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Multifunctional Foldable Knitted Structures: Fundamentals, Advances and Applications

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Abstract

Contemporary multifunctional textiles are based on hi-tech functionalization. Knitted structures can be relatively rapidly designed and produced in a variety of textures due to their composition of many interlacing loop elements and their combinations. Foldable weft-knitted structures exist in a wide range of forms from simple rolls, ribs, and pleats to more complex three-dimensional structures. They exhibit new kind of geometry and deformation mechanisms. Some of them exhibit auxetic potential. Foldable knitted structures are multifunctional and widely usable. They can be produced in a variety of structures, qualities, and dimensions: in panels, fully-fashioned, or seamless. Their possible application lies in different fields, such as fashionable and functional clothing, sportswear, medical care, packaging, interior design, sound and shock absorption, etc.

Keywords: knitted structures, textiles, clothing, foldable, collapsible, multifunctional

1. Introduction: new age of multifunctionality

Today, consumers are demanding textiles and clothing with high-performance properties, even in the traditional clothing and home textiles areas. Functional and visual appearance are very significant. Many textile and clothing producers develop products with innovative characteristics that can represent an important added value. Added value can be achieved by complex engineering design and by merging knowledge and skills of experts from various areas including craft, industrial design, materials, production technologies, marketing, psychology, ecology, etc. The properties and the characteristics that were initially developed for products for special use are nowadays often present in functional textiles for everyday use. In contemporary textiles and clothing, modern technologies play an important role. Textiles and clothing are not “just” textiles and clothing anymore. They represent an important hi-tech

field even if in the people's minds, they are still often considered as simple traditional everyday objects. With contemporary multifunctional textiles based on hi-tech functionalization, a new textile tradition has been developing, slowly changing the rooted perception of textiles and clothing.

Functionalization of textiles aims to improve native properties as well as to impart new functions in the textile products [1]. For instance, with the selection of raw materials and the design of structural parameters of non-woven, woven and knitted structures, mechanical, permeability, and comfort features of textiles can be optimized and upgraded. Textile finishing can obtain new functional properties such as UV resistance, water repellency, flame retardancy, antibiotic, antistatic, antimicrobial activity, wrinkle recovery, etc. to the fabrics.

Functional properties can be defined as all the effects that are beyond the pure esthetic and decorative functions. As described above, they can be obtained either by:

- the raw material (characteristics of the polymer or additives before fiber forming);
- yarn, fabric or 3D textile construction; or
- textile finishing,

that is by material, mechanical, or chemical functionalization.

Multiple functions are often required, leading to what we can call multifunctional textiles [2]. The term “multifunctional material” is defined to be any material or material-based system which integrally combines two (or possibly more) properties, one of which is normally structural and the other functional. Both active and passive functionality are included [3].

The basic underlying technological need for the development of multifunctional materials is that solutions to particular problems or needs cannot always be found by using a simple combination of materials with different functions, and a technological barrier is reached. Real benefit will often only be found if true multifunctionality can be achieved [3].

The potential to exploit multifunctional materials spreads over a broad range of market sectors and products. Key areas are health care, security, energy, packaging, aerospace and transport, consumer friendly textiles and wearables, defense, etc. [3]. The multifunctionality of materials often occurs at scales from nano through macro and on various temporal and compositional levels [4].

The major barrier to the development of multifunctional materials and systems is, paradoxically, the very thing that gives them their advantage over combinations of single functions—multidisciplinarity. That is, the need to pull together and establish close and sustainable links between often disparate and closed disciplines, including materials scientists, chemists, physicists, engineers, biologists, physicians, and designers. Multifunctional materials have the potential to support the sustainability agenda. For example, multifunctional structures might be designed for re-use or recyclability [3]. After the first life cycle is over, the second one can start by up-cycling.

Multifunctional materials can be both naturally existing and specially engineered [5]. Many of them may draw inspiration from nature, where size and weight are often critical and multifunctionality is a necessity rather than a luxury [3]. Biological materials routinely contain sensing, healing, actuation, and other functions built into the primary structures of an organism [4]. Textiles can take advantage of the very sophisticated and highly efficient mechanisms with which nature protects itself in hazardous environments, based on extraordinary functionalities. Processes used for the functionalization of textile materials need to be increasingly environmental friendly. The use of natural resources, energy, and chemicals needs to be minimized [2].

We have entered the era of hybridization of materials and engineering techniques, for example, highly multifunctional materials, with folded materials and knitted structures among them. Multifunctional objects are as old as mankind, but after the period of excessive consumerism, it seems that we have finally focused on fewer but combined and more efficient multifunctional objects and processes. We are in the era which grants a new meaning to the multifunctionality.

Knitted structures, especially flat knitted structures, can be relatively rapidly designed and produced in a variety of textures due to their composition of many interlacing loop elements and their combinations (front and rear loop, transfer loop, tuck, miss, rack, etc.). Mechanical functionalization involves the design of the structural and geometrical parameters which influence the performance properties of foldable knitted structure. Chemical functionalization upgrades their performance to achieve the planned characteristics. Unlike weaving, flat knitting enables manufacturing of fully fashioned and seamless products. Shaping and real three-dimensional knitting expands the boundaries of their multifunctionality.

2. Foldability as a principle of collapsibility

Collapsibility is an elementary design principle applied to a great many everyday objects [6]. Often, we are not even aware of it. For example, every day, we fold our newspaper or book after reading and fold our clothes to put them in the wardrobe.

Size adjustment to meet functional requirements is a time-honored principle in nature, too. Animals downsize to hide, relax, rest and protect themselves, and upsize to brag, threaten, fly, fight, and court [6]. In modern times, many patents have been applied for collapsible objects with space saving as their primary added value. Minimalization of equipment is very important in some areas, for example, in storage, transport, medicine, aerospace application, etc.

2.1. Genuine or quasi-collapsibles

Collapsibles are smart manmade objects with the capacity to adjust in size to meet a practical need. They are functional doubles with two opposite states, one folded and passive and one (or more) unfolded and active. They grow and shrink, expand and contract, according to functional need. To give collapsibility to an object, its volume must be redistributed in

one way or another to occupy less practical space. Practical space is space we want to free up for some other purpose. To qualify as a genuine collapsible, an object must be repeatedly collapsible and expandable. Object designed to fold or unfold only once does not qualify as collapsible. Moreover, two conditions must be met before a manmade collapsible is conceived and created. First, somebody must see advantage in reducing the size of a tool when it is not in use. And second, it must be mechanically possible to reduce the size of that tool [6].

Collapsability *per se* is never the purpose function of a tool. It is always a support function. Collapsibility may never be the most important function of a tool, but it is often the decisive factor when the buyer makes choice [6]. As mentioned above, a genuine collapsible has one-folded passive state and one or more unfolded active states. If the folded state is both active and passive (like a pair of scissors), then the object is not a genuine collapsible. Many active states and no passive state as well as no space saving define a quasi-collapsible [6].

Mollerup [6] defined twelve collapsibility principles. Most describe the action by which an object is collapsed. They include the most frequently applied methods of mechanical size reduction:

- stress,
- folding,
- creasing,
- bellows,
- assembling,
- hinging,
- rolling,
- sliding,
- nesting,
- inflation,
- fanning and
- concertina.

Most of the principles describe the action, while some of them (bellows and concertina) describe the structure. The differences between collapsibility principles are often indistinct. The boundary between collapsing by folding and collapsing by creasing (along pre-folded lines), for instance, is not always clear [6]. In some cases, the collapsibility is a result of two parallel principles.

In textiles and clothing, some principles are more common than the others. The stress and rolling are often applied for reducing the volume, for example, for a sleeping bag storage. Folding technique is used for packing clothes or for adjusting the sails surface. Creasing means folding along preset lines. Pleated window screens are both functional and decorative. Bellows collapsible racks can be used as camping equipment. Rolling is a basic principle of roller blinds operation. Fanning principle is named after a collapsible fan, a fashion accessory. Flap bags are closed by creasing, but their closing principle can be considered hinging as well; in this case, the boundary between the two principles is quite blurred.

From the presented examples, it can be seen that collapsibility can be achieved by many ways, including folding. In recent years, more and more designers of all disciplines have turned to folding to create a wide range of handmade and manufactured objects, both functional and decorative. A little time spent looking through design and style magazines will reveal a significant number of folded products, from apparel to lighting and from architecture to jewellery. Origami is one of the most vibrant buzzwords in contemporary design [7]. It is often used as a synonym for folded structures, in knitting, as well as in other textile techniques [8].

