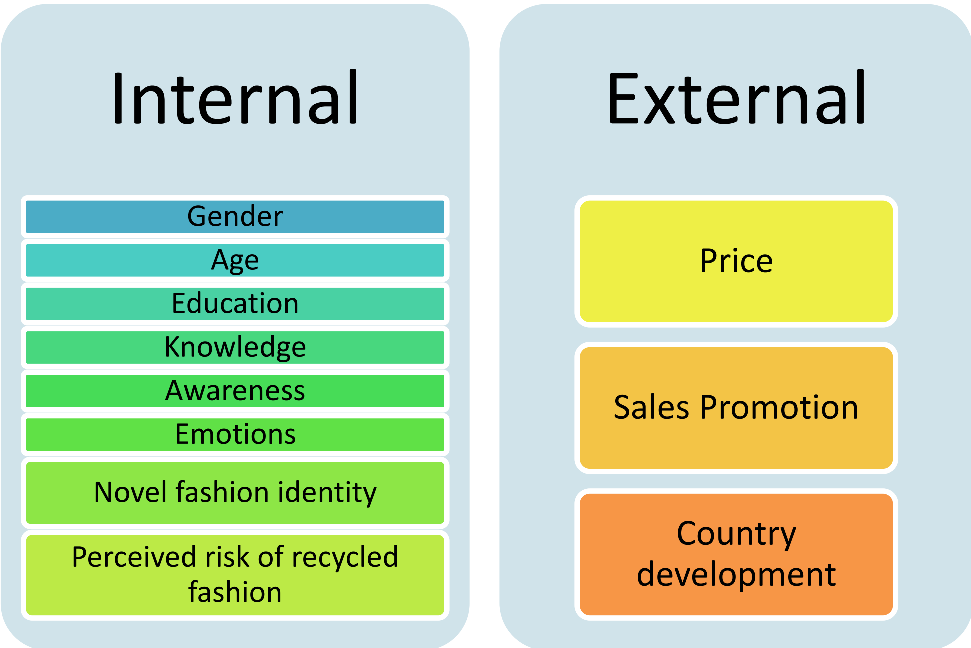

Figure 8.3 Factors affecting the consumer behaviour in textile products
Source: authors' own work.

The limits of the current linear economy model (take-use-throw away) are particularly evident in the analysis of the textile and clothing industry.

Achieving a change in this model requires buy-in from different actors, including industry, government and cities, civil society and the general public [3]. The value perceived by the consumer plays a role in their behavior, namely internally, the knowledge and awareness of consumers stands out, and externally, the price.

Personal factors and sales promotion have positive effects on consumer buying behavior. It is noteworthy that many people are not aware of the impact of their behavior on the act of purchase, in the case of those who do, they do not always act accordingly. Information on the environmental consequences of textile consumption is essential, as according to Austgulen et al. [12] environmental motivations are among the most significant.

Also, companies must have the ability to influence buying behavior by changing their value proposition and using strong marketing knowledge. Thus, marketers and policymakers should make consumers more informed by disseminating information on recycled materials and fashion issues through legal guidelines, media reports and environmentally friendly public relations in the manufacturing and marketing sectors of companies.

Younger consumers are becoming highly sensitive to social and environmental issues and their shopping habits are influenced by these principles. In this way, education is an important factor in creating a truly sustainable fashion industry, teaching young designers to design with low waste and with consideration for the product life cycle. Thus, teaching and research institutions can support the transition by incorporating circular economy principles into their teaching. In this way, bringing circular economy principles into education, from school to professional development, will equip students with the skills and thinking mindsets to become active trainers of a circular economy in general and a new textile economy in particular.

To conclude, the government may provide procurement recommendations that support promising and scalable circular business models for textiles that can help drive these models forward and spur their wider adoption in the market. Thus, both companies and policymakers trying to encourage participation in circular disposal systems must continually inform and remind consumers of the environmental importance of circular textile disposal systems.

