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INTERNATIONAL STUDIES AND EVALUATIONS IN THE FIELD OF

TEXTILE ENGINEERING

EDITOR

ASSOC. PROF. NURAY OLCAY IŞIK EMEKSİZ

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Chapter 1

SOLAR POWERED TEXTILES

Duygu ERDEM AKGÜN[1]

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1. Introduction

Wearable technology which includes smart textiles is becoming widespread each day. It refers to devices and garments that can be worn or loosely attached on a person and have the ability to collect and process data and provide communication using Bluetooth, Wi-fi, or other technologies (Godfrey et al., 2018). Smart textiles are used for defining high added value textiles which gathers the information and communication technologies with functional and emotional characteristics of fashion (Ju and Lee, 2020). Additionally, smart textiles are a good choice in comparison with electronic devices since they are easy to use and wearing them is not a burden that must be remembered. By means of facilities they offer, smart textiles are used in different sectors such as health sector, athletics, military applications and entertainment sector (Grancarić et al., 2018).

A power source is needed to activate sensors, actuators, and other electronic components on smart textile structures, and it is widely studied in wearable technology field. Although all these components require a power source to function, power levels could be differed according to the application. Power consumption of smart textiles vary from a few micro watts to tens of watts. For instance, while watches, hearing aids and pacemakers require only about tens of micro-watts, wireless communications require an average power of around 500 mW. Alkaline, Nickel-metal hydride (NiMH), Lithium-ion and Lithium-ion polymer batteries are generally used as power sources in smart textiles, but such rigid components cannot be completely incorporated into textile-based structures and negatively affect the properties of textile products such as flexibility, comfort and washability. Besides, they are bulky and requires recharging or frequent replacement (Beeby et al., 2023; Satharasinghe et al., 2020a; Stoppa and Chiolerio, 2014).

Graphite has been extensively used in the lithium-ion batteries (Zhao et al., 2022). Graphite is one of the traditional energy sources, also known as non-renewable energy, are dependent on a resource that depletes as it is used, and its permanency is not possible. Although this type of energy obtained through the natural resources of the world is seen as an important energy source for many sectors, its effects on the human life and environment is negative, such as carbon footprint. However, the global economy, rapid population growth and scarcity of natural resources also make it difficult to meet the energy demand. To reduce the carbon footprint and renewable clean energy resources instead of traditional energy resources can be used. Especially, solar powered energy resources are potential candidates since they are abundant, sustainable and harvesting them is easy (Ke et al., 2023; Niu et al., 2022).

2. Energy Storage Textiles

Batteries and supercapacitors are ideal energy storage devices and mostly used to provide the energy requirements of smart textiles (Liu et al., 2018). Technological advancements in the electronic and textile industries make it possible to produce supercapacitors or batteries integrated within a flexible textile matrix (Zhai et al., 2016).

Supercapacitors are known with their high-power density, safety and wearability that makes them suitable candidates for rising generation wearable electronics. Besides, their comparatively low energy densities (in comparison with batteries) and high self-discharge ratios limit their usage. Although advances in technology have resulted in energy storage devices that are both thin and flexible, the incorporation of such devices into a textile structure will have a significant impact on textile properties, particularly heat and moisture transfer properties. Therefore, significant research has been conducted to integrate energy storage capacity into textiles and to produce textile-based energy storage devices (Liu et al., 2018; Satharasinghe et al., 2020a).

Researchers are working on textile-based supercapacitors and lithum-ion batteries (LIBs). Textile-based supercapacitors could be found in different forms such as fiber/yarn or fabric. Normally, textile materials are non-conductive materials by their very nature, and it is obligatory to make them conductive. It can be obtained by covering them with conductive coatings like metals and carbon-based materials (Jost et al., 2011; Liu et al., 2018). Liu et al. developed a supercapacitor with coating single-walled carbon nanotubes (SWCNTs) around cotton threads by a dipping and drying process (Liu et al., 2013). Cheng et al. coated PEDOT:PSS on PET fabric using a conventional dyeing process and produced a textile based flexible supercapcitor (Cheng et al., 2020).

Textile-based lithium-ion batteries also could be existed in fiber/yarn or fabric form. Fiber/yarn shaped lithium-ion batteries can be easily woven or knitted into desired textile structures and ability to bent, twist and stretch (Liu et al., 2018). The first fiber/yarn shaped LIB was developed by Ren et al. They twisted an aligned carbon nanotube (CNT) fiber with a lithium wire (Ren et al., 2013). As well as supercapacitors, carbon-based textiles are used for fabric form LIBs. For instance, Luo et al. reported highly ordered TiO_2@α-Fe_2O_3 core/shell arrays on carbon textiles (Luo et al., 2012).

3. Energy Harvesting Textiles

Energy harvesting is derivation small amounts of electrical energy with converting ambient energy and it can be an option to energy storage textiles for powering wearable electronics and smart textiles. The most commonly investigated energy source for harvesting are mechanical sources (e.g., strain, displacement), thermal alterations, wind energy, solar energy, light and salinity gradients. In consequence of small amounts of energy harvesting, only small autonomous devices could be activated. Among the different effects which is used for energy harvesting, the widely used ones are thermoelectric, piezoelectric, triboelectric and photovoltaic effect. Although a wide range of energy harvester devices exist, implementing them into the textiles and their production is still a challenge. Besides, both battery and energy harvesting technology cannot serve the purpose of smart textiles industry (Satharasinghe et al., 2020a; Soin et al., 2016; Torah et al., 2018).

Thermal energy harvesting could be possible with thermoelectric generators by taking advantage of the temperature difference between the environment and human body. Wearable thermoelectric generators could be found in various forms. For instance, rigid thermopiles could be attached to the garments, printable thermoelectric films could be dispensed on fabric to form thermopiles, using spacer fabrics and yarns coated with waterborne polyurethane/carbon nanotube thermoelectric composites a 3D structure could be generated (Leonov, 2013; Kim et al., 2014; Wu and Hu, 2017).

Piezoelectric energy harvesting uses human motion as the energy source. Several textile based piezoelectric generators can be found in the literature. Various types of piezoelectric strands have been developed by twisting nanofibers, piezoelectric fibers or yarns by electrospinning, melt spinning etc. In addition to yarn spinning, these piezoelectric strands could be used to manufacture woven, non-woven, knitted, braided, and spacer fabric structures (Satharasinghe et al., 2020a).

The triboelectric effect is the electrical charging of two substances with different polar properties according to the triboelectric series which have different electron attracting characteristics in contact or friction (Pu et al., 2018; Zeng et al., 2014). Most of the textile based triboelectric generators generate energy using vertical pressing or rubbing. Choi et al. developed a corrugated textile based triboelectric generator which can produce energy by stretching (Choi et al., 2017). Usage of metals and polymers in the film type is mostly seen in the literature. However latest studies focus on the fiber and fabric type generators (Kwak et al., 2019).

Photovoltaic textiles are textile structures like solar cells and generates electric energy by transforming photon energy. Photovoltaic textiles could be manufactured in two ways: either a separately produced solar cell can be integrated or attached to the textile structure or solar cell materials can be deployed to form a textile structure such as polymer-based substrates, fiber, yarns, etc. However, it is anticipated to be flexible and lightweight for the application onto various surfaces without any deformation (Bedeloğlu et al.,2010).

4. Solar Energy Harvesting

The Sun, the source of life, is also a substantial source of energy for the planet Earth and reserves a large part of the natural system energy. Solar energy is mostly used for the heating, water heating and cooling. The entire concept of solar energy is regarded as the collection and use of light and/or heat energy produced by the Sun and the technologies (passive and active) used to achieve these goals. Passive technology involves the collection of solar energy without converting it into another form of thermal or light energy (e.g. for power generation). Collecting, storing and distributing of solar energy in the heat formation for heating homes (especially during the winter) is a kind of passive solar energy technology. From another point of view, active solar systems gather solar radiation and convert solar energy into heat and electrical power by mechanical equipment such as pumps or electrical equipment such as fans. The most well-known implementation of active solar systems is solar water heating system (Karamanav, 2007; Kabir, 2018).

Solar energy can be harvested by illuminating photons comes from the sunlight upon semiconductors. It was first presented by Alexandre Edmond Becquerel in 1938, a French scientist. As long as there is sunlight, energy can be produced by solar cells. A characteristic solar cell is formed of two semiconductor materials (P-type and N-type) and two electrodes (Satharasinghe et al., 2020a; Fraas and O'Neill, 2014; Luque and Hegedus, 2011). The schematic of a solar cell can be found in Figure 1.

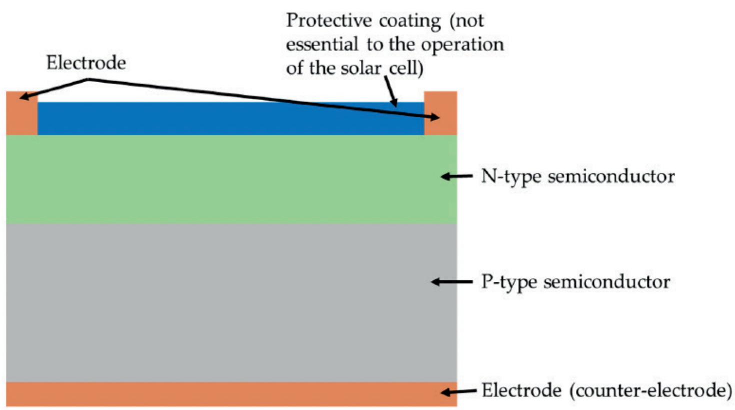

Figure 1. *Simple schematic of a typical solar cell comprising of two semiconductor materials (P-type and N-type) and two electrodes (Satharasinghe et al., 2020a)*

There are four main parameters of a solar cell. These are open circuit voltage (Voc), fill factor (FF), short circuit current (Isc), and efficiency (η). If two terminals are directly connected and the voltage is zero, current gets its maximum, and this is called as short circuit current. If there is no load and no current flowing across the cell, the voltage reaches maximum value, and this is named open circuit voltage. Fill factor is used to determine the quality of solar cell. It is acquired by dividing the maximum power derived from the actual solar cell by the maximum power derived from the ideal solar cell. For a good cell FF value between 0.7 and 0.8 is expected. Efficiency is the mostly used feature to measure the performance of a solar cell. The efficiency can be calculated by dividing the energy output of the solar cell to energy input from sun. Solar spectrum, density of sunlight and the temperature of solar cell are the factors effecting the efficiency (Chikate et al., 2015).

5. Textiles with Solar Cells

Solar panels consist of a great number of solar cells. Considering the materials used for the production, solar cells are divided into various classes. These classes can be seen in Figure 2.

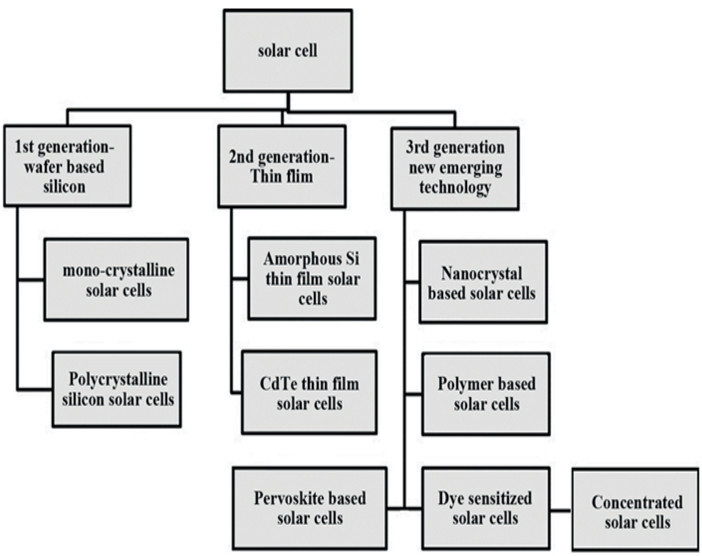

Figure 2. *Solar cell classes (Sharma et al., 2015)*

Solar cells can be investigated mainly in three generation. First generation solar cells are produced on silicon wafers. Silicon wafers could be made from a single/mono silicon crystalline or could contain many crystals (poly/multi silicon crystalline). First generation is the earliest and the mostly used technology on account of high power efficiencies. Thin film solar cells are the second generation solar cells. The types of thin film solar cells are amorphous silicon (A-Si) solar cells, cadmium telluride (CdTe) solar cells and copper indium gallium di selenide (CIGS). They are more economical than the first generation because of the reduced material amount for the production. Nevertheless, to generate the same amount of power thin film solar cells require more surface area and their efficiency is lower than other types. Lastly, the new promising technology in solar cells is the third generation. Most of the third-generation solar cell types are nano crystal based solar cells, polymer based solar cells, dye sensitized solar cells, concentrated solar cells, and perovskite solar cells (Sharma et al., 2015; Bagher et al., 2015).

With the developments in the solar cell technology, the amount of efficiency is gradually increase and state-of-the-art solar cells perform a good solar energy harvesting. However, they are not able to be integrated into mostly used objects or clothing since they are not flexible and conformable enough. Textile materials provide a lightweight and flexible base for solar cells. Integration of textile and solar panel technology opens up further areas for both industries. Moreover, many surfaces exposed to the sun are textile materials such as garments, tents, outdoor textiles, car coverings, boat sails, etc. (Mather and Wilson, 2022; Opwis et al., 2016).

Textile based solar cells have many advantages. Flexibility is the mostly mentioned advantage of textile materials. The other one is the size of the production. For instance, it is difficult to produce printed solar cells in large web widths. However, gathering printed solar cells with textile materials is a good solution for both mechanical stability and the extending to large widths. Textiles also provide flexibility in terms of production phase. Solar cells or photovoltaic materials used in the solar cells can be integrated into textiles in different stages. They can be used as fiber/yarn or can be woven or knitted to generate a fabric. Also, they can be found in different forms such as films, coating or dyes and applied to textile materials directly (Krebs and Hösel, 2015). Although there are many different production techniques, textile solar cells can be basically divided into two categories as Fiber-Shaped Solar Cells (FSSC) and Planar-Shaped Solar Cells (PSSCs). Planar-Shaped Solar Cells are directly fabricated on a textile substrate and processing is easier than Fiber-Shaped Solar Cells. However, they could absorb the light from only one side. Fiber-Shaped Solar Cells could potentially absorb sunlight from all dimensions through their cylindrical structure and due to their lightweight and flexibility properties, their integration into textiles can be employed in various applications (Hatamvand et al., 2020). Another technique is to integrate the conventional solar cells directly onto textiles. These techniques will be explained with examples in the following sections.

