5


Subhash C Anand
Faculty of Technology, Bolton Institute, Deane Road, Bolton BL3 5AB, UK

5.1 Terms and definitions

- **Warp knitting** is a method of making a fabric by normal knitting means, in which the loops made from each warp are formed substantially along the length of the fabric. It is characterised by the fact that each warp thread is fed more or less in line with the direction in which the fabric is produced. Each needle within the knitting width must be fed with at least one separate and individual thread at each course. It is the fastest method of converting yarn into fabric, when compared with weaving and weft knitting (Fig. 5.1).

- **Weft knitting** is a method of making a fabric by normal knitting means, in which the loops made by each weft thread are formed substantially across the width of the fabric. It is characterised by the fact that each weft thread is fed more or less at right angles to the direction in which the fabric is produced. It is possible to knit with one thread only, but up to 144 threads can be used on one machine. This method is the more versatile of the two in terms of the range of products produced as well as the type of yarns utilised (Fig. 5.2).

- **Single-jersey fabric** is a weft-knitted fabric made on one set of needles.

- **Double-jersey fabric** is a weft-knitted fabric made on two sets of needles, usually based on rib or interlock gaiting, in a manner that reduces the natural extensibility of the knitted structure. These fabrics can be non-Jacquard or Jacquard.

- **Course** is a row of loops across the width of the fabric. Courses determine the length of the fabric, and are measured as courses per centimetre.

- **Wale** is a column of loops along the length of the fabric. Wales determine the width of the fabric, and are measured as wales per centimetre.

- **Stitch density** is the number of stitches per unit area of a knitted fabric (loops cm$^{-2}$). It determines the area of the fabric.

- **Stitch length** is the length of yarn in a knitted loop. It is the dominating factor for all knitted structures. In weft knitting, it is usually determined as the average length of yarn per needle, while in warp knitting, it is normally determined as the average length of yarn per course.
• **Yarn linear density** indicates the thickness of the yarn and is normally determined in tex, which is defined as the mass in grams of 1 km of the material. The higher the tex number, the thicker is the yarn and vice-versa.

• **Overlap** is the lateral movement of the guide bars on the beard or hook side of the needle. This movement is normally restricted to one needle space. In the fabric a loop or stitch is also termed the overlap.

• **Underlap** is the lateral movement of the guide bars on the side of the needle remote from the hook or beard. This movement is limited only by the mechani-
cal considerations. It is the connection between stitches in consecutive courses in a warp knitted fabric.

- **Tightness factor** $K$ is a number that indicates the extent to which the area of a knitted fabric is covered by the yarn. It is also an indication of the relative looseness or tightness of the knitting. $(K = \text{tex}^{1/2} l^{-1})$, where $l$ is the stitch length.
- **Area density** is a measure of the mass per unit area of the fabric (g m$^{-2}$).

### 5.2 Weft knitting machines

Figure 5.3 shows a simplified classification of weft knitting equipment. It will be noticed from Fig. 5.3 that the latch needle is the most widely used needle in weft knitting, because it is self-acting or loop controlled. It is also regarded as more ver-
satile in terms of the range of materials that can be processed on latch needle machines. Bearded needles are less expensive to manufacture, can be produced in finer gauges and supposedly knit tighter and more uniform stitches compared with latch needles, but have limitations with regard to the types of material that can be processed as well as the range of structures that can be knitted on them. Bearded needle machines are faster than the equivalent latch needle machines. The compound needle has a short, smooth and simple action, and because it requires a very small displacement to form a stitch in both warp and weft knitting, its production rate is the highest of the three main types of needle. Compound needles are now the most widely used needles in warp knitting and a number of manufacturers also offer circular machines equipped with compound needles. The operation speeds of these machines are up to twice those of the equivalent latch needle machines.

The main parts of the bearded, latch, compound needle (fly needle frame) and compound needle (Kokett) are shown in Figs. 5.4, 5.5, 5.6 and 5.7, respectively. Variations of latch needles include rib loop transfer needles and double-ended purl
needles, which can slide through the old loop in order to knit from an opposing bed and thus draw a loop from the opposite direction.

5.2.1 Loop formation with latch needles

Figure 5.8(a) illustrates the needle at tuck height, that is high enough to receive a new yarn, but not high enough to clear the old loop below the latch. The needle is kept at this position because the loop formed at the previous course (A) lies on the open latch and stops the latch from closing. Note that once a latch is closed, it can only be opened by hand, after stopping the machine.

In Fig. 5.8(b), the needle has been lifted to the clearing position and the new yarn (B) is presented. The old loops (A) are below the latch and the new yarn (B) is fed into the needle hook. A latch guard normally prevents the latch from closing at this point.

In Fig. 5.8(c), the needle has now moved to its lowest position or knitting point and has drawn the new loop (B) through the old loop (A) which is now cast-off or knocked over. The needle now rises and the sequence of movements is repeated for the next course.

The loop formation on a latch needle machine is also illustrated in Fig. 5.9(a) and a typical cam system on such a machine is shown in Fig. 5.9(b).
5.2.2 Single-jersey latch needle machines
This type of machinery is employed throughout the world, either as a basic machine or with certain refinements and modifications, to produce fabric ranging from stockings to single-jersey fabric for dresses and outerwear, as well as a wide range of fabrics and products for technical applications. The machine sizes vary from 1 feeder 1 inch diameter to 144 feeds 30 inches diameter. Most single-jersey machines are rotating cylinder type, although a few rotating cam box machines are still used for specialised fabrics. These machines are referred to as sinker top machines and use web holding sinkers. Comprehensive reviews of single- and double-jersey knitting machinery and accessories exhibited at ITMA’95 and ITMA’99 were published that illustrate the versatility and scope of modern weft knitting equipment.1,7

5.2.2.1 Knitting action of a sinker top machine
Figures 5.10(a) to (d) show the knitting action of a sinker top machine during the production of a course of plain fabric.