Check *GreenTEX Handout – Consumption and market in the textile industry (https://greentex.p.lodz.pl/)*

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9. Financial and marketing analysis

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It is clear that Circular Economy (CE) carries the expression of a new era and new values, as it avoids the generation of waste, preserves the value of the materials and proposes experimental and innovative processes that do not neglect the reduction of impact in the extraction of resources [1-3], through the reuse and recycling of waste or by proposing new services and improving durability [4]. For a circular business model to be successful in a company, a change of mindset is needed (see Figure 9.1).

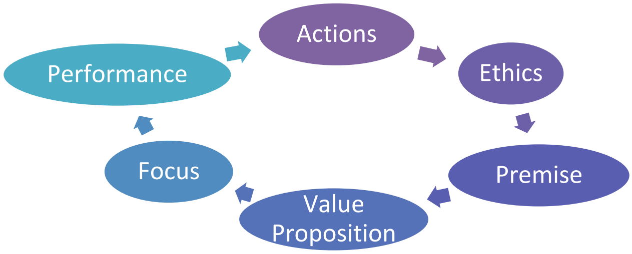

Figure 9.1. Company's change of mindset in circular business model
Source: authors' own work.

Actions other than shareholders need to be considered; other stakeholders of a business, such as society, customers and suppliers, play an important role in a CE, as they add value and quality to products (including the reverse chain), and provide important information about the design of innovative and circular product. Ethics is relevant as in a CE, collaboration is more important than competition, which puts one business above others.

The premise of doing more with less (efficiency) is not enough to realize the benefits of a CE; the consequences of the activity must also be considered (effectiveness). A value proposition focused on cost reduction is a typical strategy in a linear economy, has limitations and generates negative externalities; in a CE, the value proposition considers the added value of resources and seeks to keep it at the highest and highest level.

The focus of the company is profit for any business, but in a CE, it is achieved through innovation and the creation of new value. The performance in a CE, goes through experience and access to desired features, which are more important than product ownership, allowing companies to get closer to customers and increase loyalty. The result of all the mentioned factors generates the planning and positive regeneration of means and waste [5], therefore, it is concluded that the textile industry has impacts throughout its production chain and, although it is difficult to measure these impacts, it can use investments in sustainable alternatives and CE to spread this message to society and increase its transparency.

Many companies are choosing the 'Upcycling' method, a process of creating and improving clothing through the use of old or disposable items (see Figure 9.2).

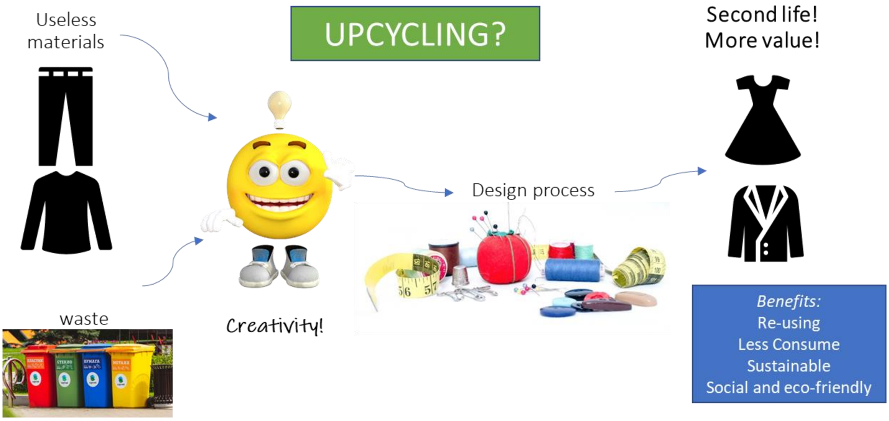

Figure 9.2. The Upcycling Process
Source: authors' own work.

The term 'Upcycling', was used for the first time and introduced in 1994 [6], and consists of a production model in which discarded surplus raw materials are used in the production process of new products, adding value to them without changing their main characteristics [7]. Waste is converted into raw material without chemical intervention and with less impact on the environment. This is a process with high creative and innovative potential [7]. This method is a very different concept of recycling.

While traditional recycling is a process that transforms old things into new ones, upcycling consists of reusing materials in their original state, discarding the use of chemical processes or interventions that have a negative impact on nature. In this way, the new technique is considered an even more ecological proposal [4]. Despite being a new practice, upcycling has been already adopted by several organizations [8]. More and more companies seek to use residues and sustainable raw materials, not being sent to landfills for reintroduction in the consumer market, being converted into new products in the production chain.