2.2. Self-folding structures

The science and technology associated with origami-inspired engineering are new and developing rapidly. It has evolved from esthetic pursuits to design folding structures across cultures and scales. The underlying principles of origami are very general, which has led to applications ranging from cardboard containers to deployable space structures which can be fabricated, assembled, stored, and morphed only through bending without any cutting and gluing. More recently, researchers have become interested in the use of active materials (i.e., those that convert various forms of energy into mechanical work) to effect the desired folding behavior. When used in a suitable geometry, active materials allow engineers to create self-folding structures. Such structures are capable of performing folding and/or unfolding operations without being kinematically manipulated by external forces or moments. This is advantageous for many applications, including space systems, underwater robotics, small-scale devices, and self-assembling systems [9, 10].

Self-folding is not exactly a new phenomenon. It frequently appears in nature for the efficient fabrication of structures but is seldom used in engineered systems. Recently, self-folding structures were developed, consisting of shape memory composites that are activated with uniform heating in an oven or a heated bath [11].

Self-folding also occurs in textiles. At the fiber level, it is shown as self-curling. In the nature, the curling property of wool (WO) results from its bilateral structure, where ortho and para cortex are arranged in asymmetrical, side-by-side order in the cross-section of the fiber. Wool fibers have, because of this difference, a helical crimped configuration. There are also man-made crimped fibers. There are two groups of spinning methods for producing bi-component fibers with self-crimping ability. In first group, there are methods where special equipment is

needed to conjugate two different components together in a side by side order. In the second group of methods, a non-symmetrical character across the cross-section of the filaments is introduced to the filament on the classical spinning devices, without any special additional apparatus. It is also clear that the formation of crimps is a result of the bilateral structure of asymmetrically cooled yarns. The consequence of the bilateral structure is the formation of crimps after drawing [12].

In flat knitting, some links-links structures exhibit self-folding after exiting the take-down zone (**Figure 1**). The folded state represents the relaxed, that is, the passive state.

Origami as an inspiration for hi-tech engineered products has been studied in depth from the practical as well as from theoretical point of view. For instance, Peraza-Hernandez et al. [13] noted that modeling and analysis of origami structures allow for the understanding of

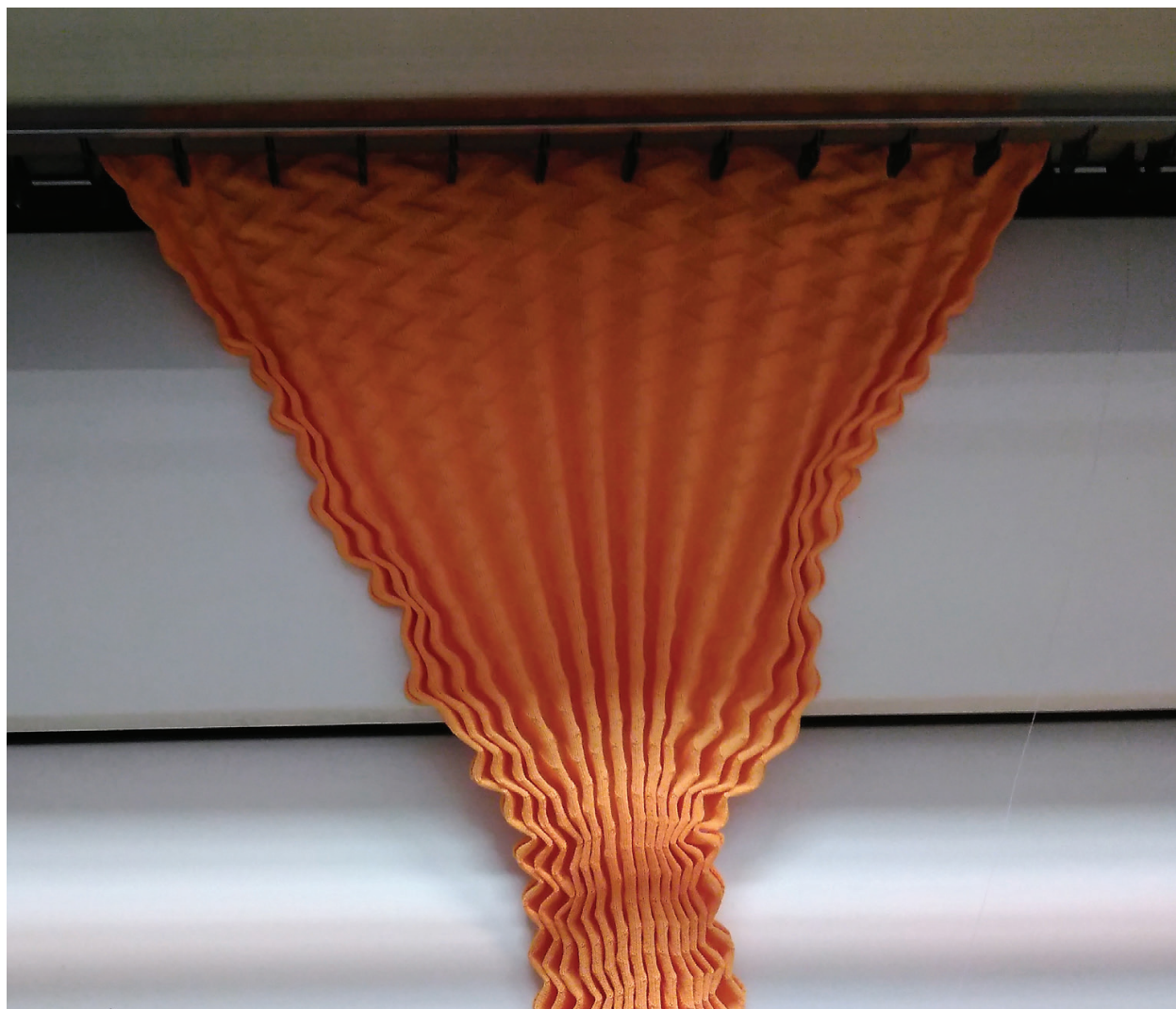


Figure 1. Self-folding of links-links structures after exiting the take-down zone.

their behavior and the development of computational tools for their design. They presented a novel model analogous to that for rigid origami, for origami structures having folds of non-zero surface area that exhibits higher order geometric continuity (termed smooth folds). Modeling of origami structures with smooth folds exhibiting elastic behavior is performed by determining the configuration of the structure that minimizes its total potential energy subject to the derived kinematic constraints. However, a generalized understanding of origami remains uncertain because of the differences between model predictions and experimental confirmations [13].

Smart materials can play a significant role in the realization of self-folding origami-inspired structures. Researchers have demonstrated self-folding behavior in many active material systems with inducing fields that include thermal, chemical, optical, electrical, and magnetic. Several combinations of materials, geometry, and inducing field are feasible, yielding an array of design options [9].

3. Multifunctional foldable textiles

3.1. Textile folding techniques

Fashion designers have long used pleated fabrics for esthetic effect and to introduce disguised fullness to women's clothing [6]. In textiles and clothing, foldable structures are a fundamental element of design. Rolls, folds, ribs pleats, and bubbles make a flat structure three-dimensional. Redistributed volume causes changes in esthetic appearance as well as in functional properties like thermal insulation, sound absorption, compression and support, strength, stiffness, handle, etc.

Origami-inspired folding of textiles can be performed by various techniques. Woven and nonwoven textiles usually exhibit folded look achieved by pressing or finishing. Folded textiles can also be formed by sewing together parallel stripes of fabric alternately on the face and the rare side. On the other hand, knitted products can be designed by integrating folds directly into the knitted structure. Creased or folded knits can involve a wide range of structures from simple ribs and pleats to more complex 3D structures [8]. Knitted pleats are worked into the fabric by varying the tension and knitting tight and loose rows, thus creating a fold line in the fabric. Young London-based Korean designer Hanjoo Kim demonstrates the creativity that can be achieved with the technique of pleating, adding both structure and movement to the fabric [14].

Many traditional textile and clothing objects have been foldable and multifunctional at the same time. In continuation, some examples of folding textiles and garments are presented. For instance, berets are made from felt. They are folded for storage and unfolded when used as a headdress. They are genuine collapsibles. Berets protect from cold and wind. They often represent various institutions as parts of their uniforms. In some periods, a beret was a fashion statement, also a revolutionary symbol.

Surgical masks are made from nonwovens. Usually, they consist of multiple layers; a filter is placed between nonwoven layers to stop bacteria from entering or exiting the mask. Most surgical masks feature pleats or folds allowing the user to expand the mask and cover the lower part of the face. As the surgical masks are made for a single use only, they are unfolded only once in their lifetime, so they are foldable by definition, but they are not considered as genuine collapsibles. Surgical masks protect transmission of body fluids from and to the wearer. They can be used as dust masks. Surgical masks with decorative designs are popular in countries in which they are worn in public to protect ordinary people from infections or allergies. They can also help to conceal a person's identity; pop singer Michael Jackson was often hiding behind a surgical mask when he appeared in public.