5.1. Integration of Solar Cells into Textiles

The easiest technique to add solar energy harvesting devices to a textile material is superficially attach flexible solar cells onto the fabric surface directly. Energy harvesting through solar textiles includes capturing photons come from sunlight and converting it into usable power (Satharasinghe et al., 2020a).

Solar shirt by Pauline van Dongen is an example of the solar cell integrated textiles. The shirt seamlessly associates 120 thin film solar cells. Functioning as a fashion garment, the shirt combines solar cells and flexible electronics. The Solar Shirt can be used for everyday use and can charge a smartphone, MP3 players, cameras, GPS systems or any other USB compatible portable devices. Also, a battery pack invisibly located in the front pocket provides energy storage for later use (Solar Shirt, n.d.).

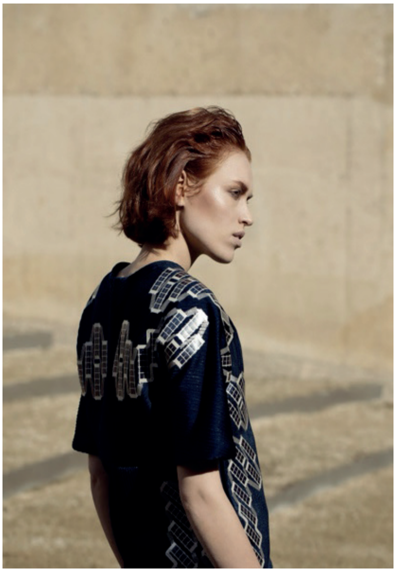

Figure 3. *Solar shirt by Pauline van Dongen (Solar Shirt, n.d.)*

Another example is the Sunslice Zenith backpack. It is a modern looking and a lightweight backpack for daily use with a powerful solar charger. This backpack has flexible copper indium gallium selenide solar cells on its outer surface. The flexible solar cells have a conversion efficiency of 16.5% (Zenith Solar Backpack, n.d.).

Figure 4. *Sunslice Zenith backpack (Zenith Solar Backpack, n.d.)*

In 2011, Ralph Lauren launched the RLX backpack with a solar panel on the back that produces 2.45 watts. A smartphone can be charged in two or three hours with this energy. The backpack is made from waterproof material, has a buckle-closed top flap, zippered pockets and a side handle for hand carriage (Ralph Lauren Solar-Powered Backpack Is Predictably Expensive, n.d.).

Figure 5. *Ralph Lauren's RLX Solar Backpack (Ralph Lauren Solar-Powered Backpack Is Predictably Expensive, n.d.)*

In 2014, Tommy Hilfiger released two solar jackets both for men and women which is able to charge electronic devices such as mobile phones or tablets by converting energy from removable solar cells installed to the back of the jackets. The jacket has a hidden cord in the lining that connects solar panels to a detachable battery pack in the front pocket and two USB ports allowing users to connect two devices simultaneously. The solar panel on the jacket is composed of flexible amorphous silicon solar cells by Pvilion. When exposed to direct sunlight, solar cells charge the battery pack which can fully charge a 1500 mAh mobile device up to four times (Arthur, 2014).

Figure 6. *Solar Powered Jacket by Tommy Hilfiger (Tommy Hilfiger Solar Clothing, n.d.)*

As seen in the examples, attaching flexible solar cells onto textile materials is a well however primitive solution for developing solar powered textiles. There are some disadvantages of these applications such as appearance and the comfort properties. The application of solar cells changes the design characteristics of the garments. Although they are in a flexible structure, they can cause discomfort if the user contacts the cells directly. One of the expected features of clothing is washability a flexible solar cells integrated garments should be durable to harsh conditions of a domestic machine wash (Satharasinghe et al., 2020a). To improve wearability features of solar powered textiles, integration level should be enhanced.

5.2. Fiber-Shaped Solar Cells

There are two main ways to fabricate a FSSC: coating active layers on a cylindrical substrate (thread, metal wires, optical fibers etc.) or building solar cells onto traditional polymeric textile fibers. The first approach provides a less complicated production method and better device performance while the second approach is widely accepted for keeping the textile features. The developed FSSCs can be embedded inside an any desired textile material or associated to form a fabric structure (Hatamvand et al., 2020; Satharasinghe et al., 2020a).

Recent research and progress efforts have led to fabrication of Fiber-Shaped Organic Solar Cells (FSOSCs), Fiber-Shaped Dye Sensitized Solar Cells (FSDSSCs), and Fiber-Shaped Perovskite Solar Cells (FSPSCs) (Hatamvand et al., 2020).

In comparison with FSDSSCs and FSPSCs, the efficiency of FSOSCs is stays low. However, FSOSCs are regarded as one of the most encouraging candidates by means of its superiority such as all-solid state, easy manufacturing, eco-friendliness, and material stability. The performance of FSOSCs directly depends on the performance of used organic semiconductors. The formerly developed FSOSCs mostly used organic semiconductor blends with polymer-based donors and fullerene-based acceptors such as P3HT:PC_{61}BM, and PTB7:PC_{71}BM for the light absorption. Another alternative for light absorption is non-fullerene acceptor materials which is easy to process and deposit on the flat surfaces and flexible substrates (Lv et al., 2022).

Lee et al. fabricated a flexible wire organic photovoltaic using two wires and a polymer coating. A phase-seperated photovoltaic layer which is consisted of a conductive polymer and a fullerene derivative was coated onto a thin metal wire. A second metal wire coated with silver film as a counter electrode was wrapped around the first wire. Both wires were laminated with a transparent polymer. It is reported that the efficiency of wires range from 2.79% to 3.27% (Lee et al., 2009).

Satharasinghe et al. investigated to create solar cell embedded yarns. For this purpose, the miniature SCs were soldered onto two fine copper (Cu) wires and then encapsulated within clear, cylindrical resin micropods and lastly covered by a fibrous textile sheath (Satharasinghe et al., 2020b).

Liu et al. developed a new type of solar cell with textile-based materials instead of liquid electrolytes. They deposited classical semiconducting polymer-based bulk heterojunction layers onto stainless steel wires for generating primary electrodes and changed metal counter electrodes with carbon nanotube thin films or condense yarns. The developed solar cells by researchers have potential in the production of low cost and flexible fiber-based photovoltaics (Liu et al., 2012).

Fiber-Shaped Dye Sensitized Solar Cells (FSDSSCs) are easy to prepare, lightweight and weavable. These features make them a promising candidate for new age wearable electronics. However, the use of FSDSSCs is limited on a large scale due to their low power conversion efficiency and flexibility. To solve these problems, Zhang et al. developed a flexible fiber shaped dye sensitized solar cell with platinum free counter electrode with polyaniline layer on the surface of carbon fibers (Zhang et al., 2019).

Casadio et al. used inexpensive TiO_2 for the first time as photoanode material and a fully organic thiazolo [5,4-d]thiazole-based sensitizer (TTZ5) and fabricated 10 cm long FSDSSCs (Casadio et al., 2021).

Third type of Fiber-Shaped Solar Cells is Fiber-Shaped Perovskite Solar Cells (FSPSCs). Perovskite is a new type of photoactive material with superior energy conversion efficiency and solution processability and offers to produce fiber-shaped optoelectronic devices with low-cost and high performance (Balilonda et al., 2022).

In 2014, Qiu et al. developed a FSPSC with continuously winding an aligned carbon nanotube onto a stainless-steel wire and photoactive materials are included between them by a solution process. FSPSC shows an energy conversion efficiency of 3.3% and can be woven/knitted into electronic textile structures (Qiu et al., 2014).

In 2015, Li et al. studied double-twisted fibrous perovskite solar cells based on flexible carbon nano-tube fiber electrodes with a maximum power conversion efficiency of 3.03%. The developed FSPSC shows a bending stability greater than 1000 cycles and sustain 89% efficiency after 96 hours in ambient conditions when sealed by a transparent polymer layer (Li et al., 2015).

In 2015, Lee et al. developed a methylammonium lead iodide ($CH_3NH_3PbI_3$) perovskite solar cell in a flexible fiber shape via a fully dipping process. They spray-deposited silver nanowires (Ag NWs) as the top electrode instead of gold. They achieved a power conversion efficiency of 3.85% and developed FSPSC is stable during bending. Their approach provides ease of fabrication, the used materials are cost efficient (Lee et al., 2015).

In 2016, Wang et al. demonstrated a wire-shaped perovskite solar cell based on TiO_2 nanotube (TNT) arrays by integrating a perovskite absorber on TNT-coated Ti wire. Ti wire was wrapped by a transparent carbon nanotube and used as a hole collector and counter electrode. By its easy fabrication process this approach is promising candidate for portable and wearable textiles (Wang et al., 2016).

In 2017, Lam et al. fabricated a textile-based flexible and washable FSPSC and used an elastomer as encapsulating material and electrodeposited it with tin oxide (SnO_2) (Lam et al., 2017).

5.3. Planar-Shaped Solar Cells

Printing, coating and lamination applications of organic photovoltaics (OPV), hybrid photovoltaics and perovskite solar cells onto textile structures for textile-based photovoltaics have been extensively investigated lately (Satharasinghe et al., 2020a). Planar-Shaped Solar Cells (PSSCs) has an easier processing due to fabrication directly on a textile substrate, compared to

FSSCs. While FSSCs could harvest sunlight from all dimensions, PSSCs could absorb light from only one side (Hatamvand et al., 2020). Some examples of PSSCs are presented below.

In 2018, Jung et al. developed a textile based PSSC with coating a thin layer of polyurethan (PU) on the prepared polyester textile using a paper transfer method (R/P lamination). The developed solar cell shows a power conversion efficiency of 5.72% with good ambient stability up to 300 hours (Jung et al., 2018).

In 2018, Saygili et al. fabricated solar cells by spin coating the hole transport material (HTM) layer with distinct doping concentrations onto the perovskite film (Saygili et al., 2018).

In 2018, Liu et al. used a fabrication method based on screen printing and spray coating and used a low temperature processed TiO_2 paste. The fabrication is made at low temperatures and compatible with Kapton and 65/35 polyester cotton fabrics. It is reported by the authors that results show a power conversion efficiency of 7.03% and 2.78% on Kapton and fabric respectively when using a platinum coated fluorine tin oxide (FTO) glass as the top electrode (Liu et al., 2018).

In 2022, Borazan et al. developed an organic solar cell by depositing poly(3,4-ethylenedioxythiophene)–poly(styrenesulfonate) (PEDOT:PSS) and poly(3-hexylthiophene): phenyl-C61-butyric acid methyl ester (P3HT:PCBM) on a stainless steel mesh fabric by dip coating and depositing a back metal electrode by thermal evaporation. The metal based solar fabric has a power conversion efficiency of 0.69% (Borazan et al., 2022).

In 2022, Yun et al. demonstrated the first flexible fabric-based gallium arsenide (GaAs) thin film photovoltaic cells. The GaAs structures were transferred on fabric via stress-assisted fast epitaxial lift-off (ELO) and Au-Au bonding technique with superior bendability (Yun et al., 2022).

6. Results, Discussion and Future Perspectives

Due to the increasing energy demand, the production and application of new energy materials and devices have attracted worldwide attention. In particular, solar energy-related energy sources are ideal alternatives to traditional fuels due to their abundance, sustainability, and ease of solar energy harvesting. Considering the important strategic needs of global energy, strengthening research on photovoltaic energy storage will provide additional technical pathways and support for carbon reduction and green energy development (Ke et al., 2023).

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Chapter 2

TEXTILE RECYCLING

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1.1. Introduction

The idea of recycling has emerged as a consequence of the depletion of natural sources. Since textile industry wastes harm the environment, environmentally friendly practices in the textile industry include "cleaner production", "recovery/reuse", "primarily reducing waste", "product modification", "recycling", "energy recovery" and " acquisition" strategies. Owing to its large production volume, the textile industry in Turkey generates approximately one million tons of waste every year. If full recovery is possible, this would equal 17% of the annual national non-ginned cotton production. It is very difficult to examine recycling under a single heading in textile production because the raw materials, machinery, energy types and costs, environmental interactions in the production process, processes and recycling of products are not the same. The highest amount of recycling class was fibre recycling (57%), after polymer/oligomer recycling (37%), monomer recycling (29%), and fabric recycling (14%), and the most used materials were cotton (76%) and polyester (63%) (Sandin and Peters, 2018).

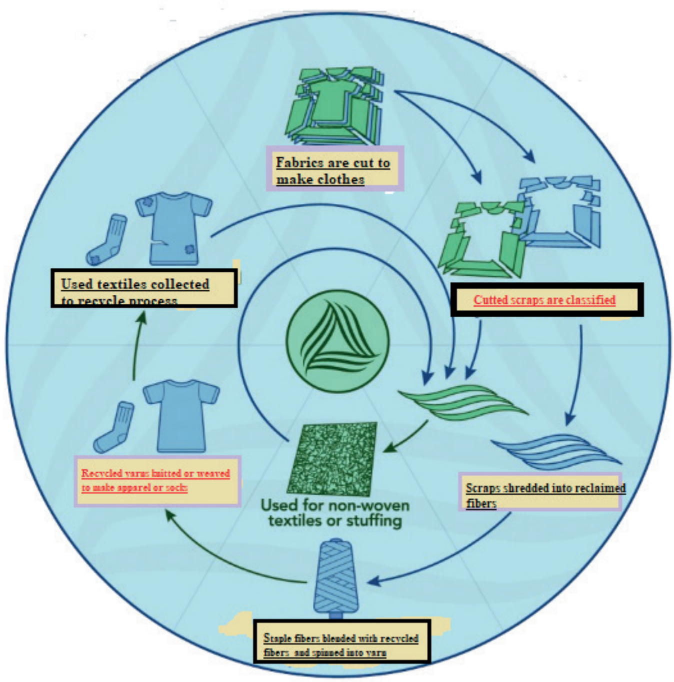

Figure 1. *Recycling of Textile Wastes*

The textile industry utilizes huge quantities of non-recyclable resources and uses unsafe materials and polluting methods. Besides, the continuous spread of fashion trends has resulted in the selling of discarded garments after only a few wears. Therefore, new solutions should be developed and implemented to reduce the use of pure resources. One recommended way is to rise recycling in the textile and clothing industry.