In 2020, BlackRock, the world's largest investment fund, published a letter to its shareholders expressing the urgency for companies to consider sustainability in their strategic objectives [9]. In this sense, the term Socially Responsible Investment (ESG) gains importance and places sustainability at the center of the allocation of financial capital. Corporate Social Responsibility is established with the goal of improve the society's quality of life.

The term ESG is derived from the concept of sustainable development [9] and recognizes the environmental, social and governance aspects of economic risk assessment along with the sizing of the company's financial aspects and, therefore, investment decisions. In this case, the company's investment and loan decisions go beyond the evaluation of financial criteria and start to consider sustainable practices. Incorporating ESG practices into corporate valuation is redefining the concept of creating corporate value [9] and for systemic sustainable business practices.

Due to the need to propose new practices centered on people's needs by systematically rethinking the consumption and production of fashion and clothing, it was necessary to rethink the sustainable business model. It is necessary to put three principles to add the value [10] of a company in terms of the impact that can be generated: (i) Focus on the customer and value willingness to pay [10]; (ii) Focus on the purpose of sustainability and (iii) Supply aligned with circular sustainability purposes [11].

Some of the main difficulties faced by companies in the European textile and clothing sector are the globalization of Internet-based technologies in a market dominated by low prices, cheap imports and international subcontracting [11]. In 2019, there were 160,000 companies in the industry employing 1.5 million people and generating a turnover of €162 billion.

The sector in the EU is based on small businesses. Companies with less than 50 employees account for more than 90% of the workforce and produce almost 60% of the value-added [11]. Global textile fiber production grew from an estimated 70.6 million tons in 2007 to 90.8 million tons in 2014, and is expected to reach 130 million tons in 2025 [12]. China and India are the two largest producers [12].

EU industry has changed dramatically, with some companies maintaining and strengthening their competitiveness, reducing mass production and focusing on a wider range of high value-added products through quality, design and technological innovation. In fact, during the economic crisis of 2008-2012, the high-end sector grew faster than the rest of the European economy, employed more than 1 million people and exported more than 60% of products outside Europe, representing 10% of all EU exports [11].

While several attempts have been made to quantify the amount of textile waste available across Europe, overcoming inconsistencies in the classification, quantification and reporting of waste proved to be a challenge. Textile collection systems vary greatly between European countries. It is estimated that between 15% and 25% of available textile waste is collected separately and thus enters a potential route of reuse or recycling [7].

By linking the environment and the economy, CE brings together a format that reduces companies' costs by integrating economy and eco-efficiency. In this sense, the term eco-efficiency emerged which translates this dynamic [10]. The CE concept provides different scales for large, medium and small companies, individuals and organizations at a local or global level, helping to improve the well-being of the system. The adoption of a CE is not just an adjustment to reduce the negative impacts of a linear economy, but is the application of a systemic production that can build long-term adaptability, create economic and business opportunities and generate environmental benefits at the same time [4].

This is an opportunity for companies to lead the way, using the vast amount of textile waste produced to meet the ongoing demand for value creation. Thus, textile companies are committed to explore this niche and to innovate in the creation of new circular business models. In addition, the business model objectives must reflect the organization's objectives and this alignment of goals to social and environmental issues, which are at the heart of business models that involve the company's mission and purpose [13]. The elaboration of a chain focused on sustainability and seeking sustainable financial return must be entirely directed at the interaction of the stakeholder and the consumer [13].

In a sustainable circular chain, the product is transformed into a new commercial purpose, generating brand appreciation, increasing the income of all involved and minimizing the impact on the environment. The company needs to act in an integrated, clear and unified way with its partners to develop socio-economic and creative solutions for the reuse of solid waste. The obvious benefits of dealing with waste must be considered in all its nuances, as in many cases it can become a simple transfer of waste and transfer responsibility for its management [7, 13].

For occasional and non-recurring situations, companies evaluate in negotiations with third parties to creatively divert waste. This consultative process often generates environmental awareness and seeks solutions for reuse in processes that minimize waste generation. As a point of hindering the business, the difficulty of working in a decentralized way is pointed out and the resignification in obtaining the financial return, since the decentralized operation of distribution of materials to third parties would incur in high logistical costs.