A fine example of capitalizing on mass-production technology can be seen in the work of Reiko Suno and Nuno fabrics, one of the most important textile design studios, founded in 1984. Nuno, meaning functional textile, specializes in creating unique fabrics. One of their products is Nuno Circle origami pleated bag, made of polyester that can be recycled [15]. The bag is constructed and sewn, then folded repeatedly at sharp angles and permanently pressed at 200°C in a special pleating process that is patent pending [16].

Japanese artist and designer Issey Miyake is considered revolutionary for his use of materials and its iconoclastic, conceptual approach to fashion. He blends traditional, historical elements of Japanese fashion, such as wrapping and folding, with cutting-edge technological innovation that have revolutionized fabric manufacturing. His designs demonstrate a desire to expand the potential for clothing outside of the purely functional. He is best known for the technique of pleating silk via a heat treatment, first used in his iconic collection "Pleats Please" in 1993 [17]. Even if Miyake is well known for his overarching esthetical-functional concept, in his case, the foldability is often a sophisticated visual effect rather than a (multi) functionality effect.

3.2. Foldable textiles for various applications

Textiles are most appreciated for their softness and pleasant touch; nevertheless, they can be used as substrates for hardening finishes or elements of composites. With appropriate coating, their behavior is similar to that of paper or other stiff foldable materials. Cutting edge technology is often inspired by past inventions. The same would be true for foldable textiles.

3.2.1. Interior and exterior textiles

Interior architecture and contemporary textiles have an odd, somewhat unresolved relationship. Although fabrics hold the potential to structure space, dampen sound, and emanate light, they are usually confined to a secondary role within the interior. Traditionally, interior textiles have been seen as soft furnishing and used as decorative accessories, but this is changing as materials such as glass filaments, carbon fibers, conductive wires, and metal mesh begin to replace architectural substrates. Although the new generation of interior fabrics are regarded as high-tech devices, they can be described as beautiful, too [18].

Many modern interior textiles have creased or pleated structure but in fact, they are not genuine collapsibles. For example, German architect Jürgen Mayer used pleated fabrics to create elliptical colons. The installation was designed for Nya Nordiska's exhibition at a design trade fair in Frankfurt [18]. The purpose of the pleats was purely esthetical, not functional. On the other hand, modern venetian blinds are made of textile composites and are genuine collapsibles [6].

Now, as in the past, a tent is a house for man on the move. Carried on truck, back, or bike, it takes up little practical space. Tent designers must accommodate a number of conflicting demands for easy handling, maximum shelter, and minimum weight, and they take great efforts to find new spatial and technical solutions to meet these demands [6]. Tents are genuine collapsibles.

3.2.2. Sport textiles

Backpackers wage a never ending struggle to minimize the weight and volume of their gear. One way of reducing volume is to stow a sleeping bag in a compression sack, which works by stress pressure. Traveler's mattress reduces for storage when the air is pressed out and held out by a stopper. When the stopper is removed, the mattress automatically takes in air and reshapes itself. This principle is stress pressure as well [6]. The flexibility of textiles allows clothes to be folded and stored when not in use or when prepared for traveling. Anoraks, raincoats, and wet-weather jackets can often be folded and stored into a sewn-in pocket.

All sailing boats are equipped with sails which are folded and unfolded to meet the weather and wind changes. Nobody takes as much interest in folding their collapsible tool as parachuters. For them, sloppy folding could be fatal [6].

A balaclava is a form of a cap designed to (partly) cover the face. Usually, only the eyes, mouth and nose, or the front of the face are unprotected. Some versions can be folded into a cap to cover just the top of the head or unfolded to cover the face or being used as a warming collar. Apart from skiing, balaclavas are used today as safety garments for firefighters and race drivers. They are made from a flame-resistant material and can contain a breathing apparatus.

3.2.3. Transport textiles

In cars, foldable sunshades made from knitted mesh are used for side windows. Their form is similar to the photographer's collapsible light reflector, invented in 1985 by John Riston. When twisted, the spring coils itself into three smaller rings, making it compact enough to stow away in a small bag [6].

Convertible cars can convert between an open-air mode and an enclosed one. They are equipped by a collapsible textile roof which is hinged to fold. The roofs of baby strollers fold in the same principle.

3.2.4. Contemporary (“technical”) fashion

Nowadays, more and more non-textile materials and non-textile technologies are incorporated in textiles and clothing to contribute to their multifunctionality. Some examples of a complex integration of materials and supporting devices can also be found in history. Bustle was a support used to expand the fullness of the back of a woman’s dress. It was worn under the skirt at the back, below the waist. Collapsible wire bustles were used in nineteenth century to facilitate seating. They were the early representatives of the “technical fashion.”

Hussein Chalayan is regarded as an inventor, philosopher, and architect among fashion designers. He approaches his collections like conceptual artist, frequently interpreting in his designs socially relevant themes such as cultural identity, tradition, and migration [19]. He was one of the first designers to engage with technological systems, and many of his collections have pioneered garments that feature wireless technology, electrical circuitry and embedded connectors [18]. For his 2007 collection entitled “One hundred and eleven,” he designed a true collapsible collection of six mechanical transforming dresses, expanding and folding to change the shape and silhouette of the garments with the aid of electronics. The hemlines were raising and lowering, the skirts were expanding and contracting.

3.2.5. Fashion accessories

Fans were once an essential feminine accessory. Foldable fans could be inspired by a peacock tail. They came into use after 1580. They functioned as a temperature controlling device by inducing an airflow over the skin. They could also be used as means for concealing identity [6, 20, 21].

An umbrella is a manmade adaptation to the changes in the weather [6]. It protects from rain, while the parasols were once used as a shield against the sun [20]. The supporting structure of umbrellas is hinged. So too are the legs of a collapsible tripod, though they may additionally expand and collapse by sliding [6]. Some umbrellas can be unfolded manually, while the others can spring open automatically. Umbrellas are genuine collapsibles.

The “chapeau claqué” is a foldable hat. It is a genuine collapsible which folds flat for storage and folds out for use [6]. It could be a raw model for future clothes and accessories occupying more and more space in our wardrobes and inducing the need for bigger and bigger living space.

4. Foldable knitted structures

Basic interlacing loop elements of a knitted structure are loop, tuck, and float (**Figure 2**). Loops, tucks, and floats have a very different appearance on the front and back (rear) side of the knitted structure, respectively. Loops are made during a complete knitting process. Tucks are made in a tucking process when the yarn is bent but not intermeshed. Floats are made in a miss process when the knitting needles are out of action. Racking, that is, lateral movement of

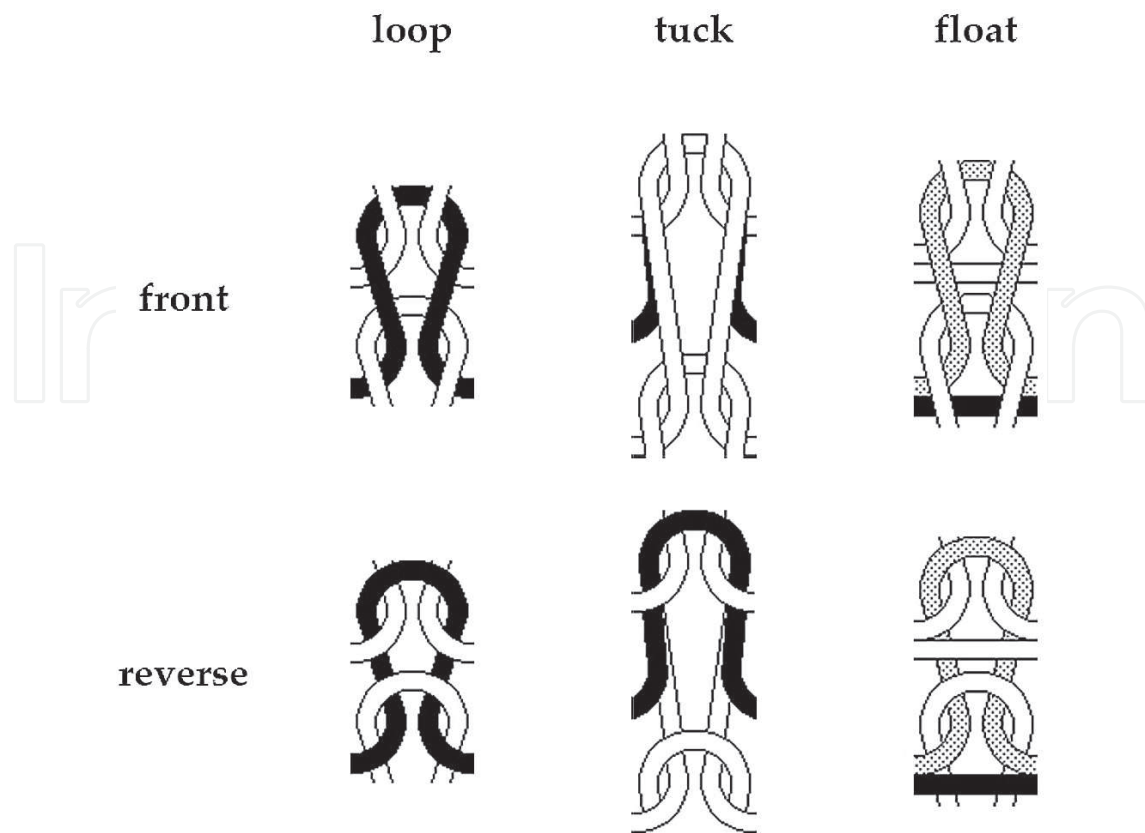


Figure 2. Interlacing loop elements.