Clothing waste management is important for sustainability. In previous studies, it was declared only 20% of clothing waste is recycled, the rest causing huge raw material losses, resulting in energy losses and negative effects on the surroundings (Lewis, 2015). Another study declared that solid waste can be recycled to increase the circular economy (Payne, 2015).

Koszewska (2018), stated that cotton fiber is preferred because of its comfort, natural appearance and moisture management features. But, cotton needs a huge amount of water, soil, pesticides and fertilizers during its growth.

The world's fiber consumption is constantly increasing and can be increased further in the future. According to available information, the amount of textile production has increased in the last two decades and the average global consumption of textile waste has risen (Durham et al., 2015).

With the development of technology, consumption amounts are increasing beyond what is needed. Excessive production and use of all resources are not considered sufficient to meet these demands. The increasing demand for textiles is not only based on more population demand but also changes with new fashion habits. Textile manufacturing wastes are unwanted but expected from spinning, weaving, knitting or garment manufacture production processes and are often depreciated. But, if such wastes can be converted to economically usable products, a great contribution will be made to the market.

Currently, annual textile fiber manufacture has passed 82 million tons, approximately 40% of which consists of cellulosic substances. With an annual manufacture of over 27 million tons, cotton constitutes approximately 1/3 of the market (Andreas, 2012). The fast increase in cotton textile industries and higher production capacity has resulted in huge outcomes of waste cotton fibers. In addition, there is an increasing demand for recycling procedures to manufacture worthy outcomes from cotton wastes (Meyabadi and Dadashian, 2012).

Textile wastes cause environmental pollution and are separated into pre-industrial/consumer and post-consumer wastes. Industrial waste is defined as textile material that is discarded after the production process and service life is completed. Nonwovens used for insulation, padding, upholstery, oil filters, hospital linens and gowns were produced from recycled fabric wastes (Goyal, 2021).

For the textile companies to be sustainable, information on the source and manufacture of sources and recycled raw materials are expected to constitute an important role of the resources utilized in the future. Recycling of post-consumer textile wastes is a new process, and major problems will arise in the coming years due to the depletion of resources. The biggest problem in this area is that the classification of natural or manufactured textile fibers. Fiber classification is made due to chemical groups and bonds.

1.2. Textile Wastes

The textile industry pollutes the environment and causes waste, from fiber to clothing. According to the a previous research, it has been determined that various fibers are compared with both natural and sustainability, and synthetic fibers acquired by traditional manufacturing processes are far behind in the sustainability ranking (Made-By, 2013).While cotton has the advantages of natural fibers, the water consumption of cotton production causes serious environmental effects on land occupation, emissions and pesticides. Cotton cultivation 7 tons/kg water (Grose, 2009).

Textile production waste is divided into three categories: (a) garbage waste - waste that needs to be cleaned before reprocessing. Examples of this are blowroom waste, carding waste, flat card slivers and filter waste. (b) clean waste - waste that does not require additional cleaning. For example; comber waste, carding machine, draw frame and carded sliver waste, filter waste from draw frames, high-speed machines, ring spinning machines and rotor spinning machines. (c) hard waste - waste that must be opened in special machinery. Examples of this are twisted roving, yarns and textile fabrics (Larney and Van Aardt, 2010).

Waste Types

a) Pre-consumer Waste: Pre-consumer textile waste generally means waste by-products from fiber, yarn, textile and apparel production. For example; mill bits, scraps, scraps or goods damaged during manufacture and most are recovered and used for automotive, furniture, bedding, furnishings, and paper industries.

Figure 2. *Pre-consumer wastes of textile (fiber, yarn, vs..)*

b) Post-consumer Waste: defined as a product that an individual anymore demands and defines to compose with wear or damage. It means second-hand or worn garments, linens, towels, and other widely used textiles. Post-consumer waste that can be recycled is clothing, blankets/curtains, towels, sheets and blankets, clean cloths and sewing residues, tablecloths, blankets, covers and bags.

Figure 3. *Post-consumer textile wastes (clothing, linens, vs..)*

In the fashion chain, sources are produced from renewable sources and consumer wastes or wastes manufactured in factories in the form of yarn. For textile companies to be sustainable, it is important to know the origin of resources and production technologies well. No major progress has been made in the recycling of post-consumer waste. Unless the awareness of the consumer is increased, there will be no progress on the benefits of the recycling method and the use of recycled products. Also, the most challenging of the post-consumer stream is poorly defined, contaminated, degraded fiber quality due to washing and abrasion. In Europe, 10% of garment waste is recycled and the remainder 8% is thrown away (~57%) or burned (~25%) (Beton et al., 2014).

Patagonia company recycles many clothes produced from Polartec polyester fabric (McDavid, 2007). In Turkey, a composite with increased mechanical and physical features is obtained by reinforcing recycled polypropylene with silk and cotton wastes. Manufacturers of upholstery and automotive needled fabrics are facing an increasing demand for polyester recycled fibers that can make good use of the traditional recycling processes used to make recycled fibers.

Recycling should be done by taking into account the polymer structure of the fibers while recycling. In blended fibers, it will be more advantageous to recycle these fibers by dissolving the fibers with a high mixing ratio. Textile recycling is divided into three different parts (Table 1). These segments are recycled at the fiber, polymer or monomer level.

• Fiber recycling means preserving the fibers after the fabric is shredded.

• Polymer recycling involves disassembling the fibers while the polymers stay stable.

• Monomer recycling refers to the breakdown of fibers and polymers into chemical building blocks.

Besides the recycled input, virgin renewable resources are needed to handle the loss of quality when polymer and fiber recycling flows are applied since it is always more advantageous to (re)start from the monomer level.

Recycling of fibers is done using mechanical, physical and chemical methods. Of these, mechanical methods are made by shredding, cutting and carding the fabric and as a result, fiber length, bendability and yarn strength decrease.

Physical methods are the method used to melt or dissolve fibers or polymers to make them suitable for reprocessing. In physical recycling, the construction of the fibers changes, and the molecules of polymers create the fibers to stay stable. Mechanical recycling includes shredding the material to change its fibrous form. During this operation, the strength of fibers decreases, so, necessary to mix with virgin fibers, especially in cotton and wool.

Chemical methods used for breaking of chemical bonds of fibers and polymers. The polymers that compose the fibers are sometimes changed into monomeric building blocks. This process can be made chemically or biologically with the help of enzymes. Chemical recycling means a chemical process to get the required raw material. This method causes the saving of more valuable products and shows technological progress.

Table 1. *Textile Recycling Classification (Harmsen et al., 2021).*

Textile Recycling Classification	**Recycling Methods**
Fibre recycling	Mechanical Methods
Polymer recycling	Mechanical- Physical methods
Monomer recycling	Mechanical -Chemical methods

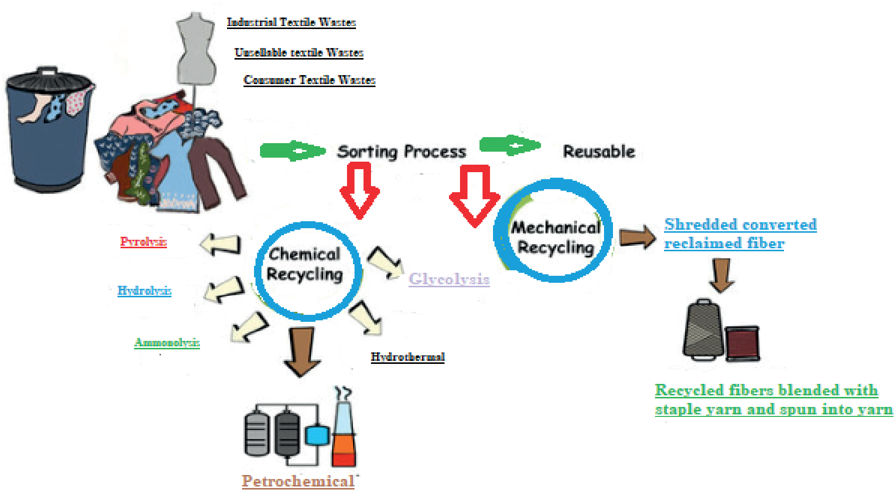

Figure 4. *Chemical and Mechanical Recycling of Textile Wastes*

1.3. Recycling of Most Commonly Used Fibers

1.3.1.Recycling of Cotton

Recycling processes of fibers vary depending on whether the fiber is natural or synthetic fibers, while natural fibers must be mechanically converted, synthetic fibers must be recycled chemically. Mechanical shredding is done by using garnet machines. The disadvantage of these machines is that the length of the fibers decreases and the fibers weaken during the tearing process of the fabrics. Mechanical recycling includes operations aimed at recycling wastes through mechanical processes such as grinding, washing and separation. For chemical recycling, the product is first separated into its components and these components are then reused as raw materials to reproduce the original product.

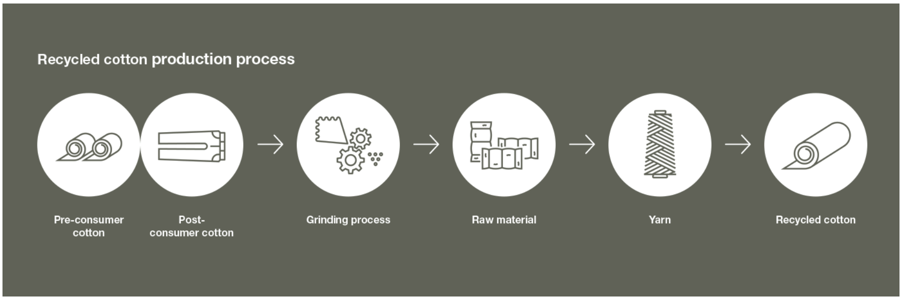

Figure 5. *Recycling of cotton (Retriewed from : https://textilsantanderina.com/textile-solutions/recycled-cotton/)*

The most common problem in the recycling of cotton is the low quality of the products obtained. For this reason, the effect of separation-shredding processes on recycled cotton on the quality of the final product should be investigated. Cotton is the most preferred fiber because of its comfort properties. According to the data reported by Lenzing, the rate of cotton in total fiber consumption was declared as 24.1% as of 2017. The recycling of cotton fiber waste generated along with yarn manufacture and recycling of cotton fibers is scarcely in clothing production (Yılmaz et al., 2017).

There is a limited number of solvents for dissolving the cellulose. During the dissolving process, only hydrogen bonds which are between the cellulose macromolecules were broken. In a previous study, an electrospinning process was used for the production of cellulose nanofiber from cotton wastes (Dashtbani and Afra, 2015).

In a study investigating the manufacture of regenerated cellulosic fibers from cotton waste, it was stated that the utilisation of mechanically recycled cotton often negatively impacts the features of the resulting clothing products, and the standard of the recycled fibers depends on the type and source of the waste (Wagner and Heinzel, 2020). If you want to have a high-quality garment including recycled fibers. In other words, the wastes that are separated correctly also determine the standard of the products manufactured from them. Since the fiber lengths will decrease during the mechanical transformation of cotton fibers during the disintegration of fabrics/clothes, thicker yarns can be produced from these yarns or the rate of recycled fiber in the yarn is kept lower. In some cases, lower-standard products such as blankets or insulation materials are produced from recycled products (Vadicherla ve Saravanan, 2017).

Ütebay et al. (2019), the waste rate of recycled fibers, recycled fiber length, spinnability of recycled cotton fibers and the features of yarns were measured.

As a result, it has been shown that little waste ratio and good yarn breaking strength results of recycled fibers are obtained by recycling cotton. In addition, recycled cotton fibers obtained from dyed fabrics were reported to be of lower quality. In addition, especially rotor spinning systems are used more often as they allow the spinning of fibers with lower fiber lengths. Considerable raw material recovery can be achieved in the case of ready-to-wear manufacturing and spinning wastes. The Gray Taguchi method to optimize the production characteristics was investigated and showed that rotor speed has the most significant impact on performance properties (Hasani and Tabatabaei, 2011). In another study, the hairiness of rotor yarns was manufactured from different proportions of cotton waste and recycled fabric waste. It was concluded that the hairiness values increased as the mechanical treatment increased and the recycled fiber content increased (El- Nouby and Kamel, 2007). Merati and Okamura (2004), examined the physical features of recycled cotton yarns, and declared that the length of fiber is effective on the tensile resistance of the yarn and the length of the fiber affects the fiber's tensile resistance.

The recycling methods of cotton were separated into :

a) Mechanical recycling: mechanical actions like opening, spinning and weaving used for this recycling. Opening is defined as taking waste from mechanical tearing and loosening. Waste cotton fibers can not be used directly when it comes to mechanical recycling because of the short length of waste cotton and the bad mechanical properties.

b) Chemical recycling: is divided into two groups. One of them non-derivative method and the other method is the derivative. In the non-derivative method, the cellulose keeps its original properties. In derivative method, immunization of chemical moieties on the molecules of cellulose to make new substances.

c) Biological recycling: the cotton wastes are changed into solid, liquid and gas biofuels with physical, thermochemical and biochemical methods. Textile wastes and cotton are renewable energy sources (Lu et al., 2023).

1.3.2. Recycling of Polyester

Polyester is a commonly used fiber in clothing manufacture. Polyester is a synthetic fiber and is therefore also melted and recycled in the recycling process. Especially the recycling of plastic pet bottles is common. The recycling process of polyester fiber is different from polyester pet bottles. Polyester wastes are the main part of the garment sector waste, but the recycling proportion is limited. 14% of waste was recycled in 2007, and a big quantity of this synthetic fiber was thrown away as waste (Candido, 2021).