On the other hand, with the development of business models that privilege circularity and sustainability, customers end up having difficulty in understanding the business model and the costs associated with the products sold, especially when customers look for price and compare with other traditional services. To accept to pay the price that the company assigns to the product [8], the client needs to be socio-environmental aware to understand the proposal and to participate in this sustainable socio-environmental concept. The company's business model must be supported by transforming waste into cultural or product value, relating social impact and revenue generation to brand concepts [8].

However, there is a set of processes to observe changes in the business model [10], both at the operational level and in the systemic view [13], when considering all phases of the product, managing the value chain parallel to the life cycle, partner engagement (suppliers, manufacturers, distributors), customers, social, environmental and economic priorities. These steps include: (i) Preparation: identify companies and markets that adhere to waste treatment processes, outline opportunities along the value chain, mainly commitment and endorsement by the organization's top management; (ii) Define Strategy: Conduct an initial assessment to understand the business and propose new practices for building a strategy focused on sustainability; (iii) Define the business model: Improve understanding of the business and detail the impact on sustainability; (iv) Execution Roadmap: the necessary steps for the implementation of the project according to the proposal of the new business model; (v) Implementation: Execute a set of actions mapped to project implementation, iterate, learn from the process, and modify actions as needed and (vi) Retrospective: Observing the results obtained, refining ideas and updating the strategic plan.

The CE offers a large potential of economic gains to companies, due to materials and energy cost savings, new markets and revenue sources, as well as due to a greater resilience to external shocks. Developing circular business models that allow these gains usually requires the implementation of financial models that differ from the more traditional financial approaches applied by businesses following a linear economy. For instance, the pay-for-use model has a very different cash flow structure to the traditional pay-for-ownership approach. These new approaches impact differently on the businesses cost structure, and therefore, on financing requirements [14].

Businesses applying CE principles are highly rewarded economically. Indeed, as stated by the potential economic gains of a transition to the CE for businesses, include [14]: (i) the opportunity for enhanced resource productivity; (ii) improved asset utilization; (iii) strengthened customer relationships and greater revenue visibility; (iv) margin stability and improvement in quality of earnings; (v) enhanced return on capital invested and (vi) higher residual value of the products in many cases.

As well as this, businesses can clearly reduce their production costs when becoming circular. Strategies include the implementation of inner circle approaches, such as reuse or refurbishment, that preserve more of the value of products, as well as the offer of more durable products that make a better use of embedded materials, energy and labour costs, decreasing this way the average cost over the use of the product. Moreover, there are two other main long-term positive impacts of circular economy that businesses get benefited from: (i) businesses adopting a circular approach may mitigate the risk of volatile resource prices as their dependency on finite resources is reduced, having more control on the resources cost; (ii) circular business models are less dependent on imported resources, and therefore, supply disruption risks are reduced too.

Check *GreenTEX Handout – Financial and marketing analysis (https://greentex.p.lodz.pl/)*

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10. Reusing and recycling

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Around 4 tons needed to be effectively recycled every day to prevent the transfer to the landfill, the company has approximately 800 containers for used clothes aside from all sorted textiles and shoes for second-hand sale or charity and cloth for cleaning in the industry. That shows the importance of effective solutions for high a volume of non-sortable clothes. The EU acts The European Environment Agency (EEA) an agency of the European Union, whose task is to provide sound, independent information on the environment [1, 2].

Check *GreenTEX Handout – European legislation (https://greentex.p.lodz.pl/)*

10.1. Reusing

Reusing is defined to use again especially in a different way or after reclaiming or reprocessing [3]. Reusing makes opportunities for the creativity of individuals and allows them to get involved when the integrity of the fabric is not completely dissolved. The study done by Žurga and col [4] involved more than 500 respondents of all ages find that even 45% of them pass their clothes to their ends and relatives, 18% are repairing and redecorating their clothes for a second life, and 24% are donating their clothes. Only about 4% of respondents are throwing their clothes into the trash bin which is s rather positive from this Slovenian study [4].