the needle-beds results in inclined and/or crossed loops which leads to additional patterning possibilities including cable and aran patterns. Transferring loops from one needle to another in the same or opposing needle bed is used for shaping and for knitting complex-knitted structures.

Single-knitted structures are made on a single needle-bed. The front side of the structure is composed of front interlacing elements, while the back side of the structure is composed of reverse loops, tuck, and floats.

Double-knitted structures are made on two or more needle beds. There are front as well as reverse interlacing elements seen on both sides of the knitted structure.

The simplest double structures are ribs (**Figure 3**) composed of alternating wales of front and reverse interlacing loop elements, respectively. Each wale contains only one type of loop interlacing elements: front or reverse. A special arrangement of front and reverse loop wales results in folding into a pleated structure.

A links-links or a purl structure is made on double-bed knitting machines equipped with double-ended latch needles or on rib machines equipped with transfer needles which enable loop transfer from one needle-bed to the other, combined with needle-bed racking. Links-link structures are composed of front and reverse loop-interlacing elements alternating in both directions, along wales as well as courses.



Figure 3. Folding of ribbed structures with various rib widths made on the same number of knitting needles.

The speciality of knitting technology is the possibility of producing continuous fabrics, knitted panels, whole garment, or seamless products as well as basic and advanced two-dimensional and three-dimensional compositions including composite substrates. Knitting technology supports and upgrades other textile and non-textile technologies. Knitted structures can be combined with other materials to achieve optimal performance [22].

Knitting process allows the production of a vast range of structures. Foldable weft knitted structures exhibit new kind of potential, geometry, and deformation mechanisms. Creased or folded knits can involve a wide range of structures from simple rolls, ribs, pleats, and bubbles (**Figure 4**) to more complex three-dimensional structures. Links-link knitting enables manufacturing of very esthetically intriguing structures which are flat-knitted but crease and fold after relaxation, forming various textures and spatial patterns. Among them, links-link structures with zigzag or other geometrical patterns are particularly promising as they are rather simple to design and produce. Foldable weft-knitted fabrics have potential applications in different fields, such as functional clothing, sportswear, medical care, packaging, sound and shock absorption, etc. [8, 23].

4.1. Rolls

Edge curlings occur in plain-knitted fabrics owing to the unbalanced yarn bending moment existing in the three-dimensional nature of the structure. The curlings occur at the upper and lower edges of a piece of fabric toward the front side and at the left and at the right edges of the fabric toward the back side (**Figure 4**). The yarn in a loop wants to adopt a straight form, but it is prevented from doing so by neighboring loops. Thus, curling can start at the edges

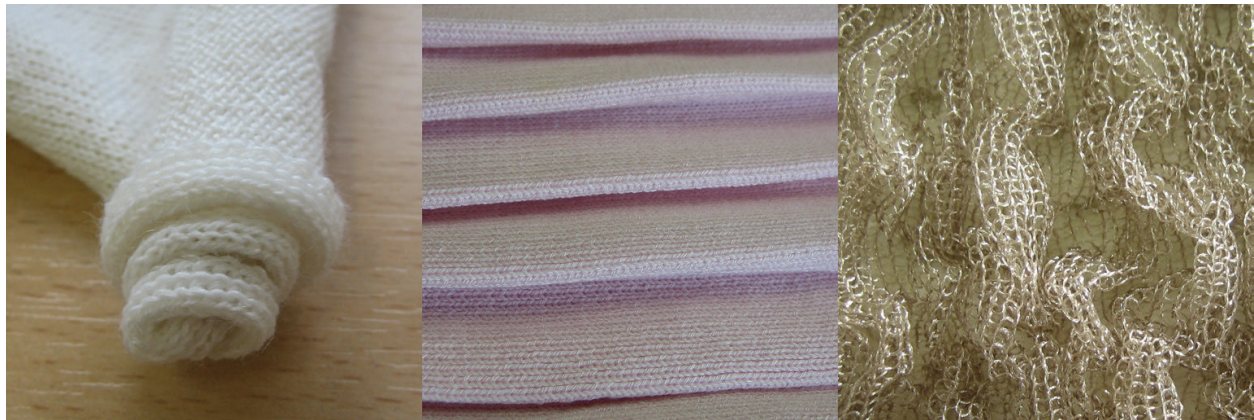


Figure 4. Foldable knitted structures: roll, pleats, bubbles.

as there is no neighboring loop on one side to prevent curling. The edge curlings can create problems during the plain-knitted clothing goods processing. In addition to the problems, there are also positive effects or advantages provided by edge curlings, such as the upper side edge curling being used to form the neck of pullovers [24]. The polo pullover closure can consist of a knitted placket band partially rolled-up to form a welt.

Formation of a curling multiplies the thickness of the knitted edge which can result in adequate breaking strength increase. In the past, this led to specific regulations for the preparation of specially shaped knitted samples for the breaking strength testing.

4.2. Ribs and pleats

Knitting ribs requires two sets of needles operating in between each other so that wales of face stitches and wales of reverse stitches are knitted on each side of the fabric [25]. Ribbed structure has a vertical cord appearance because the face loop wales tend to move over and in front of the reverse loop wales. As the face loops show a reverse loop intermeshing on the other side, ribs have the appearance of the technical face of plain fabric on both sides until stretched to reveal the reverse loop wales in between [25].

Ribs fold by relaxing and unfold by stretching in the direction perpendicular to the fabric formation. Ribbed structure is one of the basic foldable knitted structures which can be used for elastic beginnings and welts for knitwear like socks and pullovers. Due to its elastic recovery potential, ribs can be used for tight as well as compression garments. The folding effect depends on repeat (**Figure 3**), course and wale density of the structure, and material composition.

Knitted pleats (**Figure 4**) can be manufactured on double bed flat knitting machines with special needle arrangements on both beds. As every knitted structure tends to curl or fold toward the reverse side along the length of the fabric, inactive needle in either needle bed creates a wale of single reverse loops within the double structure. The knit folds toward the fabric side with the wale of reverse loops. Various arrangements of inactive needles result in various types of pleats: knife, accordion, or rolled pleats. The width of the vertical ribs influences the folding effect, for example, the extent of width-wise shrinkage.

4.3. Links-link knitted structures

Links-links or purl is the only structure having certain wales containing both face and reverse meshed loops. Although in the past structures of this type were knitted only on flat bed and double cylinder purl machines employing double-ended latch needles, electronically controlled V-bed flat machines with rib loop transfer and racking facilities are now used [25].

The simplest links structure is 1×1 , which consists of alternate courses of all face and all reverse loops and is produced by the needles knitting in one bed and then transferring over to the other bed to knit the next course. Its lateral stretch is equal to plain, but its length-wise elasticity is almost double. When relaxed, the face loop courses cover the reverse loop courses, making it twice as thick as plain structure [25].

By alternating multiple courses of all face and all reverse loops, horizontal links-link ribs are manufactured. They can fold by relaxing and unfold by stretching in the direction of fabric formation. The height of the horizontal links-link ribs influences the folding effect, for example, the extent of length-wise shrinkage.

There are also other, patterned foldable links-links structures, composed of geometrical elements like, square, diamond, zigzag lines, etc. (**Figure 5**). Each geometrical element is composed of the same type of loops, front, or reverse.



Figure 5. Various foldable links-links knitted structures.