The use of chemical methods is common in the recycling process of PET fibers. In this process, after the polyester is broken into small pieces, it is provided by partition operations such as filtration, precipitation, centrifugation and crystallization. Another method of recycling of polyester is chemical recycling. This method can be separated into methanolysis, glycolysis, hydrolysis and aminolysis. Because of low cost and low energy consumption glycolysis method is the preferred method (Sinha et al., 2010). The depolymerisation method is not convenient for PET because it generates carbon dioxide and carbon monoxide during the thermal decomposition (Encinar and Gonzalez, 2008). R-PET fibers are 20% cheaper than others althought, R-PET production decreased (Abbasi et al., 2020).

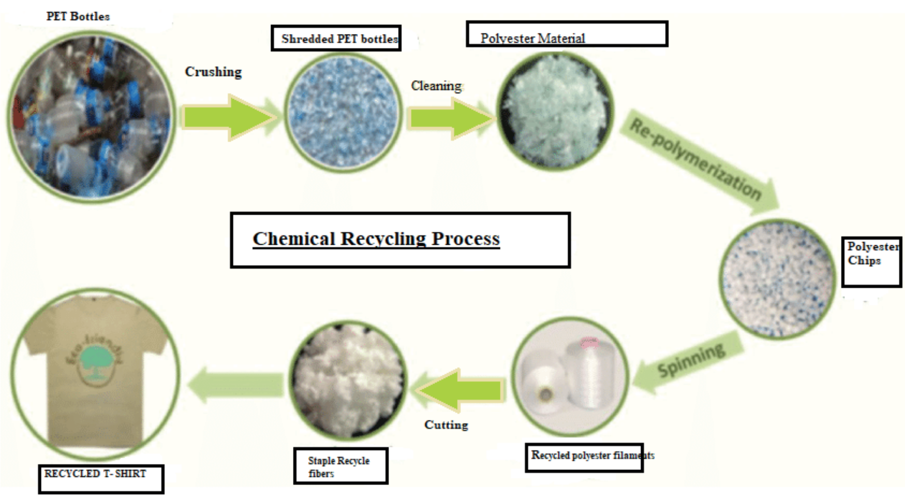

Figure 6. *Recycling of PES*

Tereschenko (2012), textile wastes can be produced by different processes of manufacture (e.g.spinning wastes, fabric residues in clothing, industry etc.). To increase the strength of recycled yarns, it is important to mix recycled cotton fibers with polyester fibers to and make spinning easier. Bartolome et al. (2012), reported that thanks to the recycling of polyester fibers, can decrease waste, decrease the utilization of petrochemical substances and decrease energy expenses.

Yüksekkaya et al. (2016), produced recycled and raw cotton, unprocessed PET, recycled PET fibers and their mixture using the rotor yarn system, and single jersey fabrics were manufactured from these yarns. With the mechanical tests, features, for example, tensile, unevenness, yarn defects, bursting strength and pilling resistance were tested. Notably, it was observed that the features of yarns and fabrics manufactured from raw fibers gave higher values than recycled fibers.

Telli and Babaarslan (2017), aimed to decrease the negative properties of recycled cotton and PET fibers with the open-end spinning. Tensile strength, breaking elongation, unevenness (CVm), yarn imperfection (IPI) and hairiness features were tested. As a result, findings supporting previous studies were obtained.

Kumar and Raja (2021), examined the thermal comfort of socks produced from raw cotton and r-PET fibers and their mixtures, and the values of thermal conductivity, thermal insulation, and permeability properties were tested. Higher permeabilities, thermal insulation and lower thermal conductivities were found in fabrics with higher recycled polyester content than untreated cotton blends.

Guo et al. (2021), used glycolysis process for recycling polyester textile waste. For this purpose small granules and large pellets catalysts were prepared. Due to recyclability, the huge pellet catalyst is simple to recycle because of its intact structure. It was concluded that polymerization-repolymerization method demonstrates a similar spinning in comparison to virgin PET.

Vinitha et al. (2023), investigated effect of using Ag-doped ZnO nanoparticles for the recycling of PET wastes with microwave-alert catalytic aminolysis and glycolysis methods. It was observed that aminolysis and glycolysis methods, showed a very economic and ecologically sustainable attempt.

Tang et al. (2024) investigated high efficient recycling of polyester wastes with diols. It was observed that dual-atom catalysts make over with high activity and stability. In addition, reconstruction of polyester wastes into valuable diols was defined in this study.

Repreve trademark was produced from post-consumer water bottles and pre-consumer wastes which consist of r-PET filament and staple yarns. It was used for the production of clothes, automotive accessories, footwear, furnishing, socks, hosiery, military and outdoor products. Post consumer products can be supplied from different ways to make r-PET yarns. For example Bionic trademark collects materials from waterways and oceans for production of r-PET PES. The environmental advantages of this method is collecting the wastes and cleaning the environment and set up waste management systems (Celep et al., 2022).

1.4. The Use of Recycled Fibers in Different Areas

1.4.1.Yarns and Clothes from Recycled Fibers

Sustainability is one of the important criteria for fashion companies for this purpose recycled materials are utilized and sustainability can be improved with recycled fibers usage (Caniato et al., 2012). Unwanted textiles or clothing in the garbage can not be thrown away by consumers because almost 100 per cent of it can be recycled (Meadows and Peek, 2009). To use recycled fibers in yarn production, must be used with virgin fibers because the mechanical tests of recycled fibers are poor. In a previous study, it was observed that the usage of 15-25% recycled fiber with virgin fiber does not change the tenacity of the yarn and 20% of recycled fiber with virgin fiber in the rotor spinning does not change the quality of the yarn. Especially, around 15% of global polyester manufacture involves recycled polyester (Adanur and Qi, 2008).

One of the many sustainability initiatives launched by clothing companies is the "Loop" clothing recycling system introduced by H&M. Another example of recycling introduced by Flippa K company which uses recycled cotton, polyamide, polyester, wool and cashmere. Danish fashion company Ganni uses post-consumer textile waste to create collections with new and colourful designs. The other purpose of the company is to invest in fibers recycling trial programs and recycle 100% of its cotton deadstock for new furniture and interior. Founded in 2005, the company House of Dagmar is themed around sustainability and one of the company's goals is to manufacture carbon-neutral clothing with 100% sustainable collections by 2025 (Golay, 2021).

Linen and household textiles are recyclable except that wet or solvent–type liquid used fabrics (Smart Reports, 2018). Recycled clothing and products can be classified according to quality, condition, and type. Approximately, 95% of second-hand textiles and clothes can recycled and can be separated into different classes (Todor et al. 2019):

- 45% can be used in apparel and can be sold as second–hand clothing sector
- 30% recycled textiles can be used as wiping rags or polishing cloths
- 20% converted to basic fiber content to manufacture furniture, insulation, automobile accessories and building materials.
- 5% can not be used because wet, dirty, broken or contaminated with solvents.

1.4.2. Nonwovens from Recycled Fibers

Nonwovens which are produced from recycled fibers can be used for insulation, agro-textiles and geotextiles. Because of the low cost and merely cover properties of recycled fibers, they are much preferred for nonwovens. Nonwovens produced from recycled carbon fibers (rCF) and thermoplastic (TP) fibers have good ecological and economic features and recycled carbon fibers are cheaper (Manis et al., 2021). Many companies have produced carpet pads/underlays using clothing waste and post-consumer recycled fibers. Carpet bases are produced from non-woven fabric using the needle punching and felting method. These methods can be four groups (a) recycled clothes and post-consumer textiles, (b) post-consumer scraps from automobile inside fibers, (c) recycled carpet waste, and (d) recycled PET bottles (Chang et al., 2009).

Production of recycled PET fibers from PET bottles starts with polymerlaying way of nonwoven manufacture. Initially, bottles were cut into flakes, and then washed and dried, and then transported to the extruder. In the end, melted PET is utilized for the production of nonwoven fabric. In another example of recycled nonwovens is Noise control applications. For example; wall claddings, acoustic barriers and acoustic ceilings, passenger vehicle noise absorbers, and various others (Santhanam et al.,2019). In another study, cotton and polyester fibers blended with different amounts to produce nonwoven composites. It was concluded that the blending ratio of 70% cotton and 30% polyester had good sound absorptivity properties (Küçük and Korkmaz, 2012).

Another example of using recycled fibers in geotextiles with polyester/ cotton for erosion control. The aim of using geotextiles for erosion control is to produce a fabric that can be replaced with anchored down, keeping seeds and soil in the ground as water passes into the fabric (Chang et al., 2009).

1.4.3. Home Textile and Upholstery Products from Recycled Fibers

Some of the recycled fibers can be used for floor covering or blankets. The rate of catch ends, together with weft yarns, which are one of the wastes of weaving machines, reaches 34% and these wastes are used in the production of floor coverings using composite technology. In other studies, while the rate of use of recycled products in clothing is low, the rate of use in home furniture and home textile production is higher (Swinker and Hines, 1997). Cleaning textiles can be produced from virgin fibers or recycled post-consumer fibers. These products are used in automobile/transportation, industry, catering, factory maintenance, and hospitals. Since cleaning textiles have very diverse uses, the use of recycled fibers in this area increases market opportunities (Sadeghi et al., 2021).

Other examples of recycled fibers used in household carpets for example nylon, polyester and olefin. In another study, fibers obtained by recycling PET bottle waste for the production of carpets used in automotive floors and polyester fiber waste were compared with fibers obtained by melt spinning of pure fiber class polyesters (Grudatt et al., 2005).

Figure 7. *Home-textile and upholstery recycled textiles*

1.4.4. Insulation Materials from Recycled Fibers

Recycled fibers can be used for the production of insulation materials for construction products because of ventilation, conduction, convection and radiation properties. Recycled products are especially used for buildings because utilizing recycled substances can exchange substances from the solid waste stream, additionally decreasing the requirement for natural sources and energy during production (Insulation Materials, 1995).

Patnaik et al. (2015), analyzed thermal and acoustic resistance products manufactured from waste wool and RPET fibers (Patnaik et al., 2015). In another study, manufactured acoustic absorption and thermal insulation products from recycled cotton, polyester and flax fibers were analyzed and the nonwoven airlay technique was used for web formation (Reif et al., 2016). Hadded et al. (2016), a new technique was found for producing valuable insulation materials from textile waste. With this technique, textile waste is transformed into linters and tablecloths by inflating or recycling them to create a porous structure. In another study, needle punched technique was used for the production of insulation materials from acrylic and wool nonwoven wastes. It was observed that the produced insulation material has better thermal properties than conventional insulation materials (Wazna et al., 2017).

Trajković et al. (2017), manufactured thermal and acoustic insulation products from polyester cutting wastes (Trajković et al., 2017). Insulation materials for roofing and building inside walls are produced from polyester cutting wastes. In another study, a compression molding process was used for the production of nylon/spandex and polyurethane insulation products (Dissanayake et al., 2018). In another study, STERED products were recycled from automotive technical textiles and used for sound absorption and flame retardancy. It was observed that this product is suitable for alternative building insulation materials (Danihelova, 2019). Majumder et al. (2021) investigated the effect of locally manufactured natural and waste/recycled materials on the thermal insulation properties of buildings.

Figure 8. *Insulation materials from recycled fibers*

CONCLUSION

Changing models, fabrics and patterns in the clothing industry are designed and marketed with a new story in clothing fashion. There has been a decrease in natural resources in the textile sector, especially due to the fast fashion approach. In addition, fast-fashion approaches increase the amount of textile waste. To solve this increasingly growing problem in the sector, sustainable materials and production methods must be used. According to the sustainability approach in textiles; production should be carried out within the framework of ecological ethics, products should not be harmful to human health, and products that have completed their lifespan and become waste should be used under the philosophy of sustainability. With recycling strategies, methods that will not harm the environment have emerged in the textile industry. Recycling waste generated during the manufacturing phase is generally possible by adding the waste material back to the production line or selling it to recycling businesses. This study aims to give information about textile recycling processes and textile waste types. In addition, information is given about the recycling process of the most commonly used fibers. Today, in the textile industry, companies include sustainable approaches among their company policies and the use of recycled fibers in clothing production is ensured. In this study, the use of yarn, clothing, nonwoven, home textile and insulation material produced from recycled fibers produced in the textile industry and the literature studies in this field are mentioned. As a result, this study will contribute to the literature about textile recycling, textile wastes and different materials produced by recycled fibers.

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Chapter 3

GARMENT DESIGN ENABLING THERMAL INSULATION BASED ON AMBIENT TEMPERATURE

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1. INTRODUCTION

Advancements in the field of intelligent or smart products are undoubtedly poised to play a significant role in the textile and fashion industries in the coming years, even becoming a part of our daily lives. Intelligent devices, as described, result from integrating specific components into fabrics, which may include specially formulated polymers or even a type of dye. Many smart textile products are designed to respond to adverse conditions in their environment. Furthermore, they can alter their nature or provide additional benefits to the user in response to external factors. For example, there have been extensive innovations in clothing fabrics that can provide extra insulation in both hot and cold conditions. Such textiles are becoming increasingly important in the fashion industry. In other words, these are temperature-regulating garments. The term "temperature" has a broad meaning. It essentially refers to maintaining body temperature at a level that maximizes performance and comfort while protecting the user. Temperature regulation is best defined as the goal of maintaining both internal body temperature and the user's comfort across various environments. The body regulates its own temperature through a set of biological processes (within ±1°C). When body temperature exceeds the limits of the thermo-neutral zone, bodily systems become less efficient, and in extreme cases, this can lead to fatal outcomes. Therefore, temperature regulation is critical for both safety and performance. Individuals in various professions and those living in high-latitude regions are often exposed to cold weather, which can lead to health issues and even injuries related to cold exposure [1]. Cold weather injuries occur when temperatures drop to the level where tissue fluid freezes, leading to frostbite. Another type of injury occurs without freezing; in this case, reduced blood flow due to low body temperature can cause nerve damage. The most common injuries from cold exposure are frostbite on fingers, toes, and ears. Additionally, cracked skin issues can arise due to the body's exposure to cold [2].

