HACKTEX VIRTUAL TRAINING MATERIALS

MOOC on ADVANCED TEXTILES MANUFACTURING INDUSTRY
Learning unit 3 Technologies for functional and smart textiles
Lesson 1

Technologies for production of 2D and 3D smart textiles

ACKTEX

Innovative smart textiles & entrepreneurship

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Content

Introduction

Smart textile products are a combination of textile and non-textile components, like metals, chemicals, electronic components, optical fibres.

The purpose of this lesson is to present concisely the textile components specific to smart products, namely yarns and fabrics, their structure and its importance on product behaviour, as well as the technology needed to produce such textile elements.

The first chapter, Functional and technological design of textiles used for smart applications, will discuss what to consider when designing a smart textile product, what options and selection criteria an engineer/designer has when developing such products in terms of raw materials and materials, but also in terms of available textile technologies. The second chapter, entitled Technologies for 1D textile structures (yarns) discusses technologies for yarns and specific yarn structures that are used to manufacture smart materials and products. The third chapter, Technologies for 2D and 3D textile structures, presents methods of manufacturing 2D and 3D fabrics with integrated smart yarns and provides typical examples of such materials.

The lesson focuses on textile technologies and structures specific to smart textiles and does not discuss the concept of functionalization of non-smart textiles, like coating and deposition techniques, laminating, printing, etc.

1. Functional and technological design of textiles used for smart applications

The design of smart textiles is a complex process that involves multidisciplinary knowledge for identifying optimum solutions to solve product problems from different points of view. This makes this stage an intensive one and needs a deep understanding of the textiles throughout their entire value chain, as illustrated in Figure 1.

Regardless of the type of the smart product, it involves non-smart textiles and smart textiles. Functionalization and integration of smart functions can be done at each stage of the textile value chain: fibres, yarns, materials or product. The designer has the options to select directly smart fibres to produce smart yarns and then smart materials or to use functionalization treatments at one of the stages mentioned in the value chain, for example applying functional layers at the surface of the textile component, using for example techniques like coating and printing.

Product design must answer two major questions:

- What type of textile materials are best suited for the product, ensuring maximum efficiency, at lowest production costs possible? How and where to integrate smart functions in a material/product? What are the available raw materials and what characteristics of these raw materials should be considered?

- What technological processes to use to obtain the smart textiles needed by the application, with the desired structure and shape, at lowest production costs possible?

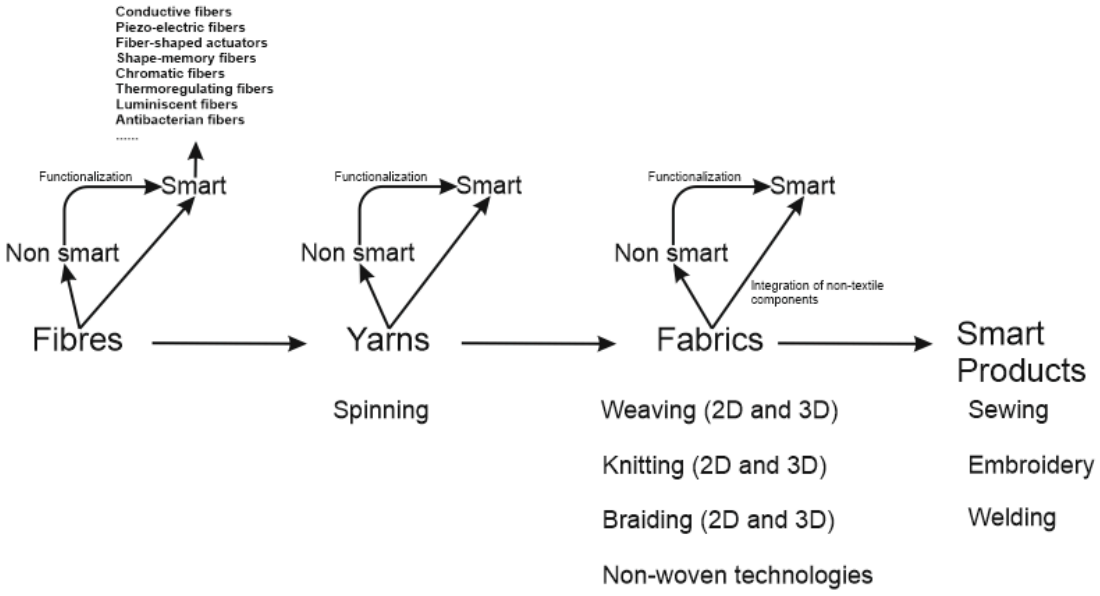


Figure 1. Value chain for the production of smart textiles

Answering these questions is done through:

- Functional design, referring to the structure, structural parameters and shape of 1D, 2D and 3D textiles, including products. The lesson will emphasize the influence of material architecture and how to control the integration of smart fibres/yarns in fabric structures, 2D as well as 3D.
- Technological design, referring to the textile processes needed to manufacture smart/textile fibres/yarns/materials/products. Of course, companies specialise in a group of products and have in general one type of technology. In this case, the options are therefore limited, but it is necessary to select the proper type of equipment for textile processing. This lesson will discuss the textile technologies used for yarns and fabrics.

When designing smart textile products, it is essential to understand the functions of the smart product required by the specific application. These functions are directly related to the properties considered determinant for the product's behaviour during use, therefore knowing them and their levels is important in the process of selection that takes place in the design stage. Standards are an important guide for design and manufacturing and the current standards for smart textiles and the evaluation of their behaviour are presented in Lesson 4.3.

Other things a designer should consider, refer to how to use structure to control the position and the geometry of smart fibres and yarns in a fabric according to products requirements and what type of fabric is best suited. Each type of material (fibres, yarns, 2D and 3D fabrics) has its own specific properties and therefore, the material selection will determine how the smart product will behave and its efficiency throughout the life cycle. Each fabric presents specific geometry and behaviour and understanding the differences will help the designer to select the optimum fabric structure.

Another important aspect is the sustainable design of smart fabrics, considering zero waste design, use of recyclable materials, and addressing the issue of recyclability based on cradle-to-cradle design. These issues and others concerning sustainability will be addressed in Unit 5.

2. Technologies for 1D textile structures (yarns)

Yarns represent an important part of the textile value chain, as they are used to produce textile fabrics, including smart/functionalised materials. Smart yarns can be produced with smart functions by using smart fibres or without smart functions, from traditional fibres, their functionalization being carried out through subsequent treatments, most important being the coating and deposition techniques. Figure 2 presents a general classification of yarns based on structural criteria.

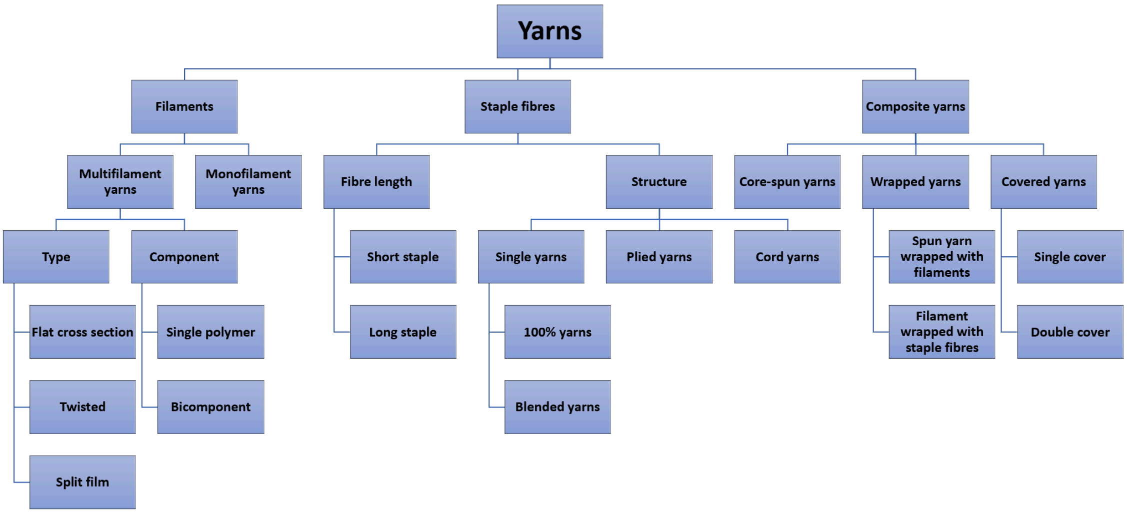


Figure 2. General classification of yarns

Yarns can be divided according to the type of fibres used into yarns produced from staple fibres (of finite length) called spun yarns and yarns produced from filaments (fibres of infinite length).

Both types of yarns can be used to integrate smart fibres. In the case of spun yarns, smart fibres can be used as the only raw material (for example, 100% stainless steel yarns, made of metal fibres) or blended with textile fibres like para-aramids, PTFE, wool, cotton, PP, PES, etc.

Filaments can be also made of smart polymers (for example, shape memory polyurethane PU polymers) or non-smart polymers can include smart polymers (bicomponent yarns) or other type of fillers (like carbon black, CNTs, microcapsules with phase change materials, etc.). The position of the two polymers in the cross section of the filament can be different, according to requirements.

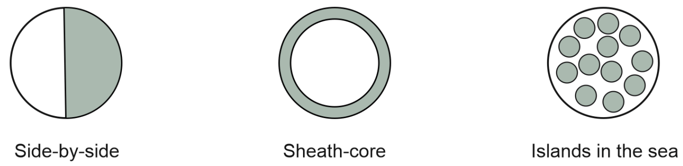


Figure 3. Possible combinations for the two polymer components

Composite yarns are produced combining spun yarns and/or filaments and are an efficient manner to impart functionality, especially electrical conductivity. Core-spun yarns are obtained by twisting fibres around a core made of other fibres, most cases a filament. These yarns can be produced either on a normal ring spinning machine or on OE spinning machines (rotor or friction) (Chattopadhyay, 2010). The sheath core structure is well suited to control yarn conductivity: a metal wire can be wrapped on a sheath of non-conductive fibres to ensure its insulation or a non-conductive filament is covered with conductive fibres, the yarn maintaining a high degree of flexibility while exhibiting electrical characteristics.

Wrap yarns are produced by wrapping a yarn around another yarn: a filament yarn can be wrapped around a spun yarn (a common way of integrating metallic wires) or spun yarns can be wrapped around filaments. They are produced using hollow spindle spinning (Angelova, 2010).

Laminated films, with a smart film sandwiched between two layers of polymer is another way of functionalizing yarns.

Mechanical spinning technologies are employed to manufacture spun yarns, regardless of the nature of the fibres (natural, artificial or synthetic), while filament yarns are produced using chemical spinning. Figure 4 presents a general view over the spinning processes.

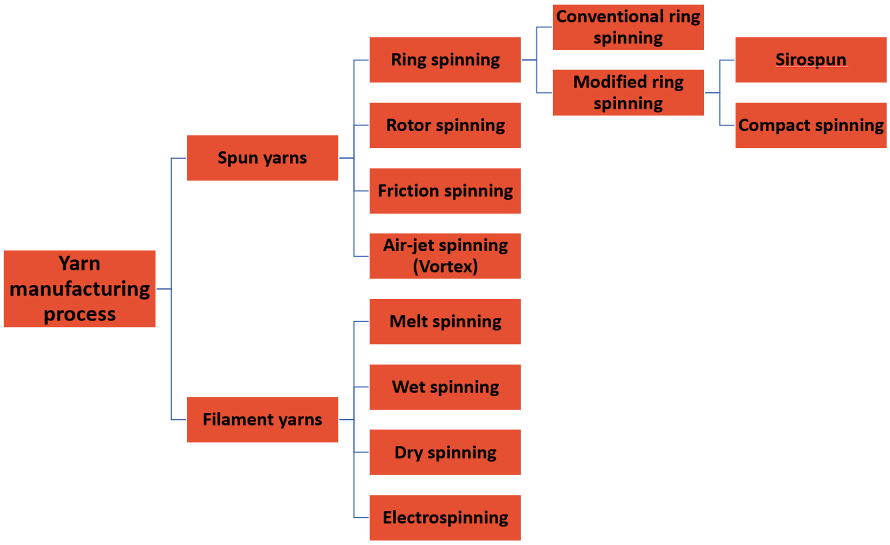


Figure 4. Classification of spinning technologies

In mechanical spinning, fibres are drafted to individual level and twisted together to form yarns. **Ring spinning** is oldest and the most common spinning process. It involves two operations:

- Preparation - the cleaning (natural fibres), opening and mixing of fibres using air flows (blow room), the carding of the resulting laps to form the carded sliver, the drawing of the sliver in two stages, the passing over the simplex/speed frame to produce the roving (with a diameter slightly bigger than the yarn diameter but with no twist). Finer yarns require the combing of yarns that takes places after carding and the first stage of drawing – first lap formation and then combing.
- Spinning - the parallel fibres in the roving are twisted to form the yarn. The roving is guided by a lappet to a ring with a spindle at its centre. The ring moves up and down, while the traveller attached to it rotates around the spindle.

The yarns manufactured with ring spinning have a large range of counts, there are no restrictions regarding the type of fibres, ring spun yarns have good strength and good quality. Still, the process is less productive and the dimensions of the bobbins are reduced.

Open-end technologies are an alternative to ring spinning (Das & Alagirusamy, 2010). The drafted fibres are collected by the tail end of a seed yarn, getting twisted during the rotational movement and forming the yarn. The yarn twisting and winding take place separately, but simultaneously. There are two major OE spinning systems: rotor spinning and friction spinning. In rotor spinning machines, the fibres are fed to a rotor where they get attached to the yarn tail. In friction spinning, the fibers are individually collected and passed through two rotating rollers, where they are attached to the seed yarn tail and twisted to form the new yarn.

Due to the elimination of certain preparation stages (roving and winding) and the higher speeds, open end spinning machines have lower energy consumption and increased productivity. The yarn packages are bigger and the yarns are more uniform. They have lower mechanical strength.

In **air-jet spinning** machines, a vortex created by one or two air nozzles twists the fibres into yarns. As most of the twisted fibres are placed at the exterior of the yarn as a sheath, parallel fibres form the core. This geometry determines a tendency to shrink and lower mechanical strength.

Melt spinning is the most common technology to manufacture filament yarns. The polymers are melted in a special tank and extruded through small openings in a plate called spinerette. The resulting filaments are cooled by air and drawn to form the multifilament yarn. Melt spinning is advantageous as it does not require the use of solvents and the process productivity is high. The technology is well suited for incorporating functional polymers or conductive fillers such as ICPs, CBs, or CNTs (Qu & Skorobogatiy, 2015).

In **wet spinning**, the polymer used to form the fibre is dissolved in solution. The solution is forced under pressure through an opening (extrusion) into a liquid bath in which the polymer is insoluble. The filaments form when the solvent is dissipated in the bath. **Dry spinning** is similar to wet spinning, but the polymer coagulates after solvent evaporation.

Electrospinning is a technology with high potential for smart textiles, as it allows the control of fibre characteristics at nanometric level. The process is based on an electrohydrodynamic phenomenon that facilitates the formation of short fibres from a polymer solution in a syringe, under the influence of a high voltage source. The polymer, that without the electric current drips from the needle of the syringe, will be deposited as fibres on a collector plate.

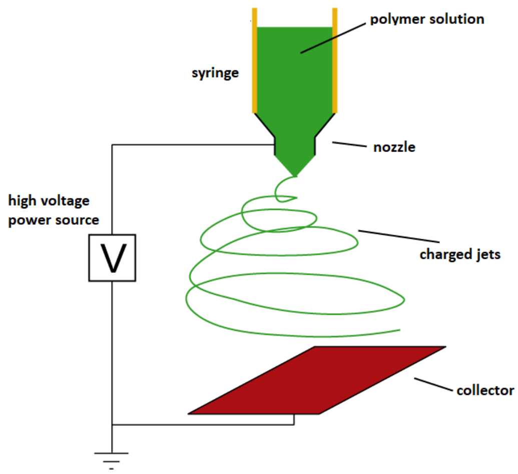


Figure 5. Principle of electrospinning, adapted from https://commons.wikimedia.org/wiki/File:Electrospinning_setup.png, credit Landcuo

Want to learn more about this topic?

In the video Carbon Fiber Melt Spinning Animation [https://www.youtube.com/watch?v=[illegible]] you will find a graphical description of the principle of melt spinning for the production of carbon fibres.

In the video Spinning carbon nanotubes [https://www.youtube.com/watch?v=[illegible]] you will find more information about how to create filaments using carbon nanotubes

In the video The World of Spinning [https://www.youtube.com/watch?v=[illegible]] by Rieter, you will find a graphical presentation of the spun spinning methods.

In the video The Electrospinning Technology [https://www.youtube.com/watch?v=[illegible]]

3. Technologies for 2D and 3D textile structures

Basically, any type of textile material can be used to manufacture products with smart functions, most common being woven fabrics, knitted fabrics, non-woven materials and braided materials. However, woven and knitted fabrics are the most used types of smart materials with integrated smart yarns/fibres and as such, this chapter will discuss the structures best suited for smart applications and the weaving and knitting technologies to obtain them.

When designing/developing a smart fabric, regardless of its nature and smart functions, fabric structure and implicitly the textile technology used to manufacture it are of utmost importance, including for the economic efficiency. The options for such fabrics are made considering all requirements imposed by the application and the specific material architecture, carefully considering which textile process offers the highest functionality and what fibre/yarn and fabric structure is best suited. Table 1 presents a short comparison between woven and knitted fabrics, exemplifying selection criteria in designing smart products.

Table 1. Comparison of woven and knitted fabrics

Comparison criterium	*Woven fabrics*	*Knitted fabrics*
Fabric architecture	*Two systems of perpendicular yarns are interlaced by passing above and under each other*	*Yarns are looped to form stitches that are interlaced with the previous stitches*
Compactness	*More compact, due to yarn interlacing closer*	*Less compact, due to looping*
Mechanical strength	*Higher, as yarns maintain a geometry close to their initial one*	*Lower, as yarns are looped, they accumulate higher stresses*
Comfort	*Woven fabrics have lower permeability to water and air*	*Knitted fabrics have higher permeability to water and air; they also have superior thermal insulation*
Flexibility	*Lower, woven fabrics are rigid*	*Higher, knitted fabrics are very flexible*
Dimensional stability	*High*	*Much lower*
Type of resulting fabric	*Fabrics are woven with continuous length*	*Fabrics can be knitted with continuous length, panels and*

		shaped panels; it is possible to knit integral products
Shape	*2D and 3D shapes possible*	*2D and 3D shapes possible*
Suitability for smart functions	*Insertion of smart yarns can be done easily for both weft and warp systems.*	*Knitting or insertion of smart yarns can be done without adaptations, for the entire fabric or only in certain areas; knittability can be an issue, if the yarn is more rigid, but there are structural possibilities that do not involve looping the smart yarns.*

3.1. 2D and 3D weaving

Weaving is a textile process in which two perpendicular sets of yarns (warp and weft) are interlaced to form a fabric. Woven fabrics are the most common textile materials and present different advantages:

- Large range of structures, with controlled properties, that can be used for clothing, decorative textiles or for technical and smart applications
- Excellent dimensional stability, low deformability
- Good mechanical behaviour
- Large range of 3D shapes, with the possibility of extending the dimensions
- Possibility of using more yarn systems, leading to hybrid structures and layers with controlled properties.

Interlacing is obtained by passing the weft yarns over and under the warp yarns in a pre-set pattern. This process is carried out on weaving machines.

In order to achieve the interlacing, the weaving machines have three primary mechanisms:

Shedding mechanism – warp yarns are moved up and down to create the upper and bottom shed lines. There are three types of shedding mechanisms: tappet, dobby and jacquard, the last one being used for the individual selection of warp yarns. The type of shedding mechanism is very important, as it controls the complexity of the woven pattern.

Picking mechanism – inserts the weft yarn in the space between raised and lowered warp yarns created by shedding, thus creating the fabric. The first type of picking mechanism was the shuttle, but currently there are many types of shuttleless weaving machines, as presented in the general classification of the weaving machines from Figure 6.

Beat-up mechanism - positions the weft yarns in the opening created by the shedding of the warp yarns, using a device called reed. The reed that is similar to a comb, also separates the warp yarns placed in its dents.

Apart from these 3 mechanisms, a weaving machine also has other mechanisms: the yarn let-off mechanism for the feeding of warp yarns during the weaving cycle and the take-up mechanism for removing the woven fabric from the weaving area and wind it on a roller.

The **shuttle insertion mechanism** was the first to be developed. The weft yarn is placed in the opening shed using a shuttle that carries the pirn. Shuttle looms are suited for different structures, can be adapted to Dobby and Jacquard mechanisms that allow for complex structures, do not require a selvedge mechanism and are reliable. However, productivity is low, they are very noisy and the strains imposed by the weaving cycle on the warp yarns and the machines themselves are very high, affecting fabric quality.

The response to the problems caused by the shuttle looms was to replace the shuttle mechanism with other solutions for weft insertion.

In the case of **projectile weaving machines**, the weft yarns are inserted into the shed opening using a metal device similar in shape to a projectile. The productivity of the projectile looms is increased in comparison to shuttle looms due to the higher insertion speed. Productivity is also increased by the use of multiple projectiles (11 to 17). Such machines can manufacture fabrics with a large range of structural complexity, from basic weaves to jacquard.

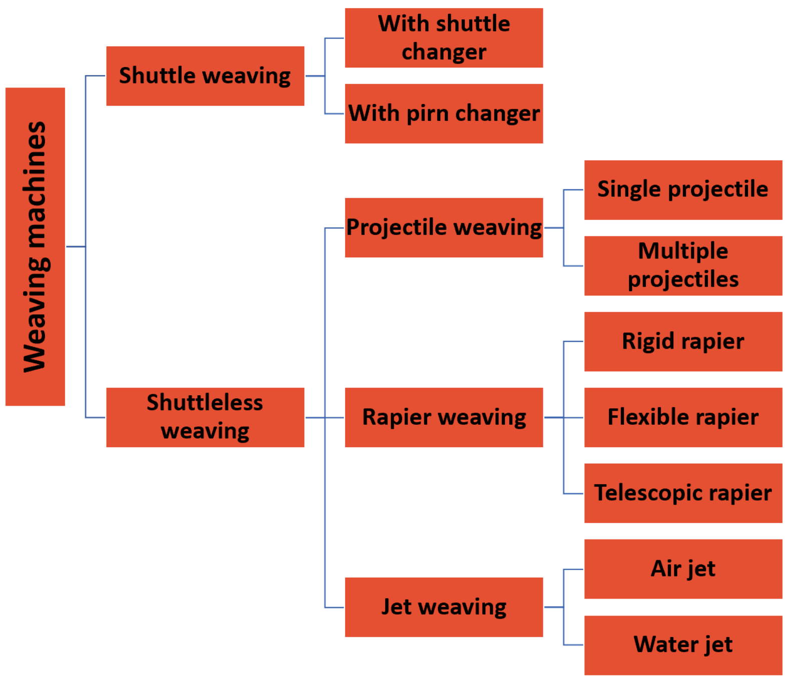


Figure 6. Classification of the weaving machines

The **rapier insertion systems** use a finger like device to introduce the weft yarns. Such weaving machines can have rigid, flexible or telescopic rapiers. Rigid rapiers are metal rods that can move along the entire width of the warp system (single rapier) or only half of it (double rapiers, where two rapiers transport the weft yarn). Flexible double rapiers are in the shape of a tape made of metal or composite materials, coiled on storing role, thus reducing the space requirements for the machine, while maintaining high weaving speeds and productivity. In the case of telescopic rapiers, there is an outer rapier and an inner tape like rapier fixed to a point on the loom. When the outer rapier enters the open shed, the inner rapier extends and carries the weft yarn to the middle, where the other telescopic rapier takes the yarn and completes its path. Apart from productivity and large range of structures, one of the main advantages of the rapier looms is the fact that the rapier system can insert weft yarns of different characteristics without adjustments, which could prove useful in the case of smart yarns.

Another possibility to insert the weft yarns is to use fluid under pressure – air or water, delivered to the shed area through a main nozzle, auxiliary or relay nozzles and a profiled reed. Such weaving machines are very productive, with a large range of possibilities, but limited in the type of yarns they can manufacture. They can produce industrial woven fabrics, including smart textiles.

From a structural point of view, woven fabrics can be grouped as (Cristian & Piroi, 2015):

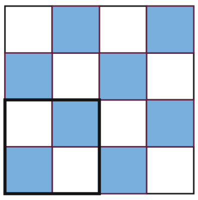
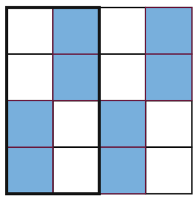
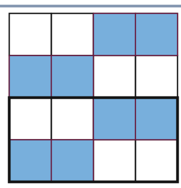
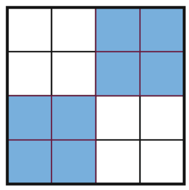
- simple fabrics, made using only two systems of yarns (warp and weft). These fabrics are considered to be 2D.
- compound fabrics, made with at least 3 systems of yarns. This group includes the so-called 2.5D and 3D structures. The following structures can be considered as compound:
    - Double warp and double weft structures, made of 3 yarn systems (2 warps and one weft or two wefts and one warp)
    - Triple warp and triple weft structures, made of 4 yarn systems (3 warps and one weft or 3 wefts and one yarn)
    - Two-ply structures, made of two layers of woven fabrics, each produced with its own warp and weft yarns. These layers can be completely connected (compact fabrics) and partially connected (with switching layers, creating limited tubular placement).
    - Multi-ply structures, with more than 2 layers, compact or partially connected.
    - Warp interlock structures are obtained when several warp systems are interlaced several systems of weft yarns.
    - Special structures – pile, terry, leno and spacer.

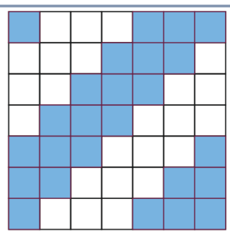
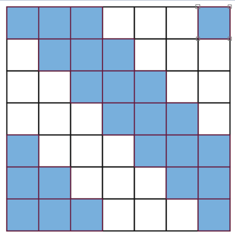
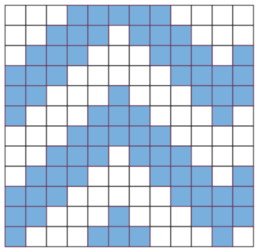
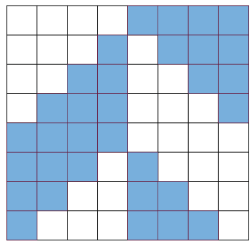
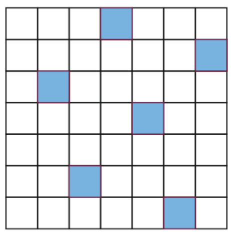
3.1.1. 2D woven fabrics

There are 3 basic weaves (Adanur, 2001) that are presented below in Table 2. To avoid using too much space, only the weaving diagram was used for representing the examples given in the Table.

Table 2. Basic weaves

Weave	*Characteristics*

Plain weave and derivatives	*It is the simplest type of weave, where the interlacing is obtained by passing each of the weft yarns (picks) over and under each of the warp yarns (ends). The pattern repeat is therefore 2 picks and 2 ends. It requires 2 or more harnesses.* *The fabric has the same aspect on both sides, has the lowest weight and is dimensionally stable on weft and warp directions. The plain weave presents the highest level of crimp, affecting the mechanical behaviour.* *The main derivatives of the plain weave are:* ● *warp rib, weft (filling) rib, for which one direction maintains the 1 over 1 under interlacing, while the other interlaces with a different repeat (regular or irregular)* ● *basket (matt) weave, where the warp and weft yarns are grouped and interlace together.*
	 *Plain weave*  *2/2 Warp rib (example)*  *2/2 Weft rib (example)*  *2/2 Basket weave (example)*
Twill weave and derivatives	*A twill weave is produced when the start of the interlacing pattern of the warp yarns is placed successively one weft yarn to the left (S twill) or to the right (Z twill). This progressive displacement of the floats (segments of yarns visible at the fabric surface) creates the twill line (visible on both sides of the fabric) and which for the common twill weaves is at 45°.* *Twill weaves give higher yarn density than plain weaves, therefore increased thickness and fabric mass. They also have fewer binding points and less crimp, improving on the mechanical behaviour; they are less rigid than plain weaves.* *There are numerous variants of twill weave, mentioning zigzag twills and broken twills.*

	 *3/3 Z twill (example)*	 *3/3 S twill (example)*
	 *3/3 Zigzag twill (example)*	 *4/4 broken twill (example)*
Satin weave and derivatives	*Satin weaves are characterized by long floats of yarns, visible on one side of the fabric. The interlacing of the two systems is not sequential, generating a uniform appearance, without any lines, as in twill weaves. Based on what yarns are considered for the face of the fabric, satin weaves can be warp faced or weft faced.* *The satin fabrics exhibit good mechanical properties, due to reduced crimp. They are flexible and do not tend to wrinkle. The yarn density is higher.*	
	 *8 harness weft satin (example)*	

3.1.2. 3D woven fabrics

Three-dimensional architecture of woven fabrics requires more than 2 systems of yarns. The yarns are placed and connected along all three axes, generating a three-dimensional architecture of the fabric. Even if 3D woven fabrics are used primarily for composite reinforcements, there are examples of applications with smart functionalization. The main advantage of such structures is the possibility of controlled 3D integration of smart yarns.

There are several classifications of fabrics with 3D geometry, some of them considered to be 2.5D (double and triple warp/weft mentioned above are such examples). Most specialists classify these fabrics considering two criteria: the 3D shape of the fabrics (Figure 7) and the manufacturing process (Figure 11).

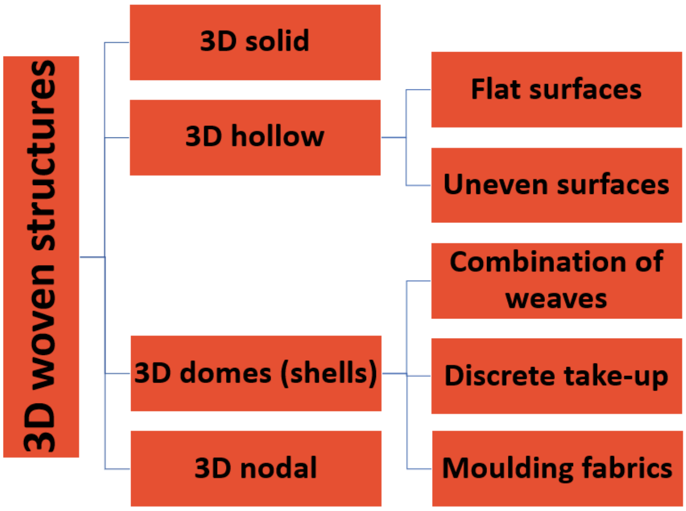


Figure 7. Classification of 3D woven fabrics according to 3D architecture

The 3D shapes that can be obtained by weaving are discussed below. In the case of solid 3D woven fabrics, their cross section can be rectangular (the thickness determined by the number of layers and yarn dimension) or profiled, one shape being exemplified in Figure 8.

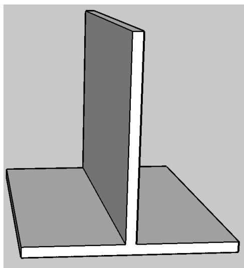
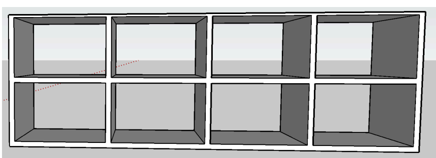
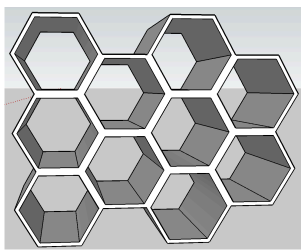


Figure 8. Profiled solid woven fabric, possible shape,

adapted from https://www.erginer.com.tr/en/composites.html

Hollow fabrics with flat surface are made with at least 3 layers (multiply structures), the one/s in the middle connecting the exterior layers. The position of the connecting layer/s can be straight (as illustrated in Figure 9.a) or under an angle (Figure 9.b). To obtain uneven surfaces, the connection between neighbouring layers is carried out according to a pattern from layer to layer.





a) Flat surfaces *b) Uneven surface*

Figure 9. 3D hollow fabrics - possible shapes,

adapted from https://www.3dweaving.com/en/products/tubular-fabrics

The principle of creating shell structures is to generate areas that have different length, so that the fabric, even if it has constant width, has a spatial geometry. Two methods can be used to produce a 3D geometry. One requires the modification of the take-up mechanism so that the yarn density is varied, resulting in curved areas in the fabric (Patent No. 6,000,442, 1999). The second method uses different weaves with different float lengths, leading to areas with different density and therefore a spatial geometry.

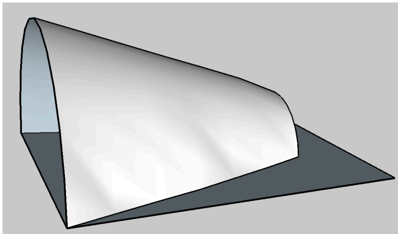


Figure 10. 3D shell fabric - example of possible shape for the discrete take-up method, adapted from https://www.researchgate.net/publication/303415956_10_Three-dimensional_fabric_structures_Part_1_-_An_overview_on_fabrication_of_three-dimensional_woven_textile_preforms_for_composites

Nodal shaped woven fabrics are obtained intersecting tubular structures, made using two-ply fabrics. The connection between plies is controlled to create shapes out of the intersection of tubes, as exemplified in Figure 11.

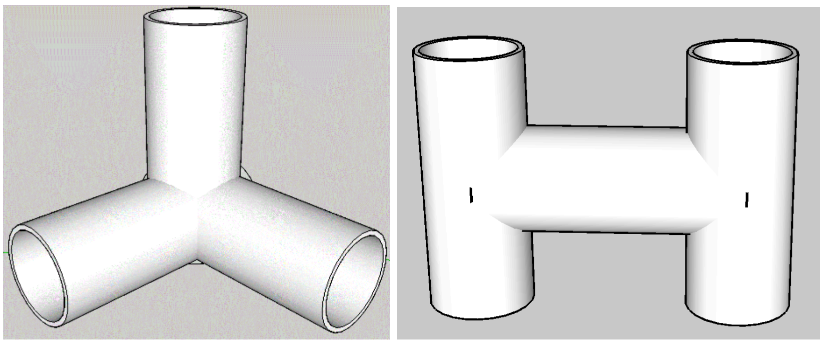


Figure 11. 3D nodal woven fabrics - possible shapes, adapted from https://tu-dresden.de/ing/maschinenwesen/itm/forschung/forschungsfelder/textile-prozesse/technologien-fuer-2d-und-3d-textilkonstruktionen/2d-3d-weben?set_language=en

The second classification criterion is the manufacturing method (Behera, 2010).

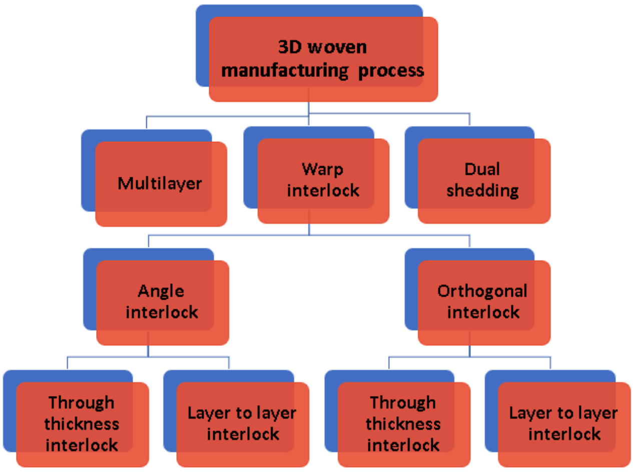
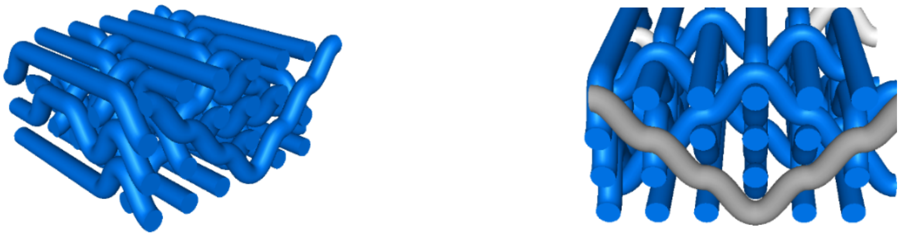


Figure 12. Classification of 3D based on the weaving techniques

Multilayer (or multi-ply) structures require the use of several warp and weft yarn systems, the warp yarns acting as binders from place to place, connecting the fabric layer to layer. Similar to two and three-ply fabrics, when completely connected will generate solid shapes (flat or profiled) and when partially connected, generating hollow fabrics (also called tubular), discussed before and exemplified in Figure 9.

The warp interlock structures are characterised by multiple systems of weft yarns that are interlaced with multiple systems of warp yarns (Cristian & Piroi, 2015) (Boussu, 2015). Specific to these structures is the fact that the warp and weft systems will not interlace to constitute by themselves distinct layers of weaves, the number of warp systems being often different from the number of weft systems. The fabric is connected through warp yarns called binder yarns, that traverse partially or completely the thickness of the fabric. If the binder yarns are placed at an angle in their path through the layers of yarns, the fabric has an angle interlock, while if the path is through the entire thickness of the fabric, then it is called orthogonal interlock. Figure 13 presents some examples of warp interlock fabrics.

Angle interlock, layer-to-layer connection



Angle interlock, through thickness connection

Ortho interlock, layer-to-layer connection

Ortho interlock, through thickness connection

Figure 13. Warp interlock structures – examples (fabric simulation, WiseTex), with permission from the author

The dual shedding principle allows the yarns to shed not only vertically, but also horizontally, therefore interlacing the warp interlock structures at layer level. However, such weaving machines, considered by some specialists to be a real 3D weaving process, are not yet widely commercialised.

Want to learn more about this topic?

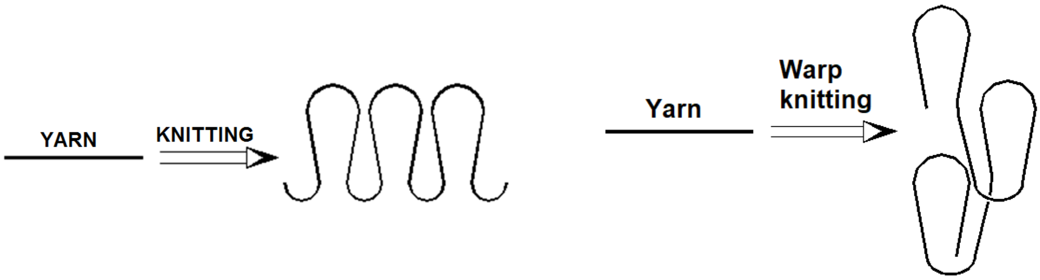
In the video Type of Weft insertions in weaving loom (https://www.youtube.com/watch?v=s0W0iDj7_hc&t=8s) you will find a graphical explanation of the existing weft insertion mechanisms.

In the video EAT CAD/CAM textile software / 3D Weave [https://www.youtube.com/watch?v=Ulay-1W7Gks] you will find more information on how to design 3D woven structures.

3.2. 2D and 3D knitting

Knitting is the textile process where yarns are sequentially looped to form stitches

- horizontally, creating weft knitted fabrics (Figure 14.a)
- vertically, creating warp knitted fabrics (Figure 14.b)



a) Yarn looping for weft knitted fabrics b) Yarn looping for warp knitted fabrics

Figure 14. Principles of weft and warp knitting

The loops formed by bending the yarns around needles are interlaced with the previous ones, forming knitted stitches. During a knitting cycle, each needle uses the old stitch to create a new stitch. Stitches are the 'bricks' of a knitted fabric and they are placed horizontally in rows (or courses) and vertically in wales. There are two types of stitches: front stitches and back (rear) stitches, illustrated for weft knitting in Figure 15.

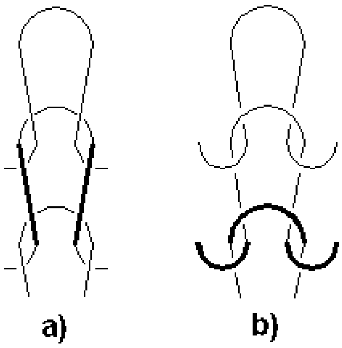


Figure 15. Front (a) and back (b) stitches for weft knitted fabrics

Knitting is a flexible technology, with a large range of possibilities in terms of structures/effects and fabric geometry that are well suited for producing smart textiles. It has different options to integrate smart yarns that will be discussed below.

Knitted fabrics have a series of characteristics that could advantageous for certain applications, most important being:

- Inherent as well as controlled high flexibility and stretch. Knitted fabrics tend to have high deformability at low forces.
- Low bending rigidity
- Increased comfort in terms of permeability, increased porosity
- Capacity to adjust to complex shapes (shape retention)
- Different structural possibilities to integrate smart yarns in selected product areas, according to requirements
- Control of the yarn path in the fabric's structure
- Possibility of obtaining 3D fabrics on regular knitting machines (weft and warp knitting)

The main problem when integrating smart yarns into a knitted fabric is their knittability. Knittability refers to the capacity of the yarns to withstand without damage:

- the bending forces, when the yarns are turned into loops by the needles
- the friction under tension forces when the yarns are robbed back during stitch formation (are pulled back on the knock-over bits)

This is especially important for conductive yarns (spun yarns/filaments or coated/laminated yarns), that can easily lose the integrity of the fibres or coating layers, affecting the performance of the smart product.

From a technological point of view, knitting can be carried out on weft and warp knitting machines. A general classification of knitting machines based on the shape and number of the needle beds is presented in Figure 16. For weft knitting, only V-bed flat knitting machines are included, as straight bar machines are less used in general and present less options to integrate smart yarns into the structure of a knitted fabric.

Weft knitting uses flat knitting machines and circular knitting machines, according to the shape of the needle beds. The most common flat knitting machines are V-bed machines, named after the position of the two needle beds. Circular knitting machines can have one bed (cylinder) or two beds, most cases cylinder and dial. A comparison between flat and circular knitting machines is presented in Table 3. The main advantage of circular knitting is its high productivity, while flat knitting allows knitting to shape (fully-fashioned), 3D knitting and to create the entire product through knitting (integral knitting).

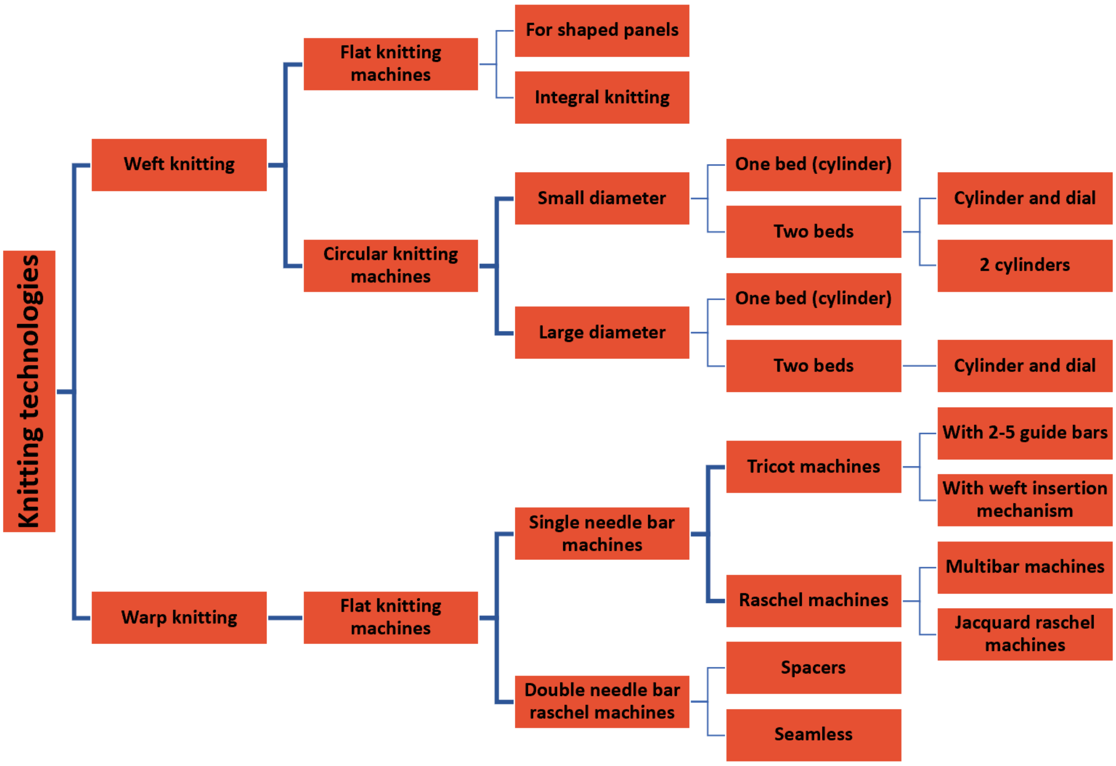


Figure 16. General classification of knitting machines

Table 3. Comparison between flat and circular weft knitting machines

	Flat knitting machines	*Circular knitting machines*
Needle bed	*Flat (Linear)*	*Circular (cylinder and dial)*
Cam movements	*The carriers move on both directions*	*The needle beds rotate in only one direction (clockwise)*
Gauge	*2.5 to 18 E*	*12 to 40 E*
Number of systems	*1 to 3*	*According to diameter*
Yarn feeding	*Negative, limited number of yarn feeders (16 to 32)*	*Positive, using a creel for large diameters; high number of yarn feeders (each system has its own feeder)*
Fabric shape	*2D: Panels (fully fashioned), 3D: shell fabrics, spacers, integral knitting*	*2D: Tubular fabrics, rectangular panels (special machines) 3D: spacers*
Productivity	*Lower*	*Higher*
Patterning possibilities	*Stitch transfer, racking, intarsia patterns, patterned plating, weft inlay*	*Warp/weft inlay, fleece patterns*

In the case of warp knitting, the process requires the use of at least one system of yarns, fed simultaneously on all needles by individual feeders called guides. This is done during preparation, called warping, where yarns placed according to threading pass from the normal format (bobbins) to high-capacity formats - warp beams. This way, a high quantity of yarns is accumulated, allowing for the high knitting speed specific to warp knitting. The productivity of this type of machines is similar to the one specific for the weaving machines.

There are two types of warp knitting machines:

- Tricot machines, with 2 to 5 guide bars, high knitting speed (up to 3000 rows/minute), used for less complex structures and for weft insertion;
- Raschel machines, with multiple patterning guide bars, lower knitting speed (up to 1500 rows/minute), used for patterned fabrics and nets.

3.2.1. 2D knitted fabrics

The structure of knitted fabrics depends on the type of knitting – weft or warp knitting. A general classification of fabric structure is presented in Figure 17.

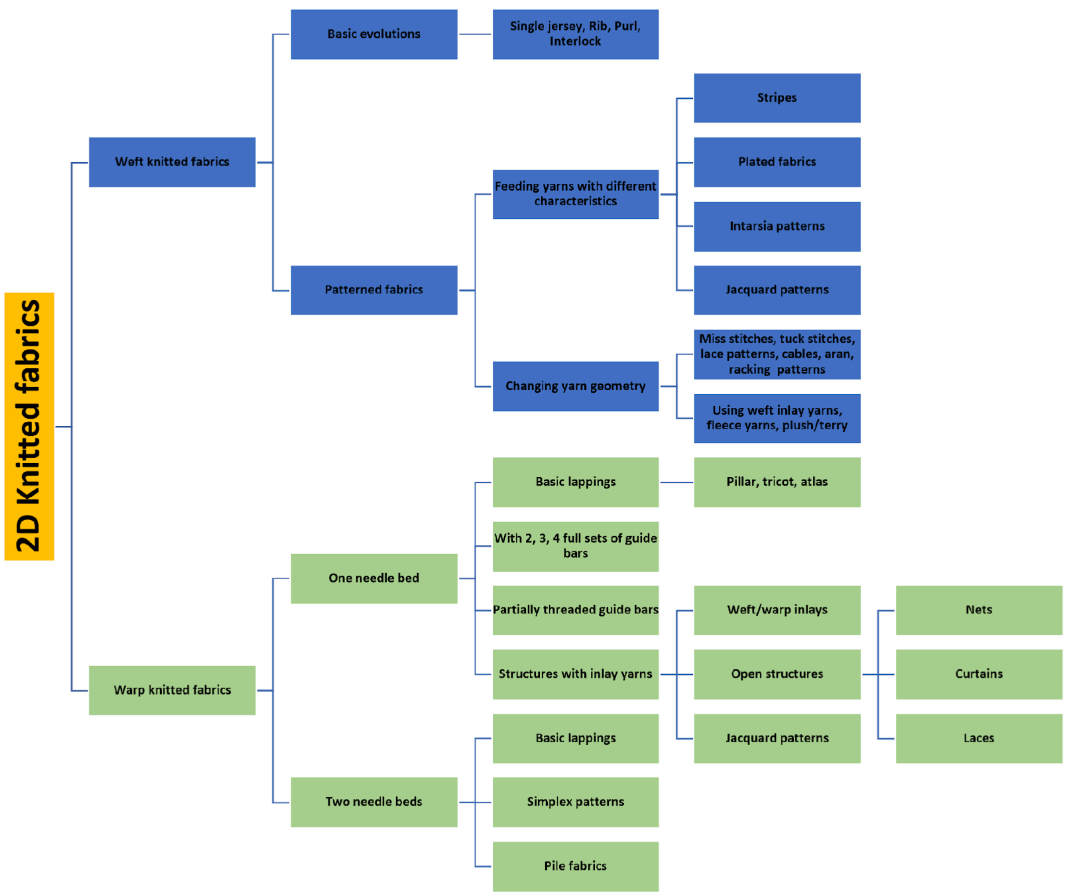
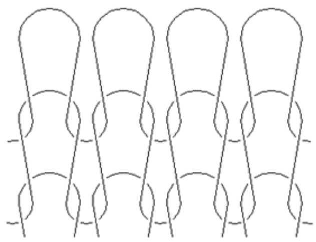
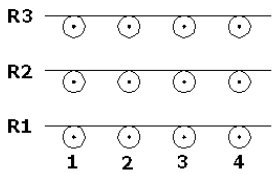
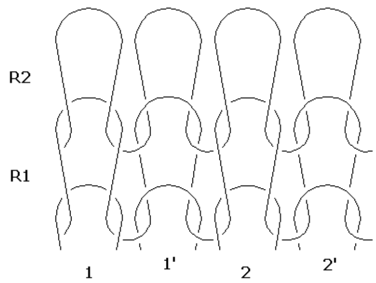
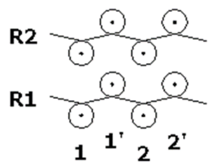
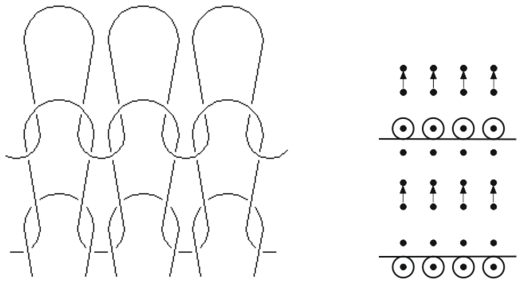
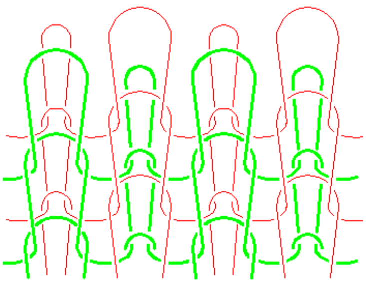
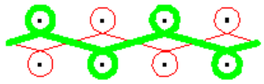


Figure 17. Classification of knitted structure for 2D fabrics

2D weft knitted fabrics can be obtained using the basic evolutions: single jersey (plain), rib, purl and interlock. Table 4 lists the characteristics of each type of evolution that should be considered when designing a smart material.

Table 4. Characterization of the basic evolutions for weft knitting

Evolution	Characteristics
Single jersey	*Single jersey fabrics have only front aspect on one side and back stitches on the other side. Produced on only one bed, stitches are placed in a single plan.* *Low thickness; lower deformability, as stitches have lower length* *Curling tendency, laddering tendency*
Example	 
Rib	*The evolution is defined as a number of front wales alternating with a number of back wales (egg., 1x1 rib, 2x2 rib, 3x1 rib, etc.)* *Produced on two beds, stitches are placed in two plans* *Front stitches tend to cover the back stitches, leading to high elasticity in the row direction. Higher thickness than single jersey.*
Example of rib structure - Rib 1x1	 
Purl	*The evolution is defined as a number of front rows alternating with a number of back rows (egg., 1x1 purl, 2x2 purl, 3x1 purl, etc.)* *Produced on two beds, stitches are placed in two plans. The rows are transferred from one bed to the other, according to the evolution's repeat.* *Back rows tend to cover the front rows, leading to high elasticity in the wale direction and high fabric thickness.*

Example of purl structure - Purl 1x1	
Interlock	*The evolution results from the combination of two rib evolutions, formed alternately on one needle from each pair of needles (front and back).* *The fabrics present front aspect on both sides, with the front wales covering completely the rear wales.* *Medium elasticity course wise. High fabric thickness.*
Example of interlock structure Interlock 1x1	 

Apart from knitting the smart yarns into the structure, another simple way of functionalization is by plating, a technique in which two yarns are fed to the needles in a constant relative position that determines one yarn to be visible on the front stitch and the other on the back stitch. The technique is well developed in both circular and flat knitting machines, the latest models of flat knitting machine allowing for reverse plating and selective plating.

In the case of patterned weft knitted fabrics, there is a large range of structures that is used for smart materials/products. This includes simpler patterns based on miss and tuck stitches. Weft inlays (Figure 18) and fleece patterns (Figure 19) allow to integrate smart yarns without the stress caused by creating the stitches (bending), especially suited for sensitive yarns like coated or laminated conductive yarns. Inlaying of weft yarns is usually done using a rib or interlock evolution, as the stitches are formed on both needle beds and maintain the yarn into the structure. Weft yarns can be inserted in each row or according to requirements.

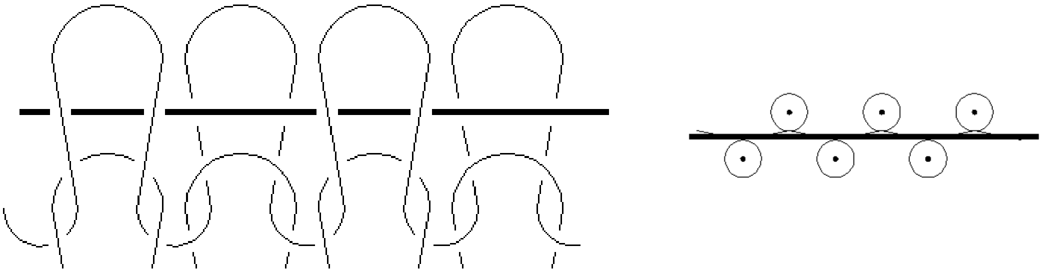
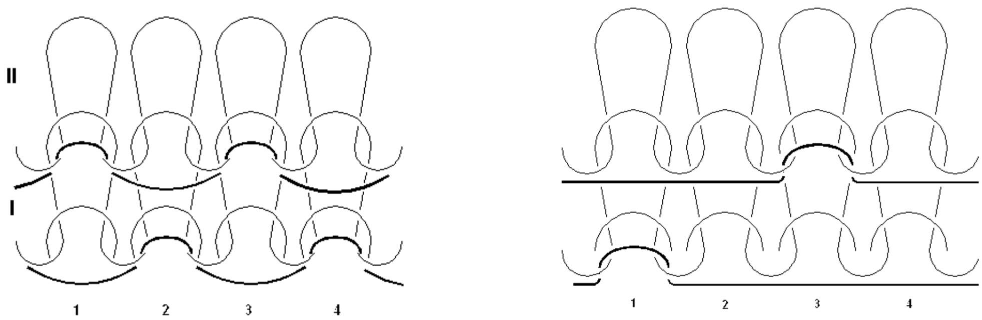


Figure 18. Example of 1x1 rib with weft inlays

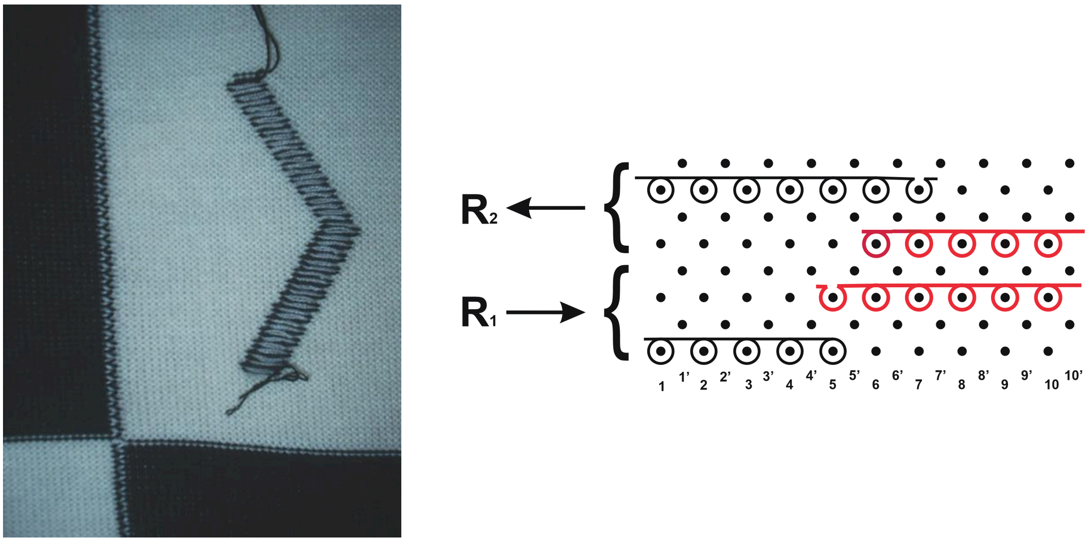
Fleece patterns can also have the ground structure plated (the so-called three threads fleece) where the smart yarn can be sandwiched between the two yarns used for plating and therefore more protected.



Fleece pattern with 1x1 tucking repeat *Fleece pattern with 3x1 tucking repeat*

Figure 19. Examples of two threads fleece fabrics

Another interesting structural possibility for smart weft knitted fabrics is intarsia patterns, defined as fabrics with independent areas made of different yarns, connected by loops. This offers the possibility of integrating smart yarns in pre-set areas in a panel and then in the product. The different areas composing a panel are knitted by different special feeders and a loop is fed to the first needle from the neighbouring area every time the carrier changes its direction, as illustrated in Figure 20. Each separate area can have its own patterns, increasing the structural possibilities to insert, for example, sensors or paths for circuits. However, this type of pattern requires flat knitting machines with intarsia feeders.



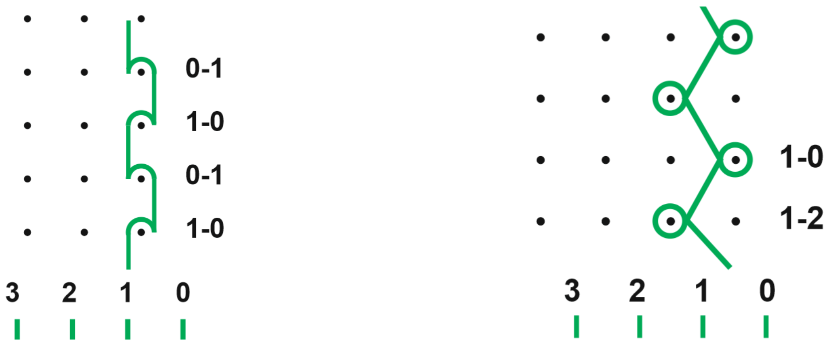
a) Example of intarsia fields with loop connection (rear aspect)

b) Detail of a knitting sequence for an intarsia pattern

Figure 20. Principle of intarsia patterns

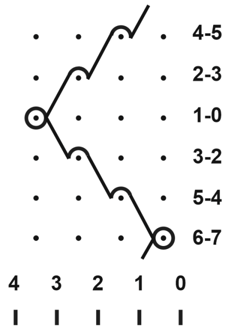
2D warp knitted fabrics are obtained using 3 basic lapping movements and their two derivates (Spencer, 2001), illustrated in Figure 21:

- pillar, tricot and atlas, most used being open-lap pillar and closed-lap tricot and atlas;
- tricot and atlas with ix1 lapping, with i being at least 2

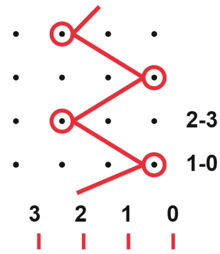


Pillar lapping (open lap)

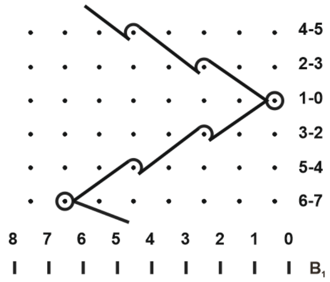
Tricot lapping (closed lap)



Atlas lapping - example



Tricot, 2x1 lapping (closed lap)



Atlas, 2x1 lapping - example

Figure 21. Types of basic lapping for warp knitting

Pillar lapping could be a solution to introduce smart yarns using a vertical placement, however, it has to be used with other guide bars, as pillar stitches do not form a fabric. Almost all of warp knitted fabrics produced on tricot machines are made with at least two systems of yarns, fed simultaneously to different guide bars that are programmed to produce these evolutions (lapping). Most common structures produced with two guide bars are locknit (charmeuse), reverse locknit, satin.

Partially threaded guide bars and certain evolutions can create openings in the fabric, with pre-set dimensions and shape, like pin net and fly net. This improves comfort characteristics related to permeability.

Warp knitting technology is also well suited for yarn insertion through warp inlays and weft inlays, making such structures ideal for the integration of smart function. When designing the path of a smart yarn inlaid in the fabric, it must be considered that these weft inlay yarns are introduced by guide bars, therefore the horizontal amplitude is limited for each row.

Mesh structures are opened fabrics with pre-set geometry, that can be obtained using pillar and weft inlays, with the possibility of including other inlay yarns for patterns. Most known mesh structures (also called nets) are marquisette, characterized by rectangular openings and tulle, that has hexagonal openings.

3.2.2. 3D knitted fabrics

Both knitting technologies can be used to manufacture fabrics with three-dimensional architecture, each with its own advantages and range of applications.

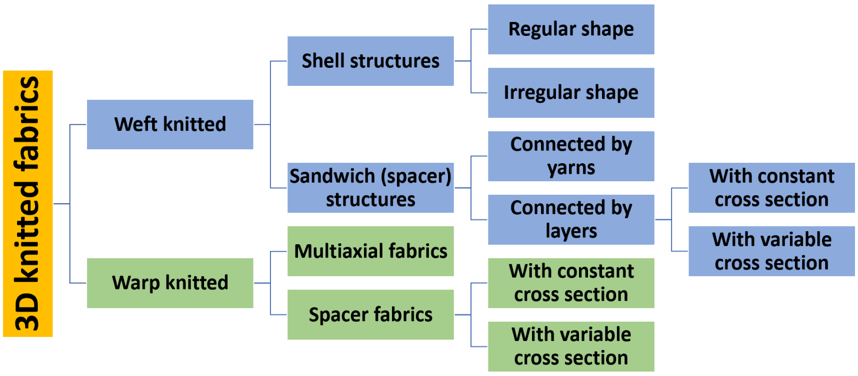


Figure 22. Classification of 3D knitted fabrics

Multiaxial warp knitted fabrics, exemplified in Figure 22, are characterised by layers of yarns placed at pre-set angles (at 0° weft yarns and angles between +20° to -20°) that are connected by knitted stitches (pillar or tricot lapping). Such structures have controlled anisotropy and are mostly used for composite reinforcement. The integration of smart yarns is possible in the layers of yarns, mostly for applications where sensors are required.

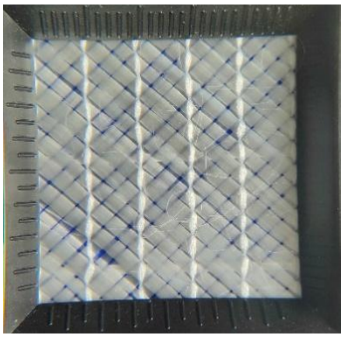


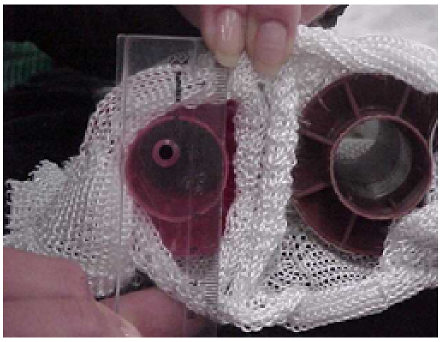
Figure 23. Aspect of a warp knitted multiaxial fabric, connected using pillar stitches

For spacer fabrics, also known as sandwich fabrics (for weft knitted spacers), the three-dimensional architecture is obtained by knitting separately two independent outer layers connected by yarns, for both weft and warp knitting or by knitted layers, only for weft knitting. The cross-sectional aspect of spacer fabrics connected by yarns is exemplified in Figure 24 for weft knitted spacers and Figure 25 for warp knitted spacers.

Figure 24. Aspect of a weft knitted spacer fabric, connected by yarns

Figure 25. Aspect of a warp knitted spacer fabric

For these structures, integration of smart functionalities can be done in the outer layers (by knitting the smart yarns - stripes, plating or as fleece yarns) or using the smart yarns as connective elements. The advantage of spacer fabrics is the control on the integration level, placing the smart yarns where they are in contact with the user or the environment, while the rest of the spacer fabric has no smart functions. The compression characteristics of the spacers recommend them for applications in medicine (orthopaedics), mattresses, shoes, composite reinforcement, etc.
In the case of weft knitting (flat knitting technology), the outer fabrics can be connected by knitted layers. This connection involves stopping the knitting on the two outer fabrics and knit a layer that will connect both. The number, shape and position of the connecting layers depend on the intended complexity of the spacer fabric. Figure 26 exemplifies 3D sandwich fabrics with connecting knitted layers of constant and variable length.



a) connective double layers of constant length

b) connective layers of variable length

Figure 26. Aspect of weft knitted spacer fabrics, connected by knitted layers

Shell structures are manufactured only on weft flat knitting machines. They are fabrics knitted flat, with fashioning lines incorporated in the fabric plan. The technique is called flechage and it allows to eliminate parts of the fabric plan by stopping progressively to knit on selected needles and then reintroducing these needles into the working width. This way, there are areas in the fabric with considerably less stitches than the rest of the fabric. The areas with more stitches will be forced into a spatial geometry. By placing the fashioning lines in the fabric plan, a large diversity of 3D shapes can be obtained, including shaped sandwich fabrics.

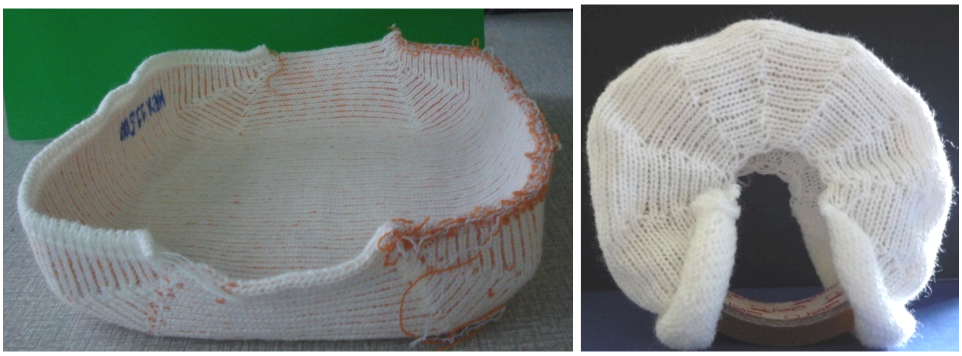


Figure 26. Examples of 3D knitted shell fabric

Want to learn more about this topic?

In the video Flat knit machine working principle [https://www.youtube.com/watch?v=Vm3T7zdJKRw] you will find how circular weft knitting machines operate.

In the video Karl Mayer Pre-Owned: Demonstration of Knitting [https://www.youtube.com/watch?v=10CbLOD8Fyk] you will find a practical demonstration of warp knitting.

In the video Knitted force sensors [https://mi-lab.org/knitted-force-sensors/] you will find examples of how to use knitting to produce sensors.

Summary

This lesson discusses the principles of textile processes used to manufacture yarns, woven fabrics and knitted fabrics. In the first chapter, the concept of functional and technological design of textiles is discussed, considering the options a material/product designer must make and the criteria these options are based on. The textile value chain and its possibilities for smart functionalization is also presented. A comparison between woven and knitted fabrics is provided.

The second chapter is dedicated to yarns, their types and technologies used to produce spun yarns (made of fibres of finite length) and filament yarns (made of fibres of infinite length). The different types of yarns are classified and characterised, appraising their suitability for integrating smart fibres.

The most relevant spinning technologies for spun yarns and their advantages and disadvantages are presented and discussed: ring spinning, open-end spinning (rotor and friction spinning), air-jet spinning. The production of filament yarns include melt spinning and solution spinning – dry, wet and electrospinning.

The structural specificities and technologies for the manufacturing of woven and knitted fabrics are discussed in the last chapter. The main mechanisms of a weaving machine are characterized and a classification of weaving machines is presented based on the weft insertion mechanism. For 2D fabrics, the basic weaves are presented and exemplified, while 3D woven fabrics are discussed according to two main criteria – shape and manufacturing method.

For knitted fabrics, the structural characteristics of the basic evolutions for 2D fabrics are presented for weft knitting and warp knitting. Other types of patterns suitable for smart functionalization are also considered. The lesson presents the 3 main types of fabrics with 3D architecture (weft and warp knitted structures), discussing the principle of manufacturing.

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Partnership

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