5. Characteristics and properties of links-link foldable structures

5.1. Folding effect

In weft links-links knitting, folding is based on the structural disequilibrium of face and reverse loops which causes the fabric to crease, contract, fold, and form into a three-dimensional structure after the take down and relaxation. Foldable structures shrink in both course and wale directions. Under applied strain in the horizontal or vertical direction, three-dimensional foldable structures smooth into a flat fabric, creases unfold and the structure expands in both directions [8, 26]. In order to establish the influence of yarn composition and structural parameters such as size of the repeating unit cell on the folding effect of links-link knitted fabrics, a set of experiments was designed by Pavko-Čuden et al. The number of the same type of loops in a course direction needed to initiate the structure folding effect was also investigated [8].

Two series of samples with 12 different links-link zigzag structures were knitted. The first series of samples (**Figures 6 and 7**) was produced with varying unit cell sizes both in the course and wale direction (from the smallest 2×2 to the biggest 24×24 loops in a unit cell). The second series (**Figures 8 and 9**) was produced with varying widths of a zigzag line in a unit cell with a constant number of courses (from the narrower 2×24 to the widest 24×24 loops in a unit cell). Both series of knitted structures were produced on the knitting machine Shima Seiki SES 122 RT of gage12E. Two yarns of different material compositions were used: WO/PAN and CV/PA.

After relaxation, the dimensions of the samples in horizontal and vertical direction were measured. Considering the repeat sizes (number of loops in each repeat), the width/loop and the height/loop values were calculated to estimate the folding potential of the samples. Smaller value of width/loop or height/loop, respectively, means better folding of the structure.

Zigzag-knitted structures with varying repeating unit cell sizes (1st series of samples) fold in both the course and the wale direction. The folding effect appears in all sizes of a unit cell for structures produced from both yarns, except for the smallest zigzag-knitted structure with a 2×2 repeat. The result shows that these structures are more closely folded in the course direction rather than in the wale direction. As the width/loop and height/loop values do not vary substantially for different repeat sizes, it can be assumed that the folding effect of these structures in both directions is good.

The width/loop values of the zigzag structures with varying unit cell sizes increase with decreasing unit cell sizes. It signifies that knitted structures with smaller unit cell sizes are

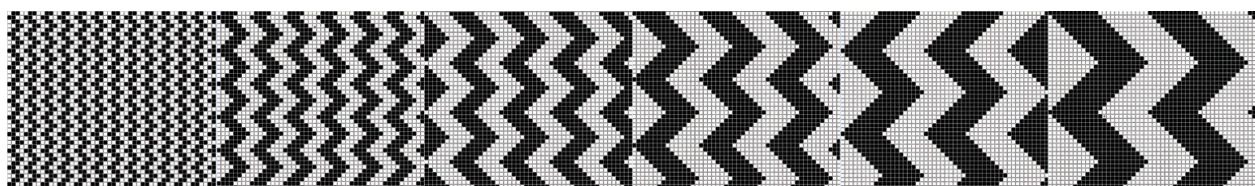


Figure 6. Pattern chart of zigzag knitted structures with different square repeating unit cell sizes (size of repeating unit cell from left to right: 4×4 , 8×8 , 12×12 , 16×16 , 20×20 and 24×24).

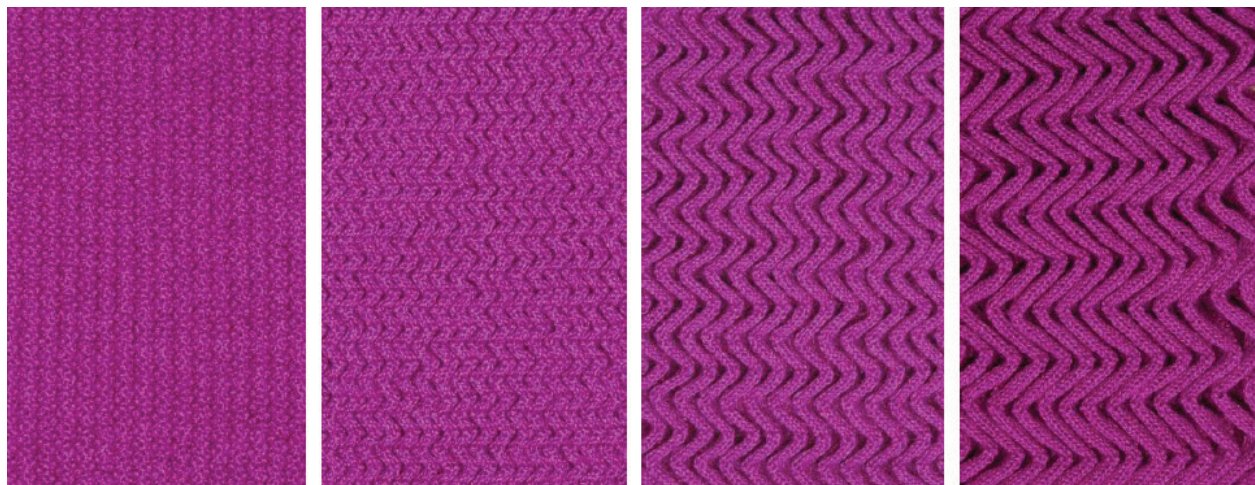


Figure 7. Zigzag knitted structures with different square repeating unit cell sizes made of WO/PAN yarn (size of repeating unit cell from left to right: 4×4 , 8×8 , 16×16 and 24×24).

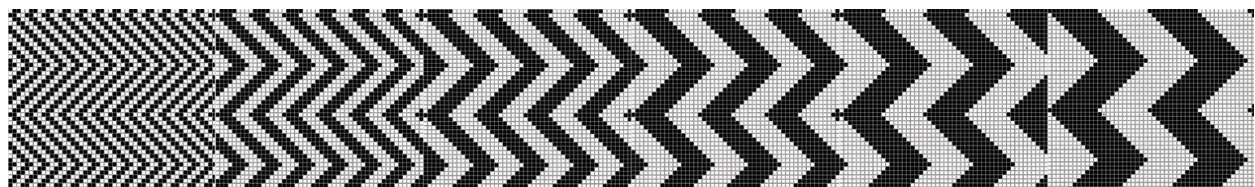


Figure 8. Pattern chart of zigzag knitted structures with different widths of zigzag line (size of repeating unit cell from left to right: 4×24 , 8×24 , 12×24 , 16×24 , 20×24 and 24×24).

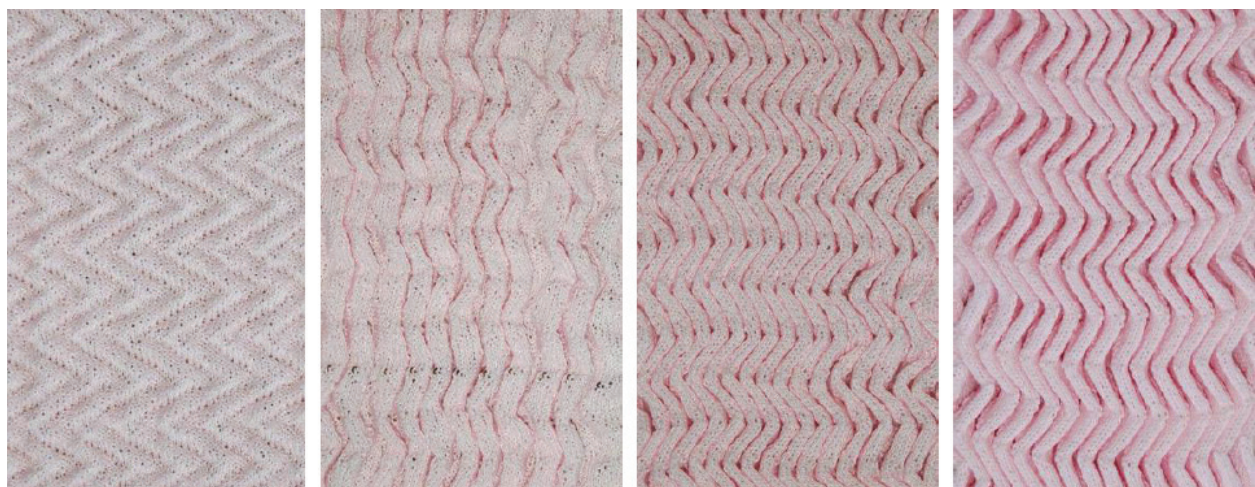


Figure 9. Zigzag knitted structures with different widths of zigzag line and a constant number of courses made of CV/PA yarn (size of repeating unit cell from left to right: 8×24 , 14×24 , 16×24 and 24×24).

less folded in the course direction. Nevertheless, even the knitted structure with the 4×4 unit cell size is well folded. The height/loop values of zigzag-knitted structures with varying unit cell sizes are more or less constant and do not change much with the variation in the unit cell size. Knitted structures made of WO/PAN fold better in the wale direction, while in the course direction, the folding is better for the knitted structures made of CV/PA yarn.