To prevent health problems from cold weather, people have two options. The first is to limit their time in cold environments, and the second is to wear a personal heating suit (KIT) to reduce cold stress. People can also heat their homes to maintain optimal body temperature. However, heating buildings can be expensive. An alternative approach is active heating with KITs to keep the body warm. It is expected that heating the microclimate around the body will save more energy compared to heating an entire house [3]. Given rising energy costs and awareness of excessive consumption, using KITs to keep the body warm during cold winters, both indoors and outdoors, would be a wise choice. The third approach is to use traditional thick, multi-layered clothing, including shoes, gloves, and hats, as a passive heating method to maintain the body's own temperature. People can wear several layers of highly insulated clothing to keep their bodies in a thermo-neutral state.

In general, electric heating products use embedded heating elements to generate heat. Most electric heating garments (EHGs) use a single electric heating wire. Other possible heating elements for such EHGs include graphite elements, electrically conductive rubbers, neutralized textile fabrics, positive temperature coefficient polymers, and carbon polymer heating fabrics [4]. The concept of applying electric heating directly to a person is not new. Researchers have explored ways to utilize the heating effect of low-voltage DC sources. One of the earliest practical attempts to incorporate electric heating into garments dates back to World War II when bomber crews were equipped with leather flying jackets outfitted with electric element cables, similar to those in electric blankets [5]. In 1942, Marick developed electrically heated clothing [6]. The heating garment covers almost the entire body and includes electric heating pads. Two textile layers were used to protect the heating element from damage. Deloire, Durand, and Mans developed a heating garment that minimally restricts user movements [7]. Additionally, it can distribute heat evenly. Heating elements with good stretch properties were placed in channels made by stitching two fabrics together along parallel lines. The heating wire was made of a resistive alloy and was extrusion-coated with a polyvinyl chloride layer capable of withstanding relatively high temperatures. Metcalf developed a vest-type garment lined with an electric heating element [8]. Subsequently, sleeves, pants, and hats were also developed. A 6-V DC power source provided electric heating to the elements in each garment.

Garments using Phase Change Materials (PCMs) can possess automatic climate control properties [9]. PCMs are combinations of different paraffin types, each with different melting and crystallization points. By altering the proportional amount of each paraffin type in the PCM, desired melting and freezing points can be achieved [10]. Alternatively, a chemical heating garment uses chemical reactions to produce heat. For instance, chemical energy can be converted into heat energy through oxidation. Chemical heating garments are commonly used in diving areas to protect divers in cold water. Chemical heating pads are convenient and inexpensive for consumers. They can be attached to any part of the human body if necessary. However, their temperature is uncontrollable, and it can be challenging for the elderly and children to decide which layer of clothing to attach them to. A heating pad attached to the underwear on certain parts of the human body can cause burns to the skin due to the pad's temperature exceeding 42°C. Preventing leakage of chemicals from a heating pad should also be considered in the design process. Additionally, the physiological reactions of chemical heating garments on the human body should be further researched. In an airflow heating garment designed for heating, there is a liquid/air circulation tube system embedded within soft tubes or other hollow media. Water is often used in liquid-flow heating garments due to its good heat enthalpy and non-toxicity. It is clear that liquid-heated garments have an effective heating effect. However, the tube system inside the garment can stiffen the garment to some extent and limit human activity. Tube material and wall thickness, tube diameter, the total tube contact surface area with the skin, and the heat transfer properties of the distribution medium can greatly affect the heating effect of a fluid/airflow heating garment. There is also a temperature difference between the inlet and outlet of the tube. Flow patterns (e.g., one-way or loop flow), fluid leakage, and the fit of the garment should also be considered in the design process. Currently, liquid/airflow heating garments are widely used and researched in the medical field. The physiological effects of a liquid/airflow heating garment on the human body in a cold environment also require further investigation. Moreover, the cleaning of such flow-heating garments needs to be well designed [11-13].

In regions where weather conditions can change rapidly, selecting appropriate outerwear can be challenging. Thick and heavy garments chosen in anticipation of colder weather can be burdensome for people who work outdoors or need to be mobile. Although there are existing studies on electric heating products, the mass production of these products is not yet widespread. Therefore, there is a need for continued efforts to design and manufacture new solution-oriented products. With the proliferation of smart textile products, research on garments enhanced with artificial intelligence has become more common. These garments typically consist of fibers that change structure in response to temperature or garments that alter their shape.

Measuring temperature and subsequent changes in the garment can provide multiple benefits from a single product, making it important from a sustainability perspective. For textile materials to be functional, they need to change in response to factors such as humidity, temperature, and pressure. To control these changes, the garment requires a sensor. If the mechanism that receives the data from the sensor is just a display or sound system, the user makes the decisions. However, if the designed product can change itself (make decisions) based on the detected values, it is considered a smart product. For example, if the indoor temperature rises above a set level, the system could display this value on a screen, emit a sound as an alarm, or alert the user through vibration. However, for the system to be considered intelligent, it should activate another system in response to the detected value, such as "turn on the air conditioning" or "open the ventilation."

The designed system in this study is planned to function as follows:

1. Measuring body temperature.

2. Activating the pump within the garment based on the difference between external and body temperatures.

3. Inflating air pockets inside the garment until the target temperature is reached.

The primary goal is not to warm the user but to maintain a stable body temperature. The use of air is due to its low thermal conductivity when stagnant. Additionally, between two textile products of the same volume, the group with more air is lighter and more resistant to temperature changes. It is essential to remember that the main goal is to design a simple yet functional and inexpensive product to address sudden temperature changes.

The paper is structured as follows:

Section 2 presents the hardware and circuit design of the garment. Section 3 covers the software system and software testing. Section 4 discusses testing experiments and efficacy evaluation Section 5 describes the garment design. and Section 6 provides a summary of the paper and outlines the next steps.

Hypothesis of the study is "Garments integrated with smart sensor technology and air pockets can more effectively maintain the user's body temperature in response to sudden temperature changes and provide greater freedom of movement compared to traditional layered clothing.". This hypothesis aims to test whether the designed smart garment can effectively regulate the user's body temperature in response to sudden temperature changes and whether it offers greater freedom of movement compared to traditional layered clothing. The garment should be capable of adjusting air pockets based on the detected differences between external and internal temperatures, ensuring comfort and mobility for the wearer during daily activities.

The purposes and targets of this study are as follows:

1. To develop a smart garment incorporating air pockets and sensor technology, capable of adjusting to environmental and body temperature changes.

2. To investigate the effectiveness of using air pockets in maintaining a stable body temperature in varying climatic conditions.

3. To provide an alternative to traditional layered clothing that offers greater comfort and freedom of movement.

4. To explore sustainable design solutions by creating a multi-functional garment that reduces the need for multiple clothing items.

Targets of the study are;

o to successfully integrate temperature sensors and other necessary hardware components into the garment for real-time monitoring and adjustment, o to ensure the smart garment can autonomously activate and deactivate the air pockets based on detected temperature changes,

o to design a lightweight and flexible garment that enhances user comfort during daily activities

o to develop a prototype that can be tested in various conditions to evaluate its performance and efficacy.

2.HARDWARE SYSTEM DESIGN

The three principles of hardware design are: Performance, Energy Efficiency, and Cost. Performance refers to the speed at which a piece of hardware can execute tasks. Performance of the system is tested by using firstly water included jar and pump which fills the air gaps. When the the cycle is completed that temperature decreases then air pump starts to fill the gaps up to system reaches to determined temperature; the pump, sensor and the apparatus includes air fragments are settled inside the jacket. Energy efficiency and cost were not measured in this study, system ensures energy by battery and the purpose was investigation of the usability of this system to keep warmness of body so this is the subject of latter study. The used system is very simple and also very cheap.

3.SOFTWARE SYSTEM and ALGORITHM

Developed Algoritm

Smart Outdoor Thermal Garment Design for Changing Climate Algorithm

Inputs:

Polyester fabric (56 g/m2)

Polyester filament fibers (200 filament-drawn, 2700 th PP CF thread)

Microcontroller (Atmel ATMega328)

Thermal sensor (WX 101W)

Air coat (32 g/m2, 4-micron thickness, polyethylene)

Micro air pump motor (3V, 30kPa 0.3 l/d)

Objective:

Design an intelligent temperature-sensitive clothing product that optimizes thermal insulation using stagnant air as a key component.

Algorithm Steps:

1.Initialization:

Set initial conditions for the prototype design.

Define the key components and their specifications.

2.Material Selection:

Utilize polyester fabric as the outer layer.

Incorporate polyester filament fibers for enhanced structure.

Integrate a microcontroller (Atmel ATMega328) for intelligent control.

Include a thermal sensor (WX 101W) for temperature detection.

Apply an air coat (32 g/m2, 4-micron thickness, polyethylene) for additional insulation.

Employ a micro air pump motor (3V, 30kPa 0.3 l/d) for managing air circulation.

3.Hypothesis:

Formulate the main hypothesis that stagnant air provides optimal resistance to sudden temperature changes.

4.Pre-Product Tests:

Conduct prototype tests with variations in design, including fiber-only, air cutter-only, and combined bag and fiber designs.

Perform tests in a controlled environment with temperatures ranging from 37.5 °C to 30 °C.

Evaluate the effectiveness of different designs in thermal insulation.

4.Data Analysis:

Analyze the test results to identify the impact of air on insulation.

Confirm the hypothesis that stagnant air offers superior resistance to temperature changes.

5.Final Clothing Design:

Incorporate air cuts within the clothing based on the test results.

Integrate the thermal sensor onto the clothing to detect temperature changes autonomously.

6.System Activation:

Implement a system that, upon detecting temperature variations, activates the micro air pump.

7.Air Fragment Filling:

Use the micro air pump to fill the air fragments inside the clothing, optimizing thermal insulation.

***Output**:*

Finalize the intelligent temperature-sensitive clothing design with enhanced thermal insulation properties.

End Algorithm

4.TESTING EXPERIMENTS

To assess the efficacy of the system in attaining its designated objectives, a glass jar containing hot pure water served as a prototype for measuring temperature changes, given the absence of a thermal model. An electronic circuit, designed to depict the instantaneous heat variations detected by a glass jar immersed in heated pure water within a controlled laboratory setting, was employed in conjunction with a thermal sensor for temperature monitoring. Throughout the testing phase, the glass jar was selected due to its ability to maintain temperature consistency.

The heat control circuit incorporated a surface-contact heat sensor, allowing for versatile sensor placement. The 4mm pneumatic air hose was substituted with a medical infusion set hose in the heat control circuit, owing to its pliability, ease of use, and absence of air leakage concerns at the connection point.

With the experimental and thermal control circuit arrangement in place, all samples underwent testing under uniform environmental conditions within a laboratory setting, where heat dissipation was delayed following the formation of air cutters and an insulation layer.

Under controlled laboratory conditions characterized by a humidity level of 65% at 20°C, experimentation involved the use of a glass bowl filled with 350 cc of heated pure water. The bowl was encapsulated in a 9-gram shell filled with 0.5 liters of air, accompanied by variations incorporating a fiber-filled shell weighing 9 grams and 4.6 grams of polypropylene (PP) fiber, each encapsulated in a 0.5-liter air-filled shell weighing 9 grams. Testing encompassed the period during which the temperature declined from 37.5 °C to 30 °C, with corresponding waiting times duly recorded.

In the conditioned laboratory environment, the glass container was filled with 350 cc of heated pure water, positioned to ensure the container's surface remained entirely submerged in water. Notably, the container was left entirely exposed, with no contact between the heat sensor's sample and the outer surface.

Figure 2. *Visual for the temperature of sample without coat*

Upon reaching a water temperature of 37.5 °C in the enclosed bowl, the initiation of thermal exchange measurements commences. These measurements persist until the temperature, as detected by the thermal probe and displayed on the indicator, decreases to 30 °C.

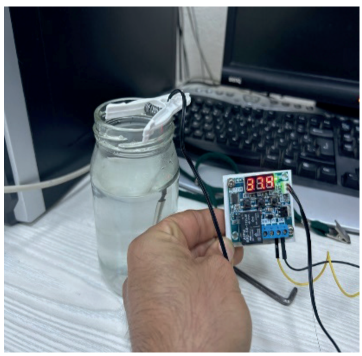

Figure 3. *Visual for water temperature measurement*

Throughout the course of the study, four distinct designs were formulated to scrutinize their individual characteristics, denoted as follows:

1. Without Coat
2. Coat and Air Pocket
3. Coat and Fiber
4. Coat and Fiber and Air Pocket

In each design, a 0.5-liter air bowl was integrated and positioned inside the shell. The product was expressly engineered to monitor time-dependent temperature fluctuations in the water enveloping the glass jar, undergoing heating within the jar until the temperature descended from 37.5°C to 30°C.

Visual representations of the described processes are presented in Figure 4a and Figure 4-b.

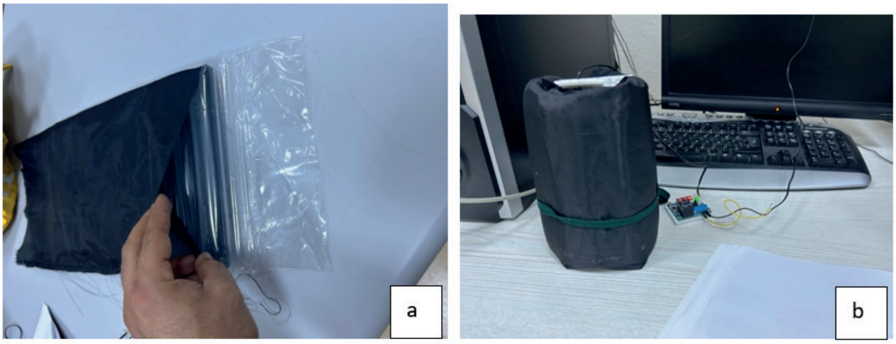

Figure 4. *Design of sample with air pocket (a) and measurement(b)*

The same measurement process was repeated by placing 9 grams of fiber inside the case.

Figure 5. *Visual of the sample coat and fiber*

The subsequent iteration of the measurement process documented a decline in the temperature of the pure water within the jar, from 37.5°C to 30°C. This particular measurement involved the incorporation of 4.6 grams of fiber and 0.5 liters of air inside the container, with the jointly positioned container enveloping the jar.