The charity or consignment concept for the second life of used clothes takes into account that the economical aspect needed no changes to the clothing style in the second use of collected clothes. Collection and resell takes local or mass collections without exceptions since the donation is not limited. Charity can be organised by non-profit organisers or producers of clothes who care about the public opinion of the customers. Awareness about the second life of textiles is necessary to prevent brand misuse problems too [5-7].

Check *GreenTEX Handout – How good business is secondhand shops (https://greentex.p.lodz.pl/)*

The complexity of collection and sorting shows that governments are showing best practice examples and providing certification important for the producers who can declare their environmentally friendly products. Textile platforms give specialised information such as Fibre2fashion and a marketplace, serving all the segments of the textile, garment, and fashion industries [8-10].

Market-based on complete online communication between people who offer and buy or donate used clothes is nowadays an increasing field. Designers use second-hand textiles for their production. Also, the internet is full of tutorials on how to reuse clothing for other objects as DIY webs or workshops. Designers and teachers can work with children in workshops at school or leisure seminars which is good for the education of children to creative work and be aware of textiles. There are no borders in the creativity to use textiles and other kinds of waste to produce original pieces, the second life of textiles in a very different way [11-14].

10.2. Recycling

Recycling is not something invented in the last 20 years, but as a process of ideal use of raw materials, it has been applied by human civilization for a long time. There is evidence already in the Middle Ages. The high value of textiles has historically driven textile recycling. Textile products and clothing were assets, not consumer goods [15].

The benefit of recycling is psychologically very debatable in general. It is difficult for a reasonable person to throw away even a thing no longer used. Recycling is not there to make it morally easier for us to throw away an object but to save resources and, as a global consequence, to extend the lifespan of our civilization [16].

Recycling textiles is difficult – it is not enough to only sort them and then melt them like metals, mix them in water like paper, or melt them like PET bottles [17, 18].

Textile recycling is a process whose complexity corresponds to the complexity of the production of existing textiles. To achieve the top properties of today’s textiles, various polymers, fibres, dyes, chemical treatments, matting agents, membranes and other inputs are combined into very complex structures – composites. We question what we want to recycle from these textiles/composites. It is impossible to test every textile piece entering recycling for the content of today's banned dyes or other content. Concerning the problems mentioned above, textile recycling products are loaded with currently banned chemicals, and their position on the market is problematic from a toxicological point of view.

The current labelling of textiles is sophisticated and mandatory for most textiles, but from the point of view of recycling, its current form is difficult to use. The problem is that the label with the textile designation can be separated from the garment, problematic legibility for worn textiles and almost zero possibility of robotic reading these labels. The current situation leads to two possible solutions: changing the labelling of textile composition and searching for recycling technologies independent of textile composition [19].

More attention is being paid to recycling technologies independent of their chemical composition. Typically, this involves product recycling, i.e. creating a layer of fibres or parts of textiles from a textile product simply by homogenization and using the resulting product, for example, as thermal insulation. In the EU, a significant change in legislation awaits us in 2025, which will make the separation of textiles from waste mandatory. This will create a giant source of textile waste that will need to be tracked and recycled [20].

10.3. Recycling technologies of textiles

Recycling on the level of 'product' is a recycling method based on finding a new user for the product. The reason is usually an inappropriate size, a change in fashion trends, deep damage, or another moral product ageing. This recycling method is widespread thanks to the common form of donating textiles to charity. The original user is motivated by the moral aspect of the collection, i.e. that the textile will help someone socially weak. It is common for textiles to be exported from the country of origin to South America or Africa. Usually, only fashionable clothes from renowned brands in excellent condition can be used. Quite often, this method is used for children's clothing, where concerning children's growth, they do not have time to carry textiles and cannot resist their parents' will. There is great potential here for wider textile recycling at the product level.

Recycling on the level of 'fabric' in the form of pieces of fabric. The first step of this recycling is the selection of suitable textiles – it is mainly about the material composition. Textiles with a high cellulose content are preferred for use in the form of ‘fabric‘. The reason for this is their high wettability and ability to retain water. Wettability is key for cleaning textiles as it allows for a relatively firm connection between the dirt and the textile mediated by water. The preparation for this recycling consists in cutting the waste textile product into smaller parts, whereby non-standard areas such as zippers, collars, and buttons are separated.

Recycling on the level of ‘parts‘ mean undefined parts of textile waste, usually with dimensions of around 10 × 10 mm. These parts behave as separate particles, they can be easily handled, and at the same time, they have very interesting thermal insulation and sound insulation properties. The preparation for this recycling consists of separating non-textile components, such as buttons and zippers, which would bring problems in the next operation which is chopping/cutting the textile waste to the required size. This is followed by mixing to ensure the stability of the average properties of the product. Synthetic fibres are beneficial in this case because they can be used as a binder in some subsequent operations [21].

Check *GreenTEX Handout – Potential of fibre fragments (https://greentex.p.lodz.pl/)*

Recycling on the level of ‘yarns‘ Separating yarn from textile waste is a less common way of recycling textiles by steaming an old sweater and knitting it into a scarf. This is typical recycling at the level of yarns – yarns are separated from textile waste and then processed into textiles. Expanding this technology industrially would be interesting for knitted products that could be knitted with a vision of future pairing [22].

Recycling on the level of ‘fibre‘ refers to separating fibres from textiles and their subsequent use, for example, as a raw material for textile technology. The separation of fibres from textile waste can be intensified by low temperature (cryogenic milling) or other methods. The result can be very short fibres. The mechanical comminution of the textile into individual fibres or parts of fibres enables or facilitates the separation of individual types of fibres.

For example, it is possible to remove polyester fibres from cotton fibres. Recycling at the fibre level is very interesting and promising. Individual fibres, including concrete, can be used as a reinforcing component in composite structures. With an appropriately chosen mechanical method of separating fibres from textile waste, it is possible to obtain spinnable fibres (that is, with a length greater than approx. 10 mm) and to process them into yarn and potentially any textile products [23, 24].

Recycling on the level of ‘polymer‘ is ideal for raw materials for textile production. We separate fibre-forming polymers from textiles, which we process as the original raw material. This process has some weaknesses: multiple types of fibres in one fabric (mixed fabrics), the possibility of contamination with different fibres, dyes and similar chemicals in the fibre mass. Fibres for textile purposes are optimized for high resistance to chemicals and solvents, so it is very difficult to dissolve the fibres. The ideal procedure would be to separate the fibres from each other and then melt/dissolve them and spin them into new fibres. A significantly less convenient but universal procedure removes all ‘unnecessary‘ fibres, such as cellulosic and protein fibres, from the mixture forming them into foil or an undefined mixed plastic [25].

Recycling on the level of ‘monomer‘ is the breakdown of polymers into smaller parts – into monometers, from which individual polymers are made. For example, in the case of polyester, it is terephthalic acid and ethylene glycol. The decomposition of polymers into monomers is advantageous due to their easy purification. Polymers can be made from these monomers again and processed into full-fledged fibres or other polymer products. This procedure is very promising, but it is quite complex and energy-intensive. A very interesting solution is the possible enzymatic decomposition of cellulose to form glucose/ethanol and the subsequent chemical separation process [26].

Recycling on the level of ‘carbon‘ since all fibres used in clothing and the vast majority of fibres used in industrial applications are organic based. These fibres, therefore, contain a significant proportion of carbon – kapproximately 80%, depending on the type of fibre. This carbon can be thermally separated by pyrolysis – pure carbon remains. This process occurs at temperatures above 600°C. Carbon can be an excellent sorbent or even a very good conductor of electricity. The goal of fibre pyrolysis is usually to obtain carbon fibres, but this is only possible in the case of non-fusible fibres with high-temperature resistance – such as para-aramid fibres (e.g. Kevlar) and, to a certain extent, cellulose [27].

Recycling on the level of ‘energy‘ is a catch-all name for the fibreration of textile waste, but it is recycling the last resort. Incineration of textiles is currently very common; approximately 95% of all textile waste is incinerated, which is a very bad business for society.

10.4. Comparison of Recycling methods

Just as there is no ideal method of textile production, there is no ideal method of recycling textile waste. It is possible to build a process that can process all textile waste in one technology, but it will not make good use of the potential of this waste.

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