Regarding the knitted structures with varying widths of a zigzag line and a constant number of courses (2nd series of samples), the differences in the width/loop values are more substantial; decreasing the width of the zigzag line quickly increases the width/loop values. The 4×24 knitted structure is very poorly folded. The height/loop value of structures with varying widths of zigzag lines does not vary considerably.

Structures made of WO/PAN evenly fold from the unit cell sizes 24×24 to 16×24 , while structures made of CV/PA evenly fold from the unit cell size 24×24 to 14×24 . Knitted structures with narrower zigzag lines are poorly folded. Hence, the width of zigzag lines for the structures with a constant number of courses substantially influences the ability to fold. Certain number of the same type of loops in a course direction is needed to provide sufficient folding effect in the relaxation process after knitting. Merely six (for the CV/PA structures), seven (for the WO/PAN structures), or less loops in this kind of arrangement of face and reverse loops do not provide sufficient folding force; thin zigzag lines are too narrow for the fabric to fold.

The same experimental design was used for the preparation of another two series of samples, knitted from the same yarns, but on the coarser machine Stoll CMS 502HP E 2.5.2 [23]. It was concluded that the yarn material composition, the size of the repeating unit cell, and the width of the zigzag line at the constant number of courses in the repeat significantly influence the folding ability of links-links knitted structure.

By experimenting, it was found that the variation of the coulliering depth setting of the front and rear cam to different levels leads to even more intriguing foldable structure (**Figure 10**). More open areas contribute to the increased porosity and permeability, while the compact areas contribute to the stiffness and therefore folding potential of the structure. Systematical investigation of links-link weft knitted structures with zigzag patterns in various repeat sizes showed that folds of the viscose/polyamide samples with higher repeats tend to sag. It was also established that additional PA monofilament stiffens the structure and increases the folding tendency (**Figure 11**). The investigation showed that the loop density has a significant impact on the folding tendency of the knitted structure.

5.2. Compression resistance

Compression is one of the important fabric properties, in addition to friction, bending, tension, and shear. Compression may be defined as a decrease in intrinsic thickness with an appropriate increase in pressure. Intrinsic thickness is the thickness of space occupied by a fabric subjected to barely perceptible pressure. The applied compressive force allows the yarn to undergo deformation non-linearly, resulting in the change of fabric thickness [27]. The relationship between the applied force (normal to fabric plane) per unit area and the resulting fabric thickness can be obtained with a simple test. The tested fabric specimen is placed horizontally on a platter and subsequently loaded and unloaded with a presser foot. The fabric thickness, which is the distance between the presser foot and the platter, is recorded as the function of applied pressure. This pressure-thickness relationship describes the compression characteristic of the fabric. The pressure-thickness curve of textile fabrics in lateral compression is highly non-linear [28].



Figure 10. Foldable links-links zigzag structure knitted with different setting of the front and rear cams (left—folded, right—unfolded).



Figure 11. Stiffening folded structure by interlacing additional PA filament (left—no filament, right—incorporated filament).

The compressibility behavior of knitted and woven fabrics depends on a number of factors, that is, fabric tightness, fabric surface irregularity, yarn hairiness, yarn compressibility, fiber material etc. The analyses of the pressure-thickness relationship performed by Alimaa et al. [29] demonstrated a very prominent effect in terms of the knit construction and yarn structure. It was observed that fabric compressibility primarily depended on the fiber material.

The composition properties of knitted fabrics were also essentially due to their knit constructions. Moreover, the loop length determined the compressibility of knitted fabrics to a great extent [29].

In order to evaluate the behavior of links-link weft knitted fabrics with a zigzag structure under compression, the same two series of samples as for the folding effect were examined (Section 5.1). The examined structures could potentially be used as a packaging and mechanical damage protection material. The influence of yarn material composition and the structural parameters of foldable structures, such as repeat size, that is, width/height ratio, on the compression properties of foldable links-link knitted structures were examined in order to evaluate their adequacy for compression-resistant materials. The compression behavior of examined foldable structures was compared to some selected actual compression materials used in packaging, such as bubble foil, textured rubber foam, and woolen felt [30]. Since the width of zigzag lines of the second series of samples distinctively influences the folding ability, only the compression properties of fully folded knitted structures were examined.

First, the compression test was performed on a dynamometer INSTRON 5567 based on the Bluehill® software compression application module. The speed of the movable pressure foot was 0.3 mm/s. The compression load was read when the distance between the movable pressure foot and the fixed flatten reached 1 mm. A circular pressure foot with 9 cm in diameter was used. Ten measurements of the maximum compressive load at the compressed thickness of the knitted structure $t_{\text{compr}} = 1 \text{ mm}$ for each sample were performed.

Then, the thickness of knitted structures was measured in a separate testing procedure where the speed of the movable pressure foot was adjusted to 0.1 mm/s to detect the contact of the movable pressure foot and the fabric surface. When the compression load was detected, the distance between the clamps was read from the compression curve. Five measurements for each sample were performed.

It can be concluded that the fiber and yarn type contribute substantially to the compression behavior of samples as they were all knitted on the same machine and under the same conditions to eliminate the influence of the knitting process.

The maximum compression load of CV/PA foldable knitted structures exceeds the maximum compression load of WO/PAN structures with comparable repeats, although the knitted structures made from WO/PAN yarn are thicker than the comparable knitted structures made from CV/PA yarn. The maximum compression load and fabric thickness decrease with the repeat reduction.

The decrease in compressive stress was not linear with the knitted structure repeat reduction. For the CV/PA knitted structures, the decrease got more distinctive with smaller repeats, whereas for the WO/PAN knitted structures, the compressive stress decreased more in the case of bigger repeats.

The compressive stress decreased similarly for the structures with the repeat widths from 24 loops to 18 loops. The foldable knitted structures with the repeat widths smaller than 18 loops differed substantially; the structures with the square repeat which were all fully

folded (first series of samples) exhibited a gradual compressive stress decrease, while for the structures designed with various widths of zigzag ribs (second series of samples), an instant drop of compressive stress was evident. These structures did not fully fold when the rib width was smaller than approximately seven loops (Figure 12).

Foldable knitted structures are compressible. To compress the examined foldable knitted structures to the thickness of 1 mm, substantial loads are required.

5.3. Auxetic potential

Auxetic materials are different from most conventional materials in that they exhibit a negative Poisson’s ratio (NPR). They expand laterally when stretched and contract laterally when compressed [31]. This counterintuitive behavior gives auxetic materials various beneficial effects, such as enhanced shear stiffness, increased plane strain fracture toughness, increased indentation resistance, and improved energy absorption properties [32, 33]. As the Poisson’s ratio is a physical parameter that is independent of the material scales, the auxetic behavior can be achieved at any material level, from molecular to macroscopic [34, 35].

Flat-knitting technology can provide a simple but highly effective way of fabricating auxetic fabrics from conventional yarns. 3D geometry of specially developed links-link knitted