All specimens underwent testing in controlled laboratory conditions, commencing at 37.5 °C. The recorded temperature variations over time are systematically presented in Table 1.

Table 1. Temperature values in minutes of samples, °C

Minute	Without coat	Coat and air pocket	Coat and fiber	Coat fiber and air pocket	Minute	Without coat	Coat and air pocket	Coat and fiber	Coat fiber and air pocket
0	37,5	37,5	37,5	37,5	40	30,2	32,0	32,4	32,8
1	37,3	37,3	37,3	37,3	41	30,1	31,9	32,3	32,7
2	37,0	37,2	37,1	37,1	42	30,0	31,9	32,2	32,7
3	36,8	37,0	36,9	36,9	43		31,7	32,1	32,6
4	36,6	36,8	36,8	36,8	44		31,7	32,0	32,5
5	36,4	36,6	36,6	36,7	45		31,5	31,9	32,4
6	36,2	36,5	36,5	36,5	46		31,4	31,8	32,3
7	36,0	36,3	36,3	36,4	47		31,4	31,8	32,2
8	35,7	36,2	36,2	36,3	48		31,3	31,7	32,2
9	35,5	36,0	36,0	36,2	49		31,2	31,6	32,1
10	35,3	35,9	35,9	36,1	50		31,1	31,5	32,0
11	35,1	35,7	35,7	36,0	51		31,0	31,4	31,9
12	34,9	35,5	35,6	35,9	52		30,9	31,3	31,9
13	34,7	35,4	35,5	35,7	53		30,8	31,2	31,7
14	34,4	35,2	35,4	35,6	54		30,7	31,1	31,6
15	34,2	35,1	35,3	35,5	55		30,6	31,0	31,6
16	34,0	35,0	35,1	35,3	56		30,5	31,0	31,5
17	33,9	34,8	35,0	35,2	57		30,5	30,9	31,4
18	33,7	34,7	34,8	35,1	58		30,4	30,8	31,4
19	33,5	34,5	34,7	34,9	59		30,3	30,7	31,3
20	33,3	34,4	34,6	34,8	60		30,2	30,6	31,2
21	33,1	34,2	34,5	34,7	61		30,1	30,6	31,1
22	33,0	34,1	34,3	34,7	62		30,0	30,5	31,1
23	32,8	34,0	34,2	34,6	63			30,4	31,0
24	32,6	33,9	34,0	34,4	64			30,4	30,9
25	32,5	33,7	33,9	34,3	65			30,3	30,8
26	32,3	33,6	33,8	34,2	66			30,2	30,8
27	32,1	33,5	33,6	34,1	67			30,2	30,7
28	31,9	33,3	33,6	34,0	68			30,1	30,6
29	31,8	33,2	33,5	33,9	69			30,0	30,6
30	31,6	33,1	33,4	33,8	70				30,5
31	31,5	33,0	33,2	33,7	71				30,4
32	31,4	32,9	33,2	33,6	72				30,4
33	31,2	32,8	33,1	33,5	73				30,3
34	31,2	32,7	33,0	33,4	74				30,2
35	31,0	32,6	32,9	33,3	75				30,2
36	30,8	32,5	32,8	33,2	76				30,2
37	30,7	32,3	32,7	33,1	77				30,1
38	30,5	32,2	32,6	33,0	78				30,0
39	30,4	32,2	32,5	32,9					

As depicted in Table 1, the four different designs exhibited varying durations for the temperature to reach 30°C. The design without fiber reached 30°C in the 42nd minute, the air pocket design in the 62nd minute, the fiber design in the 69th minute, and the combined air pocket and fiber design in the 78th minute. Notably, there is a substantial 20-minute difference observed in the time taken for the temperature to drop to 30°C between the air-pocket designs and those without a coat, as indicated in Table 1.

5.GARMENT DESIGN

The outer layer of the product utilized polyester fabric (56 g/m2), a commonly preferred material for outer clothing. The product incorporated polyester filament fibers (200 filament-drawn, 2700 th PP CF thread), a microcontroller (Atmel ATMega328), a thermal sensor (WX 101W), an air coat (32 g/m2, 4-micron thickness, polyethylene), and a micro air pump motor (3V, 30kPa 0.3 l/d). In pursuit of creating an intelligent product sensitive to temperature with a focus on minimizing thickness, stagnant air was chosen as an alternative to textile fibers. This decision is based on the lower thermal conductivity of stagnant air compared to all fibers, measuring at 0.025 watt/mK. The study's central hypothesis posits that stagnant air provides the greatest resistance to sudden temperature changes.

Based on the obtained results, the significant 20-minute difference between the tests of designs without a coat and with an air pocket was considered noteworthy, especially in the context of a distance traveled on foot. The prolonged duration of body temperature decrease in this process was deemed indicative of the success of the designed product.

Consequently, following this evaluation, it was determined that the air-pocket design was well-suited for the textile product. Subsequently, the design of the jacket was executed, demonstrating that when the temperature drops below 36 degrees, it is promptly detected by a sensor, triggering the automatic inflation of air fragments within the jacket.

The textile product was modeled utilizing the specified coat fabric, conforming to the jacket's design. Internally, air pockets were strategically placed on the right, left, and back of the front of the vest, as visually represented in Figure 6a, Figure 6-b, and Figure 6c.

Figure 6. *The empty (a), air-pocket (b) and close-up appearance of the product design*

The placement of the sensor is illustrated in Figure 7, positioned below the arm. In addition, the air cuts are interconnected, as depicted in Fig. 7-b and Figure 7-c. These air cuts are further connected to the microprocessor circuit-controlled air pump through a medical infusion set hose and pneumatic system connectors. Consequently, when the air pump is activated, all the air pieces commence inflation simultaneously. This configuration ensures a synchronized and uniform expansion of the air pockets when the air pump is engaged, contributing to the overall effectiveness of the designed textile product.

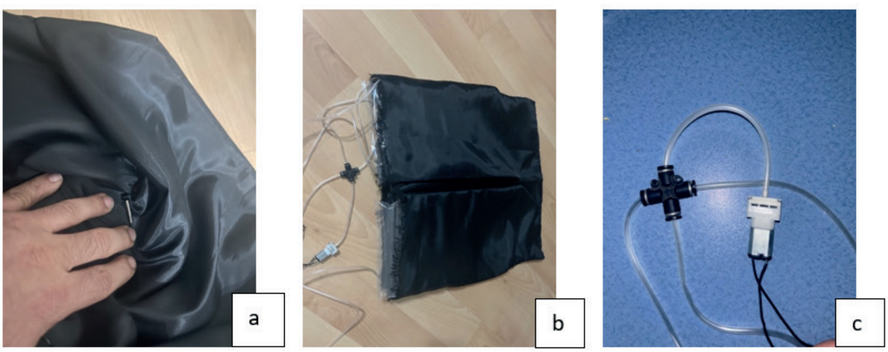

Figure 7. *Sensor placement (a), connectivity of interconnected air frames (b) and inflatable air pump and distribution element installed in the design*

6.CONCLUSION

The continuous expansion of intelligent products in everyday life, coupled with the evolving market for these products, is expected to persist. Today, wearable technology products have transitioned into textile products featuring various technologies. Innovations that integrate environmental sensitivity into technological products, translating it into actionable benefits for users, are becoming requisite rather than surprising. Previous literature studies revealed designs utilizing fibers, fluid flow, chemicals, and electrical heating systems in fabric structures to provide insulation from external environments.

In this study, a novel product was designed to detect body temperature and automatically offer thermal insulation, distinguishing itself from conventional clothing designs encountered in literature studies. Upon the body temperature falls below a predetermined threshold, the product activates, autonomously inflating air cuts at specified intervals through an air pump engine, creating an insulation layer between the user and the external environment.

The intelligent system comprises a temperature sensing sensor, signal evaluation software, a microprocessor circuit for system activation, an air pump engine for airflow, air cuts facilitating airflow, and an air hose connecting these components. This study aims to provide an alternative to existing products, emphasizing the lower thermal conductivity of air compared to fibers. The designed product is intended to be easily placed and removed from prepared pockets, allowing for washing, operation with a portable charger, and functions unaffected by external factors like rain. The design process has been completed, demonstrating significant improvements in insulation efficiency with the appropriate amount of fibers tested. Future developments may explore additional features, such as incorporating solar panels for energy supply.

Conflict of Interest

The authors have no conflict of interest.

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Chapter 4

RESEARCH ON THE DESIGN AND FEATURES OF A WEAVING MACHINE TIMING DIAGRAM

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1. INTRODUCTION

Woven fabric is formed by interlacing two sets of threads, warp and weft, positioned at a 90-degree angle. In a weaving machine, the process involves passing the weft threads transversely through the parallel warp threads following a specific pattern, then pushing the weft towards the fabric formation line to incorporate it into the already woven fabric. This is accompanied by the precise movement of warp threads, which are delivered to the weaving zone at the correct speed and with appropriate, constant tension. Additionally, the produced fabric is drawn from the weaving zone and wound onto a cloth roll at the desired weft density [1, 2].

An efficient weaving process requires the synchronized operation of sequential movements, such as shedding, weft insertion, beating-up, and cloth winding. The effective management of these processes depends on the accurate design of the weaving machine's timing diagrams [3]. Timing diagrams graphically present the movements of the mechanisms in weaving machines, allowing the optimization of production processes [4]. The efficiency of weaving machines can be enhanced through timing diagrams [5]. These diagrams simplify the understanding of the machine's complex engineering structure and facilitate the identification of potential bottlenecks in production [6]. Synchronizing each mechanism minimizes machine downtime, increasing production capacity. This synchronization is supported by integrating computerized control systems and predictive analytics in modern weaving machines [7].

Weaving machine timing diagrams maximize machine performance by synchronizing cyclical movements. In shuttle weaving machines, in particular, coordinating the movement phases of the shedding and weft insertion mechanisms is crucial. If the relationship between these mechanisms is not properly established, machine performance may decrease, and errors may occur in the production process [8]. Analyzing weaving machine timing diagrams allows for the early detection and correction of such errors. In this optimization process, cyclical movements and idle times of mechanisms are analyzed to improve efficiency [9].

When timing diagrams are accurately analyzed, the production capacity of textile machines can be significantly increased [10]. The design of timing diagrams not only ensures the synchronization of mechanical movements but also enhances the durability of weaving machines, reducing maintenance costs. This leads to more efficient production processes and lower production costs. Moreover, the accurate planning of movement phases between mechanisms ensures the long-term stable operation of machines. Modern weaving machines operate more precisely with the computer-aided design of timing diagrams [11]. Consequently, the correct design of weaving machine timing diagrams is key to improving efficiency and reducing costs in textile production processes. Optimizing timing diagrams enables faster production with fewer errors.

2. TIMING DIAGRAMS

Mechanisms that transmit non-repetitive motion to working parts over time are classified as non-cyclic mechanisms. For these types of mechanisms, no distinction is made between working, idle, and waiting phases. The coordination of working parts involved in cyclic movement is determined by the kinematic cycles and the relative position of the working, idle, and waiting parts within the machine's overall kinematic cycle. The synchronization of all movements and idle times of the mechanisms is shown in the machine's timing diagram, which is depicted in three different forms—rectangular, linear, and circular—depending on the machine type [12].

Rectangular Timing Diagram: As shown in Figure 1, a rectangular timing diagram consists of a series of horizontal strips of arbitrary width. The duration of the machine's kinematic cycle is represented in time units or as the angular rotations of the main shaft at the base of these strips. Angular rotations of the main shaft are used in cases where the movements of all mechanisms are driven by a main shaft rotating at a constant speed. For such machines, the duration of the kinematic cycle is determined by the rotation angle of this shaft.

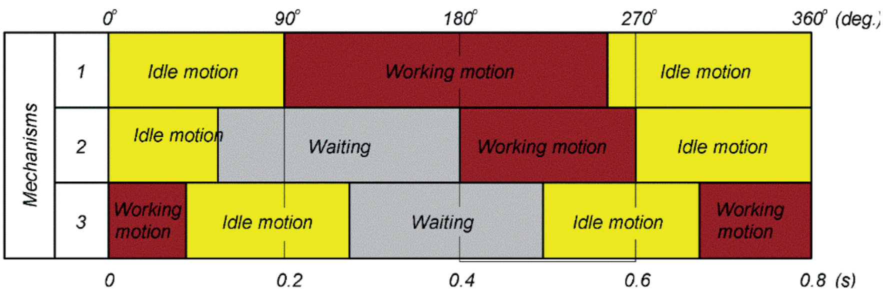

Figure 1. Rectangular time diagram

Linear Timing Diagram: A linear timing diagram is constructed in a similar manner (Figure 2). The only difference is that the intervals of the cycle are represented not by rectangles but by slanted and horizontal lines. The slanted lines represent the working and idle movements of the mechanism (the working part returning to its initial position), while the horizontal lines show the waiting phases of the working parts. When necessary, the characteristics of the working part and the direction of movement are shown on the lines.

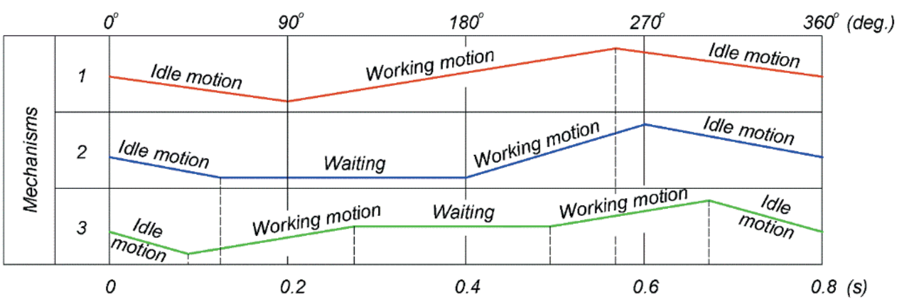

Figure 2. Linear time diagram

Circular Timing Diagram:

A circular timing diagram can be obtained by bending and joining the ends of a rectangular timing diagram (Figure 3). This circular timing diagram is drawn as concentric circles, with the number of rings corresponding to the number of mechanisms in the machine (e.g., A, B, C). The outer circle is divided into degrees representing the angular rotation of the main shaft. The rings are subdivided into equal sections along the radius, corresponding to the angles representing working, idle movement, and waiting periods of the working part.