Figure 5.10(a) illustrates the rest position. This shows the relative position of the knitting elements in-between the feeders with the needle at tuck height and the fabric loop held on the needle latch by the forward movement of the sinker towards the centre of the machine.

Figure 5.10(b) illustrates the clearing position. The needle has been raised to its
5.10 Knitting action of a sinker top machine.

highest position by the clearing cam acting on the needle butt; the old loop slides down from the open latch on to the needle stem.

Figure 5.10(c) illustrates the yarn feeding position. The sinker is partially withdrawn allowing the feeder to present its yarn to the descending needle hook, at the same time freeing the old loop so that it can slide up the needle stem and under the open latch spoon.

Figure 5.10(d) illustrates the knock-over position. The needle has now reached its lowest position and has drawn the new loop through the old loop which is now knocked over the sinker belly.

Stitch length may be controlled in a number of ways. On machines without positive feed mechanism, it is controlled mainly by the distance the needle descends below the sinker belly. Other factors such as input tension ($T_i$), yarn to metal coefficient of friction ($\mu$) and take-down tension also influence the final stitch length in the fabric. When a positive feed device is used, the length of yarn fed to the needles at a particular feed is the factor that decides the stitch length. Other factors such as input tension $T_i$, $\mu$, stitch cam setting and take-down tension influence the yarn or fabric tension during knitting, and hence determine the quality of the fabric. Stitch length is fixed by the positive feed device setting.

The sinker has two main functions and these are:

- to hold the fabric loop in a given position whenever the needles rise and
- to provide a surface over which the needles draw the loops.

Other advantages of using sinkers include:

- The control exerted by the sinker allows minimum tension on the fabric thus producing a good quality fabric with even loops.
Fine adjustments in quality and those required in the knitting of certain difficult yarns and structures are possible.

The sinker facilitates the setting-up of the machine after a partial or full press-off (after the latches have been opened manually).

5.2.3 Double-jersey machines

Figure 5.11 shows the needle layout of rib and interlock machines. Both types of machine are available as circular or flat machines, whereas straight bar or fully fashioned machines are available in rib-type only.

Rib and interlock double-jersey machines are used either as garment length machines or for producing rolls of fabric. They can be either plain or equipped with a wide range of mechanical patterning mechanisms at each feed in the cylinder. Both types can also be equipped with electronic needle mechanisms to produce large area Jacquard patterns at high speeds.
5.2.3.1 Rib machines
Rib machines use two sets of needles and can be flat, circular or fully fashioned. The needles in the two beds are staggered or have spaces between them (rib gaiting). Most machines have revolving needle cylinders but in some cases the cams rotate past stationary needles. Patterning is obtained by altering cam and needle set-out or by using various needle selection mechanisms including individual needle electronic selection with computer aided design system. Machine diameters range from 7\(\frac{1}{2}\)–20 inches for garment length and from 30–33 inches for fabric machines. An example of a modern double-jersey machine is the Monarch V-7E20, a 30 inch diameter, E20, 72 feeders 8-lock machine with RDS on dial and ACT II motorised automatic friction take-down system. The machine has 2 × 2 cam tracks and can be converted from rib to interlock or 8-lock timing in minutes. All basic non-jacquard double-jersey structures can be knitted at a speed factor of 900 (machine diameter (inches) × machine rpm).

5.2.3.2 Interlock machines
These are latch needle circular machines of the rib type, provided with a cylinder and dial. Unlike rib machines where the tricks of the dial alternate with the tricks of the cylinder (rib gaiting) the needle tricks of the cylinder are arranged exactly opposite those of the dial (interlock gaiting). Long-and short-stemmed needles are used that are arranged alternately, one long, one short in both cylinder and dial as shown in Fig. 5.11. An example of a modern high-speed interlock machine is Sulzer Morat Type 1L 144, which is a 30 inches diameter, 144 feeds, 28 or 32 gauge (npi, needles per inch), 28 rpm, producing at 100% efficiency 86.4 m h\(^{-1}\) (15.55 kg h\(^{-1}\)) of 76 dtex polyester with 14 cpc (courses per centimetre) and with an area density of 180 g m\(^{-1}\) (60 inches wide) finished fabric.

To accommodate the long- and short-stemmed needles, the cam system is provided with a double cam track. The long dial needles knit with the long cylinder needles at feeder 1 and the short cylinder needles knit with the short dial needles at feeder 2. Thus two feeders are required to make one complete course of loop.

5.2.3.3 Needle timing
Two different timings can be employed on 1 × 1 rib and 1 × 1 interlock machines.

- **Synchronised timing** is the timing of a machine that has two sets of needles where the point of knock-over of one set is aligned with the point of knock-over of the other set.
- **Delayed timing** is the setting of the point of knock-over of one set of needles on a two-bed knitting machine out of alignment with that of the other set so as to permit the formation of a tighter stitch. Broad ribs (i.e. 2 × 2, 3 × 3 etc.), and rib Jacquard fabrics cannot be produced in delayed timing because there will not always be cylinder needles knitting either side of the dial needles from which to draw yarn. Up to nine needles delay is possible, but 4–5 needles delay is normal.

5.2.3.4 Knitting action of V-bed flat machine
Figure 5.12 illustrates the different stages of loop formation on a V-bed flat knitting machine, and Fig. 5.13 shows the cam system used on a simple single system flat
5.12 Loop formation on a V-bed flat knitting machine.

5.13 V-bed single-system cams. S are stitch cams, R are raising cams and C are clearing cams.
machine. Power V-bed flat machines are used mainly for the production of knitwear for children, women and men. They range from simple machines through mechanical jacquard machines to fully electronic and computerised flat machines, even equipped with presser foot. The developments in the automation of fabric designing, pattern preparation, and electronic needle selection, as well as in the range of structures and effects which can be produced, have been tremendous and flat machines and their products are now regarded as extremely sophisticated. High quality garments can now be produced at competitive prices owing to revolutionary garment production systems feasible with presser foot. Two- and three-dimensional structures as well as complete garments without any seams or joins can be produced on the latest electronic flat knitting machines and the associated design systems.

5.3  Weft-knitted structures

The basic weft-knitted structures and stitches are illustrated in Fig. 5.14 (A to G), and the appearance, properties and end-use applications of plain, 1 × 1 rib, 1 × 1 purl and interlock structures are summarised in Table 5.1. These basic stitches are often combined together in one fabric to produce an enormous range of single- and double-jersey fabrics or garments. Weft-knitted fabrics are produced commercially for apparel, household and technical products and they are used for an extremely large array of products, ranging from stockings and tights to imitation furs and rugs.

The importance and diversity of warp- and weft-knitted fabrics used for various technical applications has been discussed by Anand, who highlighted the fact that knitted fabrics are being increasingly designed and developed for technical products ranging from scouring pads (metallic) to fully fashioned nose cones for supersonic aircrafts. Warp- and weft-knitted products are becoming popular for a wide spectrum of medical and surgical products.

5.4  Process control in weft knitting

5.4.1  Main factors affecting the dimensional properties of knitted fabrics or garments

- Fabric structure: different structures relax differently.
- Fibre(s) type: fabrics or garments made from different fibre(s) relax differently.
- Stitch length: the length of yarn in a knitted loop is the dominating factor for all structures.
- Relaxation/finishing route: the fabric dimensions vary according to relaxation/finishing sequence.
- Yarn linear density: affects the dimensions slightly, but affects fabric tightness, area density (g m⁻²) and other physical properties.

5.4.2  Laboratory stages of relaxation

- On machine – Strained state: this is predominantly length strain.
- Off machine – Dry relaxed state: the fabric moves to this state with time. The dry
5.14 Weft-knitted structures (A–G).
<table>
<thead>
<tr>
<th>Property</th>
<th>Plain</th>
<th>1 × 1 Rib</th>
<th>1 × 1 Purl</th>
<th>Interlock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appearance</td>
<td>Different on face and back; V-shapes on face, arcs on back</td>
<td>Same on both sides, like face of plain</td>
<td>Same on both sides, like back of plain</td>
<td>Same on both sides, like face of plain</td>
</tr>
<tr>
<td>Extensibility</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lengthwise</td>
<td>Moderate (10–20%)</td>
<td>Moderate</td>
<td>Very high</td>
<td>Moderate</td>
</tr>
<tr>
<td>Widthwise</td>
<td>High (30–50%)</td>
<td>Very high (50–100%)</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Area</td>
<td>Moderate–high</td>
<td>High</td>
<td>Very high</td>
<td>Moderate</td>
</tr>
<tr>
<td>Thickness and warmth</td>
<td>Thicker and warmer than plain woven made from same yarn</td>
<td>Much thicker and warmer than plain woven</td>
<td>Very much thicker and warmer than plain woven</td>
<td>Very much thicker and warmer than plain woven</td>
</tr>
<tr>
<td>Unroving</td>
<td>Either end</td>
<td>Only from end knitted last</td>
<td>Either end</td>
<td>Only from end knitted last</td>
</tr>
<tr>
<td>Curling</td>
<td>Tendency to curl</td>
<td>No tendency to curl</td>
<td>No tendency to curl</td>
<td>No tendency to curl</td>
</tr>
<tr>
<td>End-uses</td>
<td>Ladies’ stockings</td>
<td>Socks</td>
<td>Children’s clothing</td>
<td>Underwear</td>
</tr>
<tr>
<td></td>
<td>Fine cardigans</td>
<td>Cuffs</td>
<td>Knitwear</td>
<td>Shirts</td>
</tr>
<tr>
<td></td>
<td>Men’s and ladies’ shirts</td>
<td>Waist bands</td>
<td>Thick and heavy</td>
<td>Suits</td>
</tr>
<tr>
<td></td>
<td>Dresses</td>
<td>Collars</td>
<td>Outerwear</td>
<td>Trouser suits</td>
</tr>
<tr>
<td></td>
<td>Base fabric for coating</td>
<td>Men’s outerwear</td>
<td></td>
<td>Sportswear</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Knitwear</td>
<td></td>
<td>Dresses</td>
</tr>
</tbody>
</table>
relaxed state is restricted by fabric structure and fibre type. Only wool can attain this state.

- **Static soak in water and dry flat** – *Wet relaxed state*: tight structures do not always reach a ‘true’ relaxed state. Only wool and silk can attain this state.
- **Soak in water with agitation, or Agitation in steam, or Static soak at selected temperatures (>90°C) plus, dry flat** – *Finished relaxed state*: the agitation and/or temperature induces a further degree of relaxation, producing a denser fabric. Wool, silk, textured yarn fabrics, acrylics.
- **Soak in water and Tumble dry at 70°C for 1 hour** – *Fully relaxed state*: three-dimensional agitation during drying. All fibres and structures.

### 5.4.3 Fabric geometry of plain single-jersey structures

1. **Courses per cm (cpc)\(\alpha 1/l = \frac{k_c}{l}\)
2. **Wales per cm (wpc)\(\alpha 1/l = \frac{k_w}{l}\)
3. \(s = (\text{cpc} \times \text{wpc})\)\(\alpha 1/l^2 = \frac{k_s}{l^2}\)
4. \(\frac{\text{cpc}}{\text{wpc}}\)\(\alpha c = \frac{k_c}{k_w}\) (shape factor)

\(k_c, k_w, k_s\) are dimensionless constants, \(l\) is the stitch length and \(s\) is the stitch density.

### 5.4.4 Practical implications of fabric geometry studies

- Relationship between yarn tex and machine gauge is given by Equation (5.1):

\[
\text{Optimum tex} = \frac{\text{constant}}{(\text{gauge})^2}
\]

For single-jersey machines, the optimum tex = 1650/\(G^2\), and for double-jersey machines, the optimum tex = 1400/\(G^2\), where \(G\) is measured in needles per centimetre (npc).
- **Tightness factor** is given by Equation (5.2):

\[
K = \sqrt{\frac{\text{tex}}{l}}
\]

where \(l\) is the stitch length, measured in millimetres. For single-jersey fabrics: 1.29 ≤ \(K\) ≤ 1.64. Mean \(K\) = 1.47. For most weft-knitted structures (including single- and double-jersey structures and a wide range of yarns): 1 ≤ \(K\) ≤ 2. Mean \(K\) = 1.5. The tightness factor is very useful in setting up knitting machines. At mean tightness factor, the strain on yarn, machine, and fabric is constant for a wide range of conditions.
- **Fabric area density** is given by Equation (5.3):

\[
\text{Area density} = \frac{s \times l \times T}{100} \text{ g m}^{-2}
\]
where \( s \) is the stitch density/cm\(^2\); \( l \) is the stitch length (mm) and \( T \) is the yarn tex, or, Equation (5.4):

\[
\frac{k_s}{l} \times \frac{T}{100} \text{ g m}^{-2}
\]

Equation (5.4)

where \( k_s \) is a constant and its value depends upon the state of relaxation, that is, dry, wet, finished or fully relaxed. The area density can also be given by Equations (5.5) and (5.6)

\[
\text{Area density} = \frac{n \times l \times \text{cpc} \times T}{10000} \text{ g m}^{-1}
\]

Area density

where \( n \) is the total number of needles, \( l \) is the stitch length (mm) and \( T \) is the yarn tex, or

\[
\frac{n \times k_c \times T}{10000} \text{ g m}^{-1}
\]

Equation (5.6)

where \( k_c \) is a constant and its value depends upon the state of relaxation, that is, dry, wet, finished or fully relaxed.

- Fabric width is given by Equation (5.7)

\[
\text{Fabric width} = \frac{n \times l}{k_w} \text{ cm}
\]

Equation (5.7)

where \( k_w \) is a constant, and its value depends upon the state of relaxation, that is, dry, wet, finished or fully relaxed. It can also be given by Equation (5.8)

\[
n \times l = L \text{ (course length)} \therefore \text{Fabric width} = \frac{L}{k_w} \text{ cm}
\]

Equation (5.8)

Fabric width depends upon course length and not upon the number of needles knitting.

- Fabric thickness. In the dry and wet relaxed states, fabric thickness \( t \) is dependent upon fabric tightness, but in the fully relaxed state, it is more or less independent of the fabric tightness factor. In the fully relaxed state \( t = 4d \) where \( d \) is the yarn diameter.
5.4.5 Quality control in weft knitting

The dimensions of a weft-knitted fabric are determined by the number of stitches and their size, which in turn is determined by stitch length. Most knitting quality control therefore reduces to the control of stitch length; differences in mean stitch length give pieces of different size; variation of stitch length within the piece gives appearance defects, by far the most common one being the occurrence of widthwise bars or streaks owing to variation in stitch length between adjacent courses.

5.4.5.1 Measurement of stitch length, \( l \)

- **Off machine (in the fabric):**
  - HATRA course length tester
  - Shirley crimp tester.
- **On machine (during knitting):**
  - Yarn speed meter (revolving cylinder only)
  - Yarn length counter (both revolving cylinder and cambox machines).

5.4.5.2 Control of stitch length, \( l \)

- **Positive feed devices:**
  - Capstan feed: cylindrical or tapered
  - Nip feed: garment length machines
  - Tape feed: (Rosen feed) circular machines producing plain structures
  - Ultrapositive feed: IPF or MPF
- **Constant tension device:** Storage feed device: flat, half-hose, hose and circular machines producing either plain or jacquard structures.
- **Specialised positive feed devices:**
  - Positive Jacquard Feeder MPF 20 KIF
  - Striper Feeder ITF
  - IROSOX Unit (half-hose machines)
  - Elastane Feed MER2
  - Air controlled feeds for flat and fully fashioned machines. Figure 5.15 shows a tape feed. A modern ultrapositive feed and a yarn storage feed device are illustrated in Figs. 5.16 and 5.17, respectively.

5.5 End-use applications of weft-knitted fabrics

Weft-knitted fabrics are used for apparel, household and technical products. The main outlets for the different types of weft-knitted fabrics are as shown below. The knitting equipment used to produce these fabrics is also given.

5.5.1 Flat bar machines

- Machine gauge: normally needles per inch, 3–18 npi
- Machine width: up to 78.7 inches
- Needle type: latch (compound needle machines are being developed)
- Needle bed type: single (hand machines), but mainly rib type
Wheels may be taken out of action by lowering the pot-eye plate; thus allowing the yarn to run free below the level of the tape.

5.15 Tape positive feed device.

5.16 Ultrapositive feed device.
• Products: jumpers, pullovers, cardigans, dresses, suits, trouser suits, trimmings, hats, scarves, accessories, ribs for straight-bar machines (fully fashioned machines). Cleaning clothes, three-dimensional and fashioned products for technical applications, multiaxial machines are under development.

5.5.2 Circular machines

• Machine gauge: normally needles per inch, 5–40 npi
• Machine diameter: up to 30 inches. Up to 60 inch diameter machines are now available
• Needle type: latch, (bearded on sinker wheel and loop wheel, some compound needle machines)
• Needle bed type: single, rib, interlock, double cylinder
• Products
  – Hose machines: seamfree hose, tights, industrial use dye bags, knit-de-knit yarns, industrial fabrics
  – Half-hose machines: men’s and boy’s half-hose, ladies’ stockings, children’s tights, sports socks
  – Garment blank machines: underwear, T-shirts, jumpers, pullovers, cardigans, dresses, suits, trouser suits, vests, briefs, thermal wear, cleaning cloths, technical fabrics
  – Fabric machines: rolls of fabric with the following end-uses: jackets, ladies’
tops, sports and T-shirts, casual wear, suits, dresses, swimwear, bath robes, dressing gowns, track suits, jogging suits, furnishing, upholstery, automotive and technical fabrics, household fabrics.

5.5.3 Straight-bar machines (fully fashioned machines)
- Machine gauge: normally needles per 1½ inch, 9–33 (up to 60 gauge machines have been produced)
- Machine width: from 2–16 section machines – each section up to 36 inches wide (up to 40 section machines have been produced)
- Needle type: bearded or bearded and latch
- Needle bed type: single and rib
- Products: jumpers, pullovers, cardigans, dresses, suits, trouser suits, fully fashioned hose, sports shirts, underwear, thermal wear.

5.6 Warp-knitting machines

5.6.1 Introduction
The first weft-knitting machine was built by William Lee in 1589. In 1775, just under 200 years later, the first warp-knitting machine was invented by Crane, an Englishman. It was a single guide bar machine to make blue and white zig-zag striped silk hosiery and these fabrics were named after Van Dyck, the painter. With the advent of acetate continuous-filament yarns after World War I, the first bulk production of tricot fabrics was commenced by British Celanese on German Saupe 2-guide bar, 28 gauge machines. Locknits replaced the single guide bar atlas fabrics for lingerie, the latter being difficult to finish and laddered easily.

From 1950 to 1970, the growth of the warp-knitting industries in the UK and other western countries was phenomenal. The main reasons for this colossal expansion are summarised below (although developments in the various fields mentioned here were taking place concurrently). The state of the art and current developments in tricot and raschel machinery have been summarised below.

Anand also published a review of warp-knitting equipment exhibited by Karl Mayer at ITMA in 1995 and ITMA’99.

5.6.1.1 Yarn developments
- The discovery of thermoplastic yarns and their suitability, even in very low linear densities (deniers) and in flat or low-twist form, to be knitted with very low yarn breakage rates on modern high speed tricot and raschel machines
- The extra design scope offered by differential dye yarns
- Improved cover-comfort attained through textured and producer-bulked yarns
- Elastomeric yarns, which have given a tremendous fillip to the raschel power-net industry.

5.6.1.2 Machinery developments
- Higher machine speeds, (up to 3500 cpm)
- Finer gauges (up to 40 needles per inch)
• Wider machines (up to 260 inches)
• Increased number of guide bars (up to 78 guide bars)
• Special attachments such as cut presser, fallplate, swanwarp, etc.
• Some speciality raschel machines such as Co-we-nit and Jacquard machines and, more recently, redesigned full-width weft insertion raschel and tricot machines
• High speed direct-warping machines and electronic yarn inspection equipment during warping
• Electronic stop motions for the knitting machines
• Larger knitting beams and cloth batches
• Modern heat-setting and beam-dyeing machinery
• Electronic warp let-off, electronic patterning, electronic jacquard and electronic fabric take-up mechanisms
• Loop-raised fabrics
• Stable constructions, such as sharkskins, queenscord, etc.
• Various net constructions utilising synthetic yarns
• Mono-, bi-, tri- and multiaxial structures for technical applications
• Three-dimensional and shaped (fashioned) structures for medical and other high technology products.

It is well known that the warp-knitting sector, particularly tricot knitting has grown in step with the expansion of manufactured fibres. In 1956, 17.8 million lbs of regenerated cellulosic and synthetic fibre yarns were warp knitted; the figure reached a staggering 70.6 million lbs in 1968.

In the mid-1970s, the tricot industry suffered a major setback, mainly because of a significant drop in the sale of nylon shirts and sheets, which had been the major products of this sector. It is also true that the boom period of textured polyester double-jersey was also a contributing factor in the sudden and major decline in the sales of tricot products. A change in fashion and the growth in the demand for polyester/cotton woven fabrics for shirtng and sheeting was another cause of this decline. The two major manufacturers of warp-knitting equipment, Karl Mayer and Liba, both in West Germany, have been actively engaged in redesigning their machinery in order to recapture some of the lost trade. The compound needle is the major needle used on both tricot and raschel machines, and many specialised versions of warp-knitting machines are now available for producing household and technical products. One of the major developments in warp knitting has been the commercial feasibility of using staple-fibre yarns for a wide range of products. It is also significant to note that the warp-knitting sector has broadened its market base and has expanded into household and technical fabric markets, such as lace, geotextiles, automotive, sportswear and a wide spectrum of surgical and healthcare products. The current and future potential of warp-knitted structures in engineering composite materials has been discussed by Anand.5

5.6.2 Tricot and raschel machines
The principal differences between tricot and raschel machines are listed here:

1. Latch needles are generally used in raschel machines, while bearded or compound needle machines are referred to as tricot machines. Compound needle
raschel machines are also now fairly common. The compound needle is the most commonly used needle on warp knitting equipment.

2. Raschel machines are normally provided with a trick plate, whereas tricot machines use a sinker bar.

3. In raschel machines the fabric is taken up parallel to the needle stems; in the tricot machines, however, it is taken up at approximately right angles to the needles.

4. Raschel machines are normally in a coarser gauge; they are also slower compared with tricot machines, because more guide bars are frequently used and they also require a longer and slower needle movement.

5. Raschel machines are much more versatile in terms of their ability to knit most types of yarns such as staple yarns, and split films, etc. Only continuous-filament yarns can be successfully knitted on most tricot machines.

6. Generally, warp beams are on the top of the machine on raschel machines; on tricot machines, they are generally at the back of the machine.

A simplified classification of warp-knitting equipment is given in Fig. 5.18; it will be noticed that apparel, household and technical fabrics are produced on modern warp-knitting machinery. It is in fact in the technical applications that the full potential of warp knitting is being exploited. It is virtually possible to produce any product on warp-knitting equipment, but not always most economical.

The simplest warp-knitted structures are illustrated in Fig. 5.19. It can be seen that both closed- and open-loop structures can be produced and there is normally very little difference in the appearance and properties between the two types of loops.

5.6.3 Knitting action of compound needle warp-knitting machine

In Fig. 5.20(a) the sinkers move forward holding the fabric down at the correct level in their throats. The needles and tongues rise with the needle rising faster until the hook of the needle is at its highest position and is open. In Fig. 5.20(b) the guides then swing through to the back of the machine and Fig. 5.20(c) shows the guides shog for the overlap and swing back to the front of the machine.

Figure 5.20(d) shows the needles and the tongues starting to descend, with the tongues descending more slowly thus closing the hooks. The sinkers start to withdraw as the needles descend so that the old loop is landed onto the closed hook and the new loops are secured inside the closed hook.

In Fig. 5.20(e) the needle descends below the sinker belly and the old loop is knocked-over. At this point, the underlap occurs and in Fig. 5.20(f) the sinkers move forward to hold down the fabric before the needles commence their upward rise to form a fresh course.

5.6.4 Knitting action of standard raschel machine

In Fig. 5.21(a) the guide bars are at the front of the machine completing their underlap shog. The web holders move forward to hold the fabric down at the correct level, whilst the needle bar starts to rise from knock-over to form a fresh course.

Figure 5.21(b) shows that the needle bar has risen to its full height and the old
loops slip down from the latches onto the stems after opening the latches. The latches are prevented from closing by the latch guard. The web holders then start to withdraw to allow the guide bars to form the overlap movement.

In Fig. 5.21(c) the guide bars swing to the back of the machine and then shog for the overlap and in Fig. 5.21(d) the guide bars swing back to the front and the warp threads are laid into the needle hooks. Note: only the front guide bar threads have formed the overlap movement, the middle and back guide bar threads return through the same pair of needles as when they swung towards the back of the machine. This type of movement is called laying-in motion.

In Fig. 5.21(e) the needle bar descends so that the old loops contact and

5.18  Simplified classification of knitting machinery.

5.20  Knitting action of compound needle warp-knitting machine.
close the latches, trapping the new loops inside. The web holders now start to move forward.

Figure 5.21(f) shows the needle bar continuing to descend, its head passing below the surface of the trick-plate, drawing the new loops through the old loops, which are cast-off, and as the web holders advance over the trick-plate, the underlap shog of the guide bar is commenced.

The knitting action of bearded needle warp-knitting machines has not been given here because in the main the machines likely to be used for technical textile products would use either latch or compound needles. Also the proportion of new bearded needle machines sold has decreased steadily over the years. This is mainly due to the lack of versatility of these machines in terms of the variety of yarns that can be processed and the range of structures that can be normally knitted on them. The displacement curves for the three main types of needle are shown in Fig. 5.22.
It is obvious that compound needle machines would operate at faster rates, provided all other factors are similar.

5.7 Warp-knitted structures

5.7.1 Stitch notation

Some of the more popular stitches used in the production of warp-knitted fabrics are given in Fig. 5.23. These stitches, together with the number of guide bars used, a comprehensive range of types and linear densities of yarns available, fancy threading, controlling individual run-ins and run-in ratios, and various finishing techniques are combined and modified to construct an endless variety of fabrics. The lapping movements of the individual guide bars throughout one repeat of the pattern are normally indicated on special paper, called point paper. Each horizontal row of equally spaced dots represents the same needles at successive courses. The spaces between the dots, or needles, are numbered 0, 1, 2, 3, 4, and so on, and show the number of needles transversed by each guide bar. Although three links per course are normally employed, only two are actually required; the third (last link) is only used to effect a smoother movement of the guide bar during the underlap. The first link determines the position of the guide bars at the start of the new course. The second link determines the direction in which the overlap is made. The links, therefore, are grouped together in pairs and the lapping movements at each course are separated by a comma. For instance, the lapping movements shown in Fig. 5.23(c) are interpreted as follows:

- (1-0) is the overlap at the first course
- (0,1) is the underlap at the same course, but made in the opposite direction to the overlap
- (1-2) is the overlap at the second course, and
• (2,1) is the underlap at the second course, but made in the opposite direction to the previous underlap.

It will also be observed from Fig. 5.23 that when the underlap is made in the opposite direction to the immediately preceding overlap, a closed loop is formed, but when the underlap is made in the same direction as the immediately preceding overlap, or no underlap is made, then an open loop will result.

It is vital to ensure when placing a pattern chain around the drum that the correct link is placed in contact with the guide bar connecting rod, otherwise the underlap will occur on the wrong side of the needles, or open loops may be formed instead of the intended closed loops.

5.7.2 Single-guide bar structures
Although it is possible to knit fabrics using a single fully threaded guide bar, such fabrics are now almost extinct owing to their poor strength, low cover, lack of stability and pronounced loop inclination on the face of the fabric. Three examples of single guide bar structures are shown in Fig. 5.24.

5.7.3 Two-guide bar full-set structures
The use of two guide bars gives a much wider pattern scope than is possible when using only one, and a large proportion of the fabrics produced in industry

5.23 Stitch notation in tricot knitting. (a) Open pillar, (b) closed pillar, (c) tricot stitch, (d) 2 x 1 closed lap, (e) 3 x 1 closed lap, (f) 4 x 1 closed lap, (g) open tricot stitch, (h) two-course atlas, (i) misslapping, (j) laying-in.
are made with two guide bars. The first group of fabrics to consider are those made with fully threaded guide bars, as many different effects may be obtained by altering the lapping movements and these effects may be increased still further by the use of colour, mixing different yarn, linear densities or using different yarn types, such as yarns with different dyeing characteristics, textured yarns, and so on.

5.7.3.1 Loop plating
With two fully threaded guide bars, each loop in the fabric will contain two threads, one supplied by each bar. The underlaps made by the front guide bar are plated on the back of the fabric and the loops from this bar are plated on the face of the fabric, whereas the loops and the underlaps formed by the back guide bar are sandwiched between those from the front guide bar (see Fig. 5.25). It will be observed from Fig. 5.20(c) that when the guide bars swing through the needles to form the overlap, the ends will be crossed on the needle hook (normally the two bars form overlaps in opposite directions). As the guide bars return to the front of the machine, the threads of the front guide bar are first to strike the needles and are wrapped around the needle hook first, whereas the back guide bar threads are placed later and above those from the front guide bar. If the tensions of the two warp sheets are similar and the heights of the guide bars are correctly adjusted, the front bar loops will always be plated on the face of the fabric. Any coloured thread in the front guide bar will thus appear prominent on both fabric surfaces, an important factor to be remembered in warp-knit fabric designing (see Fig. 5.25 for loop plaiting).
5.7.3.2 Different structures

The two guide bars may make their underlaps in the same or opposite directions. If made in the same direction, the fabric will show distortion similar to the single bar fabric (see Fig. 5.29(a)) as the loops will be inclined. If, however, the underlaps are made in opposite directions, an equal tension will be imposed in both directions, and loops will be upright.

The structure of the simplest fabric made with two guide bars is shown in Fig. 5.25 and is known as full tricot. The appearance of full tricot may be varied by threading the guide bars with different coloured threads to give vertical stripes of colour.

The most common fabric of all is locknit and its structure and the lapping movements are shown in Fig. 5.26. When correctly knitted, the fabric shows even rows of upright loops on the face of the fabric, and the two needle underlaps on the back of the fabric give a smooth sheen. It has a soft handle and is very suitable for lingerie. If the lapping movements for the bars are reversed to give reverse locknit, the fabric properties are completely changed (Fig. 5.29(e)). The short underlaps will now appear on the back of the fabric and will trap in the longer ones to give a more stable and stiff structure, with far less width shrinkage from the needles than ordinary locknit. The underlaps of the back guide bar may be increased to give even greater stability and opacity with practically no width shrinkage from the needles. An example of this is sharkskin, whose structure and lapping movements are shown in Fig. 5.27. Another stable structure is shown in Fig. 5.28, and is known as queenscord. The long back guide bar underlaps are locked firmly in the body of the fabric by the chain stitches of the front guide bar. Both sharkskin and queenscord structures can be made more stable, heavier and stronger by increasing the back guide underlaps to four or five needle spaces. The vertical chains of loops from the front
The guide bar may be used to give single wale vertical stripes of colour, such as pin stripes in men’s suiting.

If the guide bars making a sharkskin are reversed, that is, if the front bar makes the longer underlaps, the resultant fabric is known as satin which is a lustrous soft fabric similar to the woven satin. Because of the long floats on the back of the fabric,
satin laps are used to make loop-raised fabrics. The raising machine is set so that the underlaps are raised into loops without actually breaking any filaments. In order to achieve the maximum raising effect, the two guide bars in a loop-raised fabric are normally made to traverse in the same direction, and open loops may also be used. The lapping movements of three-needle satin are shown in Fig. 5.29(b) and those for a three-needle loop-raised fabric are shown in Fig. 5.29(a). The density and height of pile can be increased by increasing the front guide bar underlaps to four, five or six needle spaces.

Yarns may be introduced into the fabric without actually knitting. Figure 5.30 shows the structure lapping movements and pattern chains of a laid-in fabric. The laid-in thread is trapped between the loop and the subsequent underlap of the guide bar which must be situated in front of the laying-in bar. In order to lay-in a yarn, therefore, that yarn must be threaded in a guide bar to the rear of the guide bar (knitting bar), and it must make no overlaps. Laying-in is a useful device because a laid-in thread never goes round the needle, and therefore very thick or fancy yarns may be introduced into the fabric, such as heavy worsted yarn or metallic threads. Figure 5.31 shows the laid-in thread being trapped in the fabric by the front guide bar threads knitting an open tricot stitch (0-1, 2-1).

5.7.4 Grey specification of a warp-knitted fabric
A complete grey specification of a warp-knitted fabric should include the following details:

1. gauge of machine in needles per inch
2. number of guide bars in use
3. number of ends in each warp
4. types and linear densities of yarns used
5. run-in per rack for each warp
6. knitted quality of the fabric in courses per centimetre
7. order of threading in each guide bar
8. lapping movements of each guide bar during one repeat of the pattern or details of the pattern wheels or pattern chains
9. relative lateral positions of the guide bars at a given point in the lapping movements
10. any special knitting instructions.

5.7.5 Fabric quality
The main parameter controlling the quality and properties of a given structure is the run-in per rack, or the amount of yarn fed into the loop. Run-in per rack is
5.30 Laid-in structure.

5.31 Principle of laying-in.
defined as the length of warp fed into the fabric over 480 courses (1 rack = 480 courses). In two-guide bar fabrics, the run-in per rack for each guide bar may be the same or different, depending upon the fabric structure. For example, in full tricot structures (front: 1-2, 1-0 and back: 1-0, 1-2), it is normal to use the same run-in per rack from both beams or 1 : 1, whereas in three-needle sharkskin fabrics (front: 1-2, 1-0 and back: 1-0, 3-4), the run-in per rack required from the back beam would be more than the front beam say 1 : 1.66.

The run-in may be altered in two different ways, first by altering the total run-in of the bars, and second by altering the ratio or difference between the bars. Altering the total run-in will affect the finished number of courses per centimetre and hence the area density of the fabric, the stability and the cover, but not the general shape of the loop. Altering the difference between the guide bars will change the balance of the fabric, affect the inclination of the loops and, because it puts more or less strain on the individual yarns, change the strength.

Fabric take-up on the machine is adjusted to attain trouble-free knitting and also to effect ease of finishing.

5.7.6 Tightness factor
The tightness factor \( K \) of a knitted fabric is defined as the ratio of the fabric area covered by the yarn to the total fabric area. It is regarded as a measure of looseness or tightness of the structure, and influences dimensions such as the length, width, and thickness and many other fabric characteristics such as area density, opacity, abrasion resistance, modulus, strength and shrinkage.

If the tightness factor of a single-guide bar fabric is defined as in Equation 5.2

\[
K = \sqrt{\frac{\text{tex}}{l}}
\]  

(5.9)

where \( l \) is the stitch length, measured in millimetres, and tex is the yarn linear density, then the tightness factor of a two-guide bar, full-set fabric is given by Equation (5.10)

\[
K = \sqrt{\frac{\text{tex}_f}{l_f}} + \sqrt{\frac{\text{tex}_b}{l_b}}
\]  

(5.10)

where suffixes \( f \) and \( b \) refer to front and back guide bars, and \( l \) is the stitch length equal to (run-in/rack)/480 and is measured in millimetres. If the same tex is employed in both bars, then

\[
K = \sqrt{\text{tex} \left( \frac{1}{l_f} + \frac{1}{l_b} \right)}
\]  

(5.11)

For most commercial two-guide bar full-set fabrics \( 1 \leq K \leq 2 \) with a mean tightness factor value of 1.5.6

5.7.7 Area density
The area density of a single-guide bar fabric can be determined from Equation (5.12)

\[
\text{Mass of the fabric} = \text{cpc} \times \text{wpc} \times l \times T \times 10^{-3} \text{gm}^{-2}
\]

\[
= s \times l \times T \times 10^{-2} \text{gm}^{-2}
\]  

(5.12)
where $s$ is the stitch density ($\text{cm}^{-2}$) or ($\text{cpc} \times \text{wpc}$), $l$ is the stitch length (mm) and $T$ is the yarn tex.

Similarly, the area density of a two-guide bar full-set fabric would be Equation (5.13):

$$\text{Mass of the fabric} = s[(l_1 \times T_1) + (l_b \times T_b)] \times 10^{-2} \text{gm}^{-2}$$  \hspace{1cm} (5.13)

where suffixes f and b refer to the front and back guide bars. If the same tex is used in both guide bars, then the above equation can be written as Equation (5.14):

$$\text{Mass of the fabric} = s \times T \times 10^{-2}(l_1 + l_b) \text{gm}^{-2}$$

or

$$= s \times T \times 10^{-2}\left(\frac{\text{Total run-in}}{480}\right) \text{gm}^{-2}$$  \hspace{1cm} (5.14)

If the stitch density, that is, the number of loops $\text{cm}^{-2}$, stitch length in millimetres of the individual guide bars and tex of yarns employed in individual beams are known, the fabric area density can be readily obtained using the above equation in any fabric state, that is, on the machine, dry relaxed or fully relaxed.

The geometry and dimensional properties of warp-knitted structures have been studied by a number of researchers including Anand and Burnip.6

5.7.8 End-use applications of warp-knitted fabrics

Specification for tricot machines is:

- **Type of needle**: compound or bearded
- **Machine gauge**: from 18 to 40 needles per inch (E18–E40)
- **Machine width**: from 213 to 533 cm (84–210 inches)
- **Machine speed**: from 2000 to 3500 courses per minute (HKS 2 tricot machine operates at 3500 cpm)
- **Number of needle bars**: one or two
- **Number of guide bars**: from two to eight
- **Products**: lingerie, shirts, ladies’ and gents’ outerwear, leisurewear, sportswear, swimwear, car seat covers, upholstery, technical fabrics, bed linen, towelling, lining, nets, footwear fabrics, medical textiles.

Specification for raschel machines is:

- **Type of needle**: latch or compound
- **Machine gauge**: from 12 to 32 needles per inch (E12–E32).
- **Machine width**: from 191 to 533 cm (75–210 inches)
- **Machine speed**: from 500 to 2000 courses per minute
- **Number of needle bars**: one or two
- **Number of guide bars**: from two to seventy-eight
- **Products**: marquisettes, curtains, foundation garments, nets, fishing nets, sports nets, technical fabrics, curtain lace, power nets, tablecloths, bed covers, elastic bandages, cleaning cloths, upholstery, drapes, velvets, carpets, ladies’