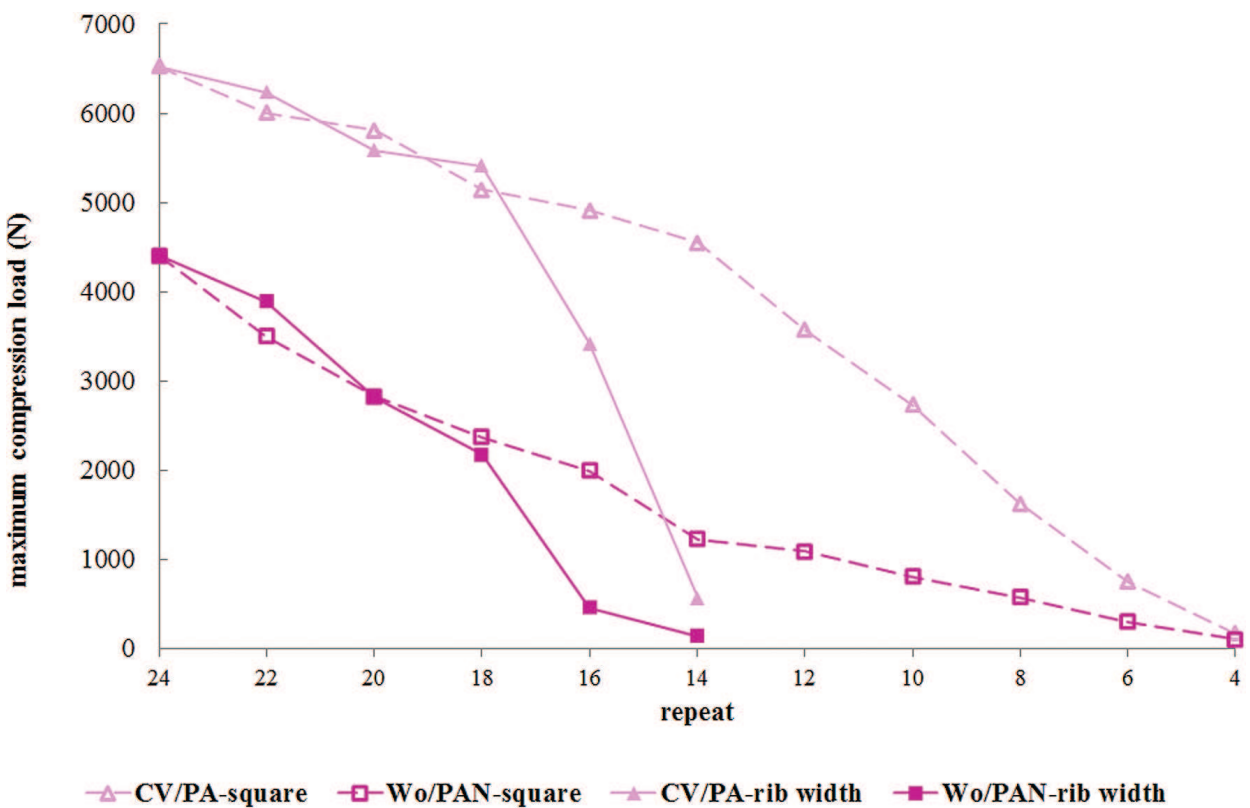


Figure 12. Comparison of compressive stress at maximum compression load for foldable zigzag knitted structures with various repeats: square—same number of courses and wales in repeat; rib width—different widths of zigzag ribs and constant number of courses in repeat [30].

structures enables a new deformation mechanism called “opening of the folded structure.” The fabrics that are more closely folded can result in a smaller opening angle and consequently have higher NPR values. A negative Poisson’s ratio as low as $\nu = -0.5$ was reported in the scientific literature for such structures; nevertheless, the examined fabrics exhibited auxetic effect only in one direction [26].

Buhai et al. [36] stated that the structural parameters of the knits are influenced by two factors: yarn fineness and stitch length. They concluded that the auxetic effect is influenced by the stitch length values; as these values are lower, the fabric is tighter and maintains its shape better. The auxetic effect increases as the values of the stitch length decrease.

The purpose of the investigation of the foldable links-link knitted structures by Drol and Pavko-Čuden [37] was to compare auxetic properties of foldable links-link knitted fabrics made of different yarns, on flat knitting machines with different gages, different densities of knitted structure, and different repeats. Foldable zigzag-ribbed structures with auxetic potential were produced from three different conventional yarns. The yarn selection was based on the material composition, which affects the elasticity and stiffness of the yarn and thus the anticipated rigidity, stability and folding of the zigzag rib knit structure with auxetic potential. Due to the expected rigidity, cotton and multifilament viscose yarn were selected, while due to the expected extension and elastic properties of knitted fabrics, a yarn made of a wool and acrylic mix was selected. Different sizes of basic geometric units of knitting, that is, width and height of the zigzag ribs were achieved by knitting on knitting machines with different gage, while different compactness/stiffness of the knitted structures was achieved by knitting in different densities, that is, by setting different couliering depths. The samples were knitted on a flat-knitting machine STOLL CMS 340 TC with gage 8E and flat multigage knitting machine STOLL CMS 340 TC E6.2 that allows knitting with gage 6E (every second needle knitting) and 12E (all needles knitting). Knitted samples were prepared in two densities, respectively, by two positions of the couliering depth for each course density. Auxetic effect of the fabrics was determined on the basis of measurements of the fabrics’ dimensions during extension in the knitted courses direction and by Poisson’s ratio calculation (**Figure 13**).

It was found that in most cases, the samples exhibit the highest auxetic effect at 60–90% extension. Knitting with 45° inclination of ribs exhibits the best folding tendency. Fabrics produced on knitting machines with finer gage exhibit higher auxetic effect. Material composition and knitting machine gage have a great impact on the Poisson’s ratio of foldable links-link knitted fabrics with zigzag ribs.

5.4. Sound insulation

During recent years, the subject of noise has received increasing amount of attention to the scientists, technologists, and public as a whole. For a healthy and a pleasant environment, controlling the sound hazards is an important issue. There is a medical evidence that the human body will take sound as “pollution” if the ambient sound levels exceeds 65 dB. This sound pollution leads to significant health problems including hypertension, dizziness, depression, sleep disturbance, hearing loss, decrease in productivity/learning ability/scholastic performance,



Figure 13. Measuring dimensional changes for evaluating auxetic potential.

increase in stress-related hormones, and most commonly, loss of hearing. Therefore, unwanted and uncontrolled noise should be reduced using noise barriers and noise absorbers. Properly designed textile materials may be considered as noise control elements in a wide range of applications, including wall cladding, acoustic barriers, and acoustic ceilings [38–40]. Sound absorbing materials are commonly used to soften the acoustic environment of a closed volume by reducing the amplitude of the reflected waves. Many natural and manmade raw materials have been used as sound absorbers.

Two methods for measuring acoustical properties of fabric materials have been most common: the impedance tube method and acoustic chamber method. The impedance tube method uses rather small test samples, it is faster and generally reproducible, while for the acoustic chamber method, large reverberation rooms and large test samples are used.

To evaluate the sound absorbing potential of foldable link-links knitted structures, different three-dimensional flat weft knitted fabrics made from various yarns were produced (**Figure 14**), including 100% wool and 50% wool/50% PAN as basic yarns, and 100% polyamide filament which was added to basic yarns as reinforcement thread [41]. The thickness and the mass/unit area of the knitted samples were measured.

For the finishing of knitted fabrics, two hardening agents were used: Tubicoat A 41 (CHT, Bezema, Switzerland) and Beaippret liquid (CHT Bezema Switzerland). After finishing, the handle and esthetic look (change of color, color uniformity, dimensional stability) of the samples were evaluated by a survey. The Tubicoat finishing agent in 40% concentration exhibited the best handle and esthetic appearance. The results of the survey revealed that the knitted



Figure 14. Presentation of foldable links-links structure as used for sound absorption test (left – folded, right – extended).

structure presented in **Figure 13** was the most appropriate for sound absorbing panels. The sound absorption coefficient of the foldable knits was measured by the impedance tube (Kundt tube) method. The results were compared to the sound insulation performance of the commercial woolen felt.

The results showed that the selected foldable structure can be used as sound insulating material as it exhibits good sound absorption properties. Further interesting and attractive foldable structures can be developed for sound insulation with similar thickness, compactness, and mass/unit area. Woolen structure showed the best acoustic properties, followed by wool/PAN structure reinforced with polyamide filament. 100% wool structure with added polyamide thread and 50% wool/50% PAN structures also exhibited good acoustic properties. Hardening agent significantly reduced the sound absorption coefficient. Incorporating nylon into knitted structure improved the stiffness of the structure; it decreased the sound absorption coefficient in the case of woolen structure and increased the sound absorption coefficient in the case of wool/PAN structure.

5.5. Antibacterial properties

The suitability of foldable seamless knits for the storage of bread and bakery products has been studied by Rant, Pavko-Cuden and Tomsic. It was assessed by testing the antibacterial properties of the selected foldable knitted structures made from various raw materials (Tomsic B 2017, personal communication, January 23).

First, the soil burial test according to SIST EN ISO 11721-1:2001 standard was performed for determining the resistances of foldable knitted fabrics made from various yarns to microbiological deterioration. Apart from a basic single knitted structure, a zigzag links-links knitted

structure with 4×4 square repeating unit cell was selected. The selected yarns were made of 100% combed cotton, 100% cotton with added polyamide filament, flax/viscose blend (FLAX-CV), natural bamboo/modal blend (BAMB-MOD-N), carded 100% cotton, 100% lyocell (LIO), 100% viscose, wool/viscose blend, lyocell/viscose blend, lyocell/cotton blend (LIO-BW), cashmere/polyamide/viscose (CASH-PA-CV), and 100% wool. The time of exposure was 12 days. Afterward the knitted samples were carefully removed from the soil. The samples were rinsed in water, sterilized by soaking in 70% ethanol at room temperature for 30 min and dried. Initially, the deterioration of samples was visually assessed. After that, the rate of biodegradation of the examined samples was determined by color measurement with a spectrophotometer SPECTRAFLASH 600 PLUS (Datacolor International, USA) using the CIELAB color system. ΔL^* values of the buried and unburied samples were determined and compared.

The results of the study showed that the ΔL^* values of the foldable knitted structures were lower than for the single-knitted structures. The visual assessment of the samples also showed that in most cases, the foldable knitted structures were less deteriorated than the single-knitted structures. The results proved that the foldable links-links knitted structures have better antibacterial properties compared to the single structures.

According to the results, foldable links-links knitted samples from flax/viscose blend (FLAX-CV), natural bamboo/modal blend (BAMB-MOD-N), lyocell/cotton blend (LIO-BW),

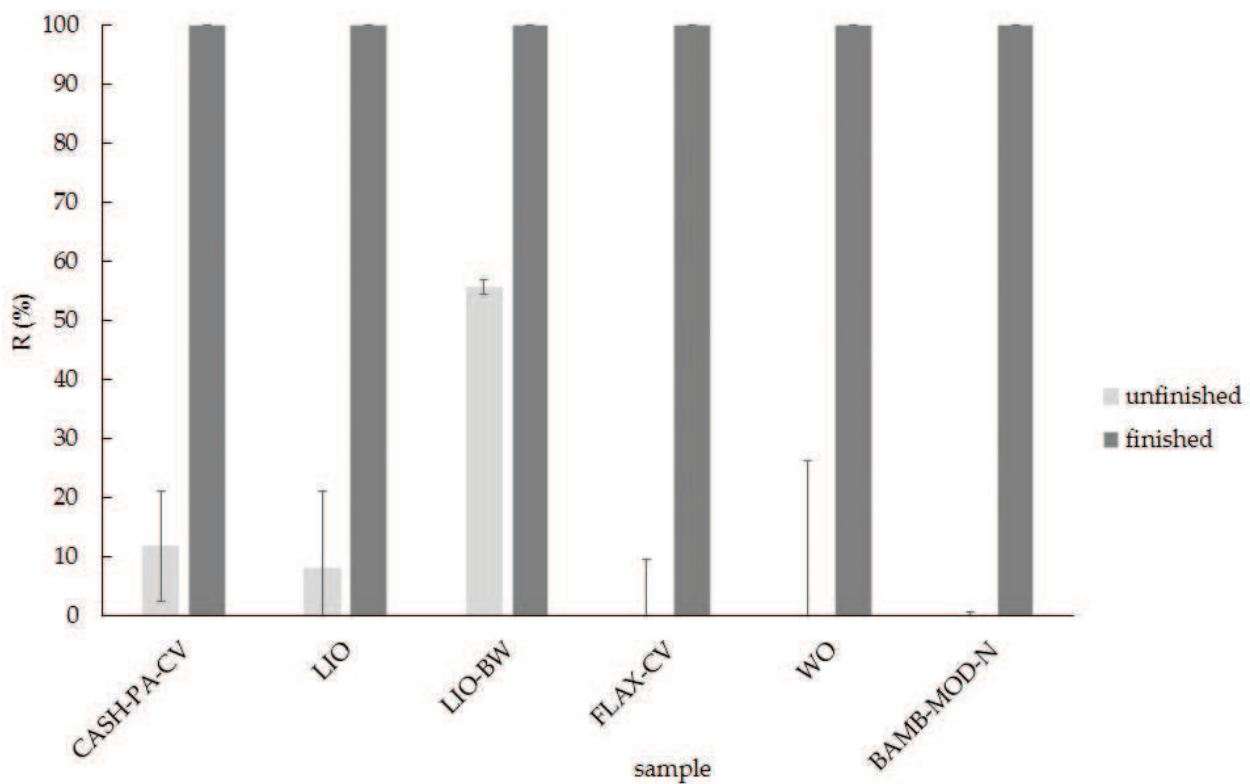


Figure 15. Antibacterial properties of foldable knitted structures made from various yarns before and after treatment with antibacterial finishing agent.

100% lyocell (LIO), cashmere/polyamide/viscose (CASH-PA-CV), and 100% wool (WO) were selected for further investigation.

In order to achieve antibacterial activity, Bioshield Excalibur (Izinova Ltd., Bled) finishing agent was selected, which is chemically alkyl dimethyl (3-trimethoxysilylpropyl) ammonium chloride. Its antibacterial activity is based on bio-barrier formation mechanism. Antibacterial activity of the examined knitted samples was estimated by determination of bacterial reduction according to the ASTM E 2149-01 standard method. Bacterial reduction of the samples was evaluated against Gram-negative bacteria *Escherichia coli* (ATCC 25922).

The results (**Figure 15**) showed that the selected antibacterial finish was fully effective, reflecting in complete growth reduction of the tested bacteria. On the other hand, untreated foldable links-links knitted samples exhibited rather important differences in the reduction of *E. coli* growth. The samples made from lyocell/cotton blend exhibited 55% reduction, the reduction of cashmere/polyamide/viscose blend was 11%, while the reduction of the rest of the samples was less than 10%. Better results for the samples made from natural bamboo/modal yarn were expected due to the original antibacterial properties of the natural bamboo fibers.

6. Potential multifunctional application of foldable knitted structures

Foldable weft-knitted fabrics have a big potential for applications in different fields. They can be used for fashionable knitwear, functional garments, and para-garments (textiles that are put onto the body but are not garments: for example, certain medical textiles) as well as for various non-clothing purposes.

They are compressible. They can be usable in functional knitwear to alleviate pressure on certain parts of the body. As advanced unconventional packaging material, they could protect fragile objects from mechanical damage. They could also replace or complement spacer knitted fabrics in padding, for example in medical cushions, seat covers for the automotive industry, mattresses, etc.

In interior design, they can be used as room partitions when mounted on a frame for thermal insulation and protection from light. They can replace embossed rubber foam which is often used as sound insulating material. For that purpose, they can be designed as modular elements available in various colors and textures to be fixed on walls and ceilings. Due to their featured texture, they can be used as interior decoration. Dimensional changes caused by folding and unfolding make them suitable for lampshades if made from transparent and stiff material or for multifunctional shading-lightening objects if LED elements are incorporated (**Figure 16**).

A combination of innovative mechanical functionalization, that is, selection of optimal raw materials and intriguing knitted structures, and successive high-performance chemical functionalization could result in new, reusable, and recyclable household food packaging, for example for storage of bread and bakery products or fruit.



Figure 16. Multifunctional interior textiles: collapsible sound diffusers/shades/lights (simulation) designed by Andrej Vilar, Slovenia.

The current problem with the wider use of foldable knitted structures lies in their bi-axial extensibility which is substantially reduced when the foldable panels are sewn together. If joined in the extended state, the folding ability is hindered and the esthetic appearance of the sewn together piece is affected. If sewn together in a relaxed state, the extensibility is significantly reduced. Flat knitting allows seamless production, therefore seamless foldable links-links knitted products can be manufactured. For that reason, seamless foldable-knitted structures can be used for casual and functional knitwear as well as for fashion accessories.

7. Future scope

Textiles are transcending their traditional functions and are morphing into uniquely tactile interfaces through which broader sensory stimulus can be perceived. Because fibers, fabrics, and textile techniques are becoming seamlessly integrated with technology, textiles represent an interconnected collective that links many disciplines. Our world seams polarized around sensory extremes: hard and soft, protection and exposure, intransigence, and tactility. As textiles embrace new types of fibers and fulfill new roles, they bridge these polarities better than any other material. Textiles are dramatically transforming the world around us, and as they do so, they also inspire radical new visions for the future [18].

Foldable knitted structures exhibit bi-polar attributes. They can be folded or extended, transparent or opaque, flat or curved. They can be multifunctional. Foldable knits are very complex structures, exhibiting unusual behavior; for example, auxetic behavior was proved for some zigzag foldable links-links structures. Therefore, in-depth research into their characteristics, above all into the impact of material, structural and geometrical parameters, finishing, repeated use, textile care, etc. is anticipated.

3D printing is a rapidly emerging technology which is often claimed to be the base for a new industrial revolution. Integration of 3D printed elements and flat knitted structures into novel textile composites, including foldable composites is another area of the future research.

8. Conclusion

Foldable knitted structures are multifunctional and widely usable. They can be produced in a variety of structures, qualities and dimensions: in panels, fully-fashioned or seamless. They exhibit a supreme esthetics and have a big potential for the use in multiple areas. Some of the foldable knitted structures exhibit auxetic properties which have lately become a subject of extensive research. Foldable knitted structures, links-links knits among them, can be considered a promising development line of sustainable hi-tech knitting technology and design, especially if combined with other technologies. The development of sustainable, re-usable and up-cyclable, and genuine self-folding knitted collapsibles should be encouraged.

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