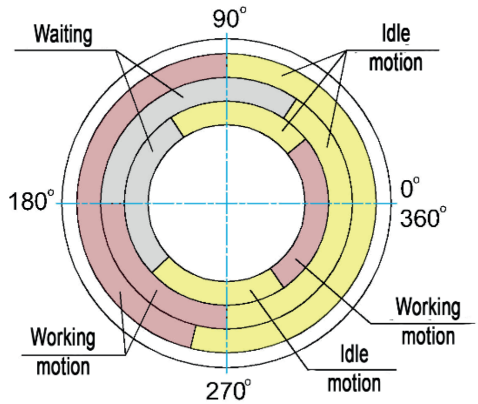

Figure 3. Circular time diagram

The analysis of a timing diagram allows for the determination of the sequence of operations of the mechanisms, their interactions, and the ratio between working, idle, and waiting times. However, the timing diagram does not provide information about the magnitude or kinematics of the movements of the working parts.

The magnitude, kinematics, and coordination of the movements of the working parts are presented in a synchronous diagram. A synchronous kinematic diagram is drawn in a rectangular coordinate system. Along the horizontal axis (abscissa), the duration of the kinematic cycle and its intervals are shown, while the vertical axis (ordinate) represents the actual displacements of the working parts. Figure 4 presents a timing diagram that shows the synchronous kinematic diagram of the machine mechanisms depicted in Figures 1, 2, and 3.

The design of synchronous kinematic diagrams is carried out either during the design of new machines or when modernizing existing ones. In the design of new machines, the problem of transitioning from technological calculations to kinematics is solved. In the case of modernizing existing machines, the kinematic cycles and working durations of the machine's mechanisms are revised, and the kinematic scheme is developed to increase the machine's efficiency and operational continuity coefficient.

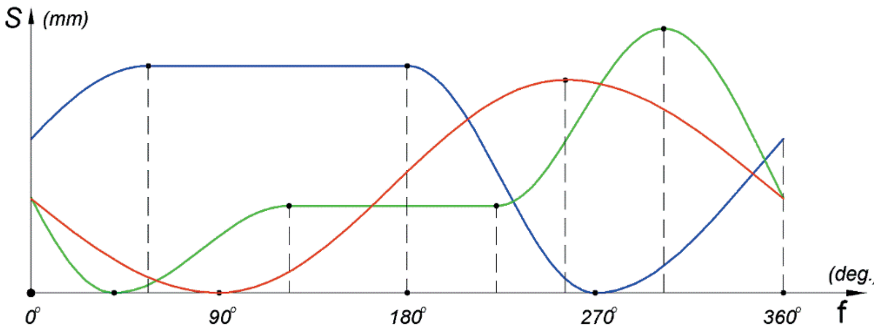

Figure 4. Synchronous kinematic diagram

The efficiency of a machine is inversely proportional to the duration of the kinematic cycle. Therefore, the primary objective of timing diagram design is to ensure the maximum efficiency of the machine by improving the coordination of the mechanisms and minimizing the time required for the kinematic cycle. If the achieved performance does not meet the technical requirements, it is necessary to adjust the kinematic parameters and the technological operating conditions of the machine to reduce the working, idle, and waiting times of the working parts.

3. DESIGN OF THE TIMING DIAGRAM FOR A WEAVING MACHINE

The design of a timing diagram begins with an analysis of the machine's technological process, followed by an approximate calculation or selection of the necessary movements and speeds for the working parts.

The shedding, weft insertion, and beating mechanisms are considered primary mechanisms, while the warp let-off and cloth take-up mechanisms are classified as auxiliary mechanisms. In addition to these, depending on the type of machine, weaving machines may include several control and management mechanisms. If we sequentially activate the primary and auxiliary mechanisms, the technological cycle time of the machine will be equal to the sum of the working and idle times of the mechanisms. That is:

$$t_{cycle} = \sum t_{work.i} + \sum t_{idle.i} \tag{1}$$

where $t_{work.i}$ and $t_{idle.i}$ are the working and idle times, respectively, of the shedding, weft insertion, beating, warp let-off, and cloth take-up mechanisms.

Since the working parts must return to their initial position after performing their required task, the total movement they execute is equal to the sum of their working and idle movements. Consequently, the machine's cycle diagram in a sequential working environment is as shown in Figure 5.

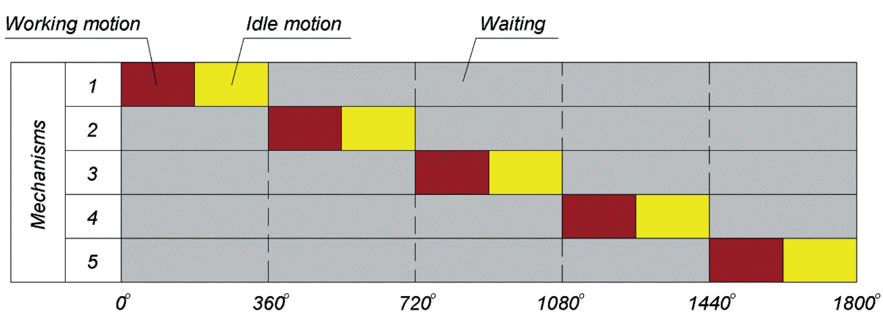

Figure 5. Cycle diagram of the machine in a sequential working environment

In Figure 5, the gray areas represent the idle states of the mechanisms. Reducing the cycle time is possible by partially or entirely eliminating these idle periods. Achieving this requires operating the mechanisms in shared time intervals. This process necessitates drawing synchronous kinematic diagrams to find time intervals where the movements and operations of the mechanisms do not interfere with each other, followed by a joint analysis of these diagrams.

The weft insertion system is the primary mechanism that determines the type, speed, and efficiency of weaving machines. Therefore, the analysis starts with the weft insertion mechanism. Various weaving machines, such as shuttle weaving machines, shuttleless weaving machines, rapier weaving machines, and air-jet weft insertion systems, exist. This analysis begins with an example of a shuttle weaving machine, as shown in Figure 6.

3.1. Shuttle Weaving Machine

In shuttle weaving machines, a cam-arm weft insertion mechanism is used. The working time of the mechanism $t_{çal.1}$ is calculated based on the shuttle's displacement and speed during its acceleration phase. Since the cam mechanism does not require an idle phase, the time for the working part to return to its initial position, i.e., the idle time, is determined from:

$$t_{idle.1} = t_{cycle.1} - t_{work.1} \quad (2)$$

where $t_{cycle.1} = t_{cycle}$ is the full cycle time of the cam shaft, and:

$$t_{cycle} = 60/n \quad (3)$$

where n is the number of revolutions per minute made by the machine.

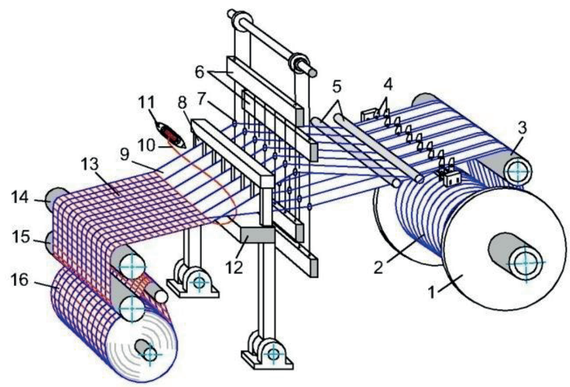

Figure 6. Shuttle weaving machine [13]

The shuttle's flight time serves as a fundamental parameter for determining the movement phases of the other mechanisms:

$$t_{sh.fl} = L_{sh.fl.} / V_{sh.av} \quad (4)$$

In Equation 4, $L_{sh.fl}$ is the distance traveled by the shuttle, and $V_{sh.av}$ is the shuttle's average flight speed (Note: The shuttle does not move during the mechanism's idle phase)[1].

The purpose of the shedding mechanism is to move the heald frames controlling the warp threads from the lower position to the upper position, or vice versa, within the cycle time. Since the idle phase of the mechanism is used as the working phase in the subsequent cycle, $t_{idle.2} = 0$. Due to technological requirements, the shedding mechanism must remain idle during the working time of the weft insertion mechanism. The waiting time of the mechanism must be greater than the shuttle's passage time through the shed. Thus:

[1] When the mechanism makes an idle movement, the shuttle does not move.

$$t_{wait.2} > t_{sh.fl} \tag{5}$$

and:

$$t_{work.2} = t_{cycle} - t_{wait.2} \tag{6}$$

Depending on the type of weft insertion mechanism and operating conditions, the beating mechanism may operate continuously or intermittently. In shuttle weaving machines, a continuously operating four-arm beating mechanism is recommended. In this case, the cycle time of the mechanism is equal to the sum of the working and idle times:

$$T_{cycle} = t_{work.3} + t_{idle.3} \tag{7}$$

One of the fundamental conditions for fabric production is that the beating operation should start as the shed is closing. Furthermore, since the shuttle is placed on the beating mechanism, weft insertion must occur during the beating mechanism's idle phase, i.e., when the reed is moving backward. Additionally, the warp let-off operation is carried out based on the tension of the warp threads, and because this operation is not kinematically linked to the other mechanisms, it is not included in the timing diagram.

The movement phases of the cloth take-up mechanism are coordinated with the shedding mechanism. Since the cloth should remain stationary during the opening of the shed, the mechanism is activated during the waiting phase of the shedding mechanism. That is:

$$t_{work.4} + t_{idle.4} \square t_{wait.2} \tag{8}$$

Since the shuttle is changed while it is waiting on the right side, the weft control and shuttle-changing mechanisms operate over two complete rotations of the main shaft. The shuttle-changing process is performed during the period when the beating mechanism reaches its maximum kinetic energy. This period coincides with the moment when the weft thread is pushed against the fabric edge, i.e., during the fabric formation phase.

After determining the approximate working times of the mechanisms, the next step is to draw synchronous kinematic diagrams. However, since cam mechanisms are used in two of the three primary mechanisms to achieve the required displacement, it is sufficient to draw a revised timing diagram instead of synchronous kinematic diagrams. The reference point for drawing the diagram is the moment when the reed begins to move backward. The timing diagram is shown in Figure 7.

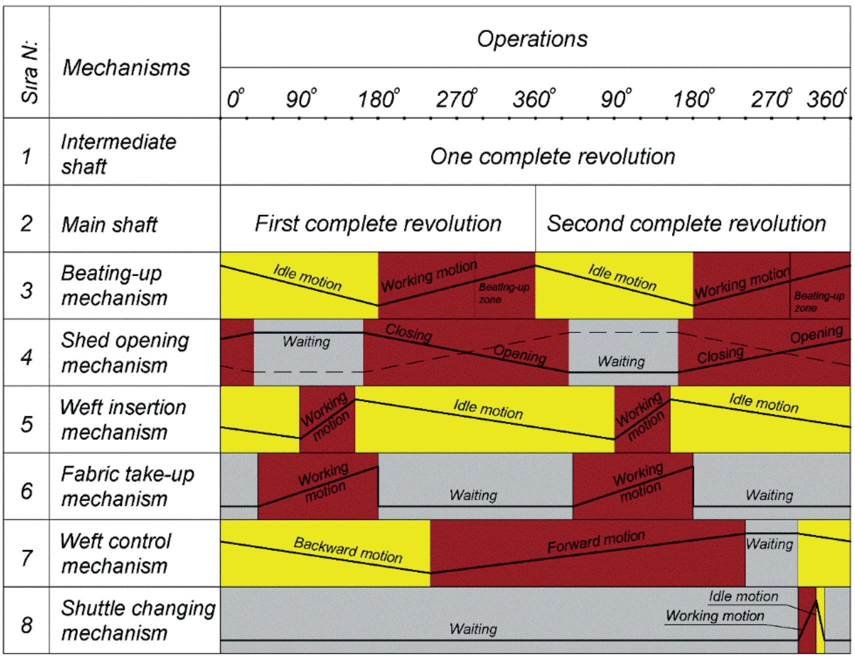

Figure 7. Time diagram of shuttle weaving machine

In modern weaving machine timing diagrams, the movement phases of the primary and auxiliary mechanisms differ from those of shuttle weaving machines. The main reason for these differences is the need for the beating mechanism to remain idle during the weft insertion process. Furthermore, the presence of mechanisms that enable the delivery of the weft thread from a stationary bobbin necessitates the synchronization of these mechanisms with the primary mechanisms in the timing diagram.

3.2. Shuttleless Weaving Machine

The design of the time diagram for a shuttleless weaving machine involves a large number of mechanisms (18 in total), aside from the main mechanisms, that ensure the complete execution of the technological process and determine the machine's performance and efficiency. Seven of these mechanisms are connected to the main mechanisms and are therefore included in the time diagram.

In the shuttleless weaving machine, the primary mechanism that defines the type, speed, and efficiency of the machine is the weft insertion mechanism. Therefore, its analysis is conducted first. In this mechanism, motion is transmitted to the shuttle using a torsion spring. The torsion spring is twisted by a cam mechanism that moves in a 1:1 ratio with the main shaft of the machine.

The working time of the mechanism, $t_{cycle.1}$, is determined by the dynamic analysis of the torsion spring [14]. During the positioning of the shuttle and the fixation of the weft thread, the weft insertion mechanism must pause. In addition, an extra waiting time is required for re-establishing the contact between the cam surface and the follower after the torsion spring is released. Hence, the cycle time of the mechanism can be written as:

$$t_{cycle} = t_{work.1} + t_{idle.1} + t'_{wait.1} + t''_{wait.1} \quad (9)$$

The machine's cycle time is calculated based on the speed at which the weft thread passes through the shed. Let's calculate this based on the data for a shuttle loom with a fabric width of 200 cm [8]:

Given data:

- Total displacement of the shuttle: $L = 2.3\ m$

- Mass moment of inertia of moving parts reduced to the torsion axis: $I = 0.69\ Ncms^2$

- Modulus of elasticity of the spring material: $G_{01} = 0{,}8 * 10^7\ {}^{N}/_{cm^2}$

- Moment of inertia of the torsion spring's cross-section: $J_{01} = 0{,}1d^4 = 0.506\ cm^4$;

- Length of the torsion spring: $l = 71\ cm$

- Shuttle acceleration time:

$$t_{work.1} = \frac{\pi}{2k} = \frac{\pi}{2\sqrt{\frac{J_{01} * G_{01}}{l * I}}} = 0.00551\ s;$$

- Shuttle's initial velocity:

$$v = \dot{\varphi}_{max} R = 150 * 0.185 = 27.7 \frac{m}{s}\ ;$$

- Assuming the shuttle maintains a constant speed during weft insertion, the time for the weft to pass through the shed is:

$$t_{weft} = L / v = 2.3 / 27.7 = 0.083\ s$$

This time is approximately one-third of the machine's cycle time:

$t_{cycle} = 3\ t_{weft} = 0.246\ s$ *ve* $n = 240\ rev/min$

The shuttles, after passing through and being braked, are transported to the left side of the machine using a chain conveyor located at the bottom. The shuttle is then lifted by the shuttle elevator, which prepares it for the next throw. During this preparation process, the weft is fed into the shuttle's yarn catcher and secured. The elevator's movement is driven by a cam mechanism, and it must remain stationary during the operation of the weft insertion mechanism. Thus, the time diagram for the elevator's movement is adjusted accordingly.

Depending on the fabric structure, independent movement is transmitted to the frames, and as the technological process requires the frames to pause during weft insertion, a double cam mechanism is used as the main driving mechanism for the shedding.

The shedding times are calculated using equations (5) and (6). The waiting time is selected based on the fabric width and corresponds to the machine's main shaft rotation between 90° and 100°. In the time diagram, the waiting time is set to $t_{wait.2} = 90^o$, which is sufficient for the shuttle to pass through the shed.

The shuttle's linear motion at high speed is guided by a stationary reed using a dual-cam mechanism. This mechanism consists of three components, allowing the reed to be accurately positioned. In rotary dual-cam mechanisms, the working angle should be taken as greater than 60° [15]. In this case, the angle is set to 70°, resulting in:

$\varphi_{work.3} = \varphi_{idle.3} = 70^o$

and

$\varphi_{wait.3} = \varphi_{cycle} - \varphi_{work.3} - \varphi_{idle.3} = 360^o - 70^o - 70^o = 220^o$

The removal of the fabric from the fabric formation area and its winding onto the cloth beam is performed by the cloth beam shaft, which moves at a certain cycle ratio based on the weft density. This mechanism is independent of the timing of the main mechanisms and is not shown in the time diagram.

The warp tension control and the unwinding of the warp threads from the warp beam are carried out by a special warp let-off mechanism. The let-off process begins 200° after the start of the beating-up operation and ends with the main shaft's 90° rotation (Note: In modern looms, warp let-off is performed using a servo motor).

The control of the warp threads and the braking of the machine are synchronized with the other mechanisms. To avoid disrupting fabric formation, efforts are made to control the warp threads during the idle periods of the beating-up and weft insertion mechanisms, ensuring the warp thread tension remains stable. The working angle of the mechanism is set between 60° and 65° of the main shaft's rotation.

Since the shuttle accelerates within a very short time and the direct supply of the weft thread from the bobbin may cause thread breakage, the weft thread is pre-accumulated in the weft compensator before insertion. This mechanism, known as the weft compensator, adjusts the tension of the weft thread during its passage through the shed.

By initiating the compensator's movement before the shuttle begins its flight, the weft thread's tension remains at zero during the shuttle's launch, preventing breakage. The compensator's start time is synchronized with the shuttle's movement and corresponds to approximately 15° of the main shaft's rotation. The movement time of the compensator arm is set between 75° and 80°.

The weft brake mechanism, which regulates and controls the tension of the weft thread during its placement in the shed, operates in coordination with the weft compensator mechanism. The complexity of this mechanism's movement can be observed in the time diagram.

Since the weft thread is supplied directly from the bobbin, additional operations such as catching, cutting, and incorporating the thread into the fabric selvage are required. The time diagram includes two mechanisms for these processes: left and right centering devices, and the scissors mechanism. These mechanisms pause during the weft insertion process. The working time for the scissors mechanism is set between 1° and 4°.

In handlooms, changing the color and variety of the weft thread is relatively easy. However, achieving this through mechanisms has required the resolution of significant technical challenges. In shuttleless weaving machines, changing the weft thread's color and variety is achieved by using a multi-shuttle weft insertion method.

In shuttleless weaving machines, a complex weft compensator system is used to accomplish this task. The number of compensator arms corresponds to the number of weft varieties. In practice, mechanisms with two or four arms are used, and their working conditions and processes are similar to those of single-arm mechanisms.

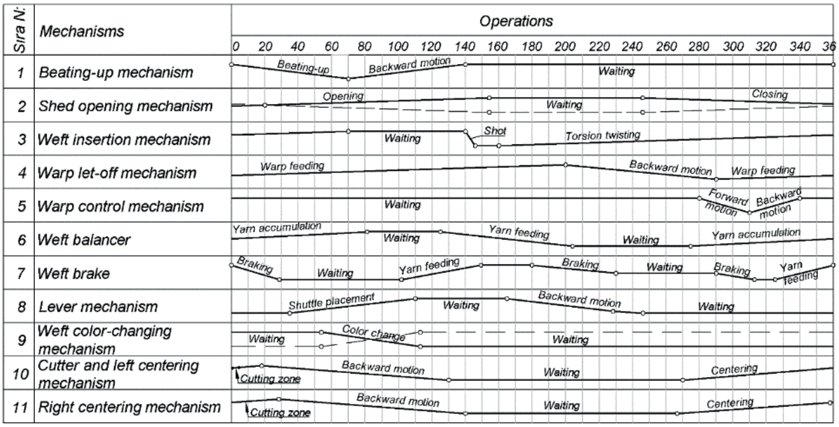

Figure 8. Time diagram of the operation of the shuttleless weaving machine

The revised time diagram, based on research findings, is shown in Figure 8. The diagram illustrates the cycle diagrams of the four main mechanisms of the machine and the seven special mechanisms that distinguish shuttleless weaving machines from other types of weaving machines. The reference point for drawing the diagram is the moment when the reed begins to move toward the fabric line.

3.3. Rapier Weaving Machines

In rapier weaving machines, the weft insertion process is carried out by a pair of rapier grippers that move reciprocally within the shed, assisted by additional components. Compared to shuttle-based weft insertion methods, rapier mechanisms are simpler in design, capable of working with all known yarns, and have no limitations on the number of colors, while offering easy control of the weft yarn. The main drawback of rapier weaving machines is their larger space requirement compared to shuttle and air-jet machines. In rapier machines, since the rapiers must move back and forth across more than half the width of the fabric, special mechanisms such as lever, gear-lever, or cam-lever systems are used to transmit motion to the rapiers. A common feature of these mechanisms is that their moving parts possess large reduced masses.

Since the transfer of the weft yarn from the delivery rapier to the receiving rapier takes place in the middle of the shed, the motion phases of the weft insertion and the beat-up mechanisms are symmetrically placed in relation to each other. The timing diagram phases of the shedding, warp release, and fabric take-up mechanisms are nearly the same as those in shuttle weaving machines and are revised based on fabric width. A key difference between rapier and shuttle machines is the ease of transferring weft yarn directly from the bobbin to the rapier without the need for a weft accumulator.

Given that the weft yarn is pulled from the bobbin and inserted into the shed, mechanisms for cutting the weft yarn, forming the fabric edges, and changing the weft color are required in these machines.

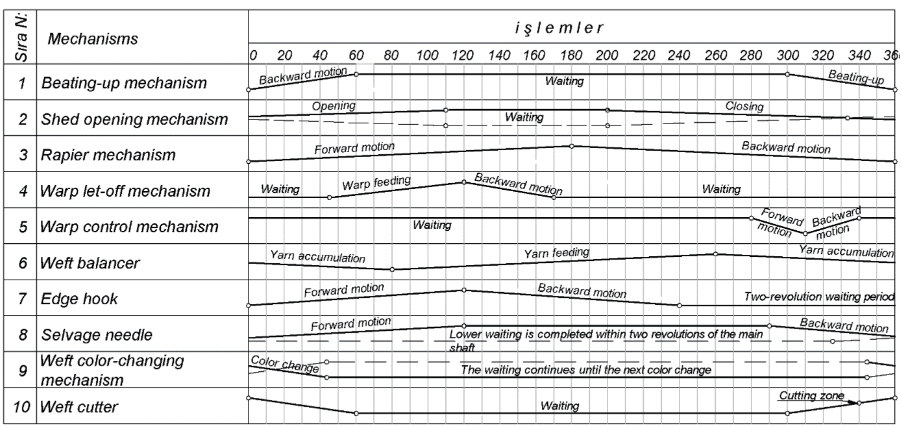

Figure 9. Rapier weaving machine time diagram

Based on this information, the timing diagram is shown in Figure 9. In this diagram, the cyclic timing of the machine's four main mechanisms, as well as the six specific mechanisms that differentiate rapier weaving machines from others, are illustrated. The point of reference for the diagram is the moment when the reed begins its backward motion from the fabric line.

3.4. Air-Jet Weft Insertion System

The air-jet weft insertion system is currently the fastest and most efficient method used in fabric production. Since there is no physical weft carrier, this system offers advantages over other systems in terms of both speed and productivity [16]. In the air-jet system, the weft yarn is drawn from the bobbin, passed through a tension controller, and then prepared for insertion by the weft measuring device. The yarn is then propelled by the main jet to complete the insertion process. Due to the absence of a weft carrier, there is no need for the reed mechanism to pause for long periods, allowing the machine to operate at high speeds. The waiting time of the reed mechanism is selected within a range of 80 to 100° depending on fabric width. Since the movement of warp yarns affects the air jet, it is crucial to complete the shedding process before the air jet is triggered. Warp yarns are brought to a waiting position at 90°.

Because the tension force generated by the air jet on the weft yarn is insufficient and varies over time, weft accumulation mechanisms are employed in these machines. These mechanisms rotate at a constant speed and are therefore not shown in the timing diagrams. In the air-jet system, guiding hooks, gripping teeth, and clamping mechanisms are used to measure, control, and ensure the desired tension of the weft yarn. These mechanisms work in synchronization with the air-jet system. Similar to rapier weaving machines, since the weft yarn is pulled directly from the bobbin and inserted into the shed, cutting, selvage formation, and weft color-changing mechanisms are required.

The revised timing diagram for air-jet weaving machines is shown in Figure 10.

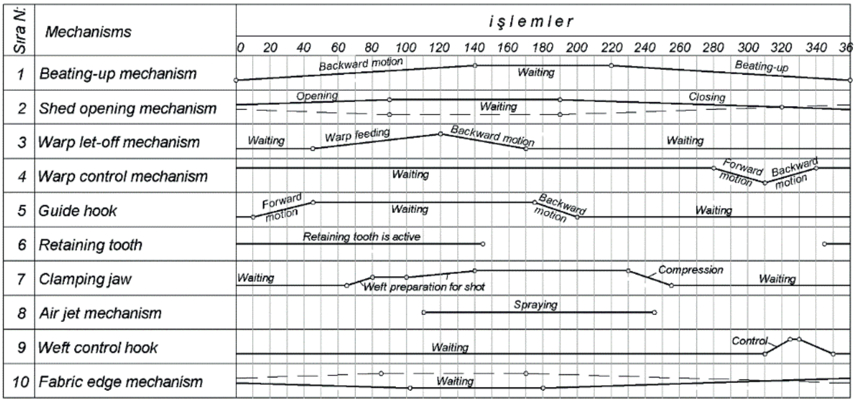

Figure 10. Air-jet weaving machine time diagram

In Figure 10, the cyclic timing diagrams of the machine's four main mechanisms and the six special mechanisms that distinguish air-jet machines from others are presented. The reference point for the diagram is the moment when the reed begins its backward motion from the fabric line.

4. Conclusion

The timing diagram of a weaving machine plays a crucial role in optimizing textile production processes. By analyzing the diagram, manufacturers can identify potential bottlenecks and inefficiencies, allowing them to implement improvement and optimization strategies. Whether it involves fine-tuning the timing of the shedding process or optimizing the tension of the warp threads, the insights gained from the diagram enable enhanced performance and competitiveness.

The design of weaving machine timing diagrams is flexible, adapting to a wide range of fabric types and production requirements. From producing complex jacquard patterns to high-speed plain weaves, weaving machine timing diagrams provide the framework necessary to achieve desired outcomes with precision and consistency.

In this study, weaving machine timing diagrams were examined, focusing on how they are designed for different types of machines. The timing diagrams allow for the analysis of the motion phases of various mechanisms in weaving machines, helping to identify synchronization issues and potential challenges.

For shuttle weaving machines, the movements of the shedding, weft insertion, and beat-up mechanisms were analyzed through timing diagrams, and it was suggested that proper coordination between these mechanisms could increase production speed. Additionally, it was emphasized that the motion phases of the shuttle must be carefully arranged to improve the overall performance of the machine.

In projectile weaving machines, the timing diagram of the torsion-assisted weft insertion mechanism was examined, highlighting the importance of phase synchronization for more efficient operation. Similarly, in rapier weaving machines, synchronizing the back-and-forth motion phases of the rapiers can make weft transfer more efficient, and careful planning of these movements can accelerate the production process.

For air-jet weaving machines, it was emphasized that proper planning of the motion phases during weft insertion could lead to faster and more efficient production. The arrangement of the timing diagrams for high-speed mechanisms in these machines can increase production capacity.

In general, the analysis and correct use of timing diagrams can enhance the efficiency of weaving machines, minimize errors, and reduce costs.

In conclusion, the design and characteristics of weaving machine timing diagrams symbolize engineering excellence and creativity. As the backbone of textile production, weaving machines rely on the careful planning of cyclical motions and processes captured in these complex diagrams. By understanding and utilizing the insights obtained from these representations, manufacturers can explore new avenues for efficiency, quality, and competitiveness in the dynamic environment of textile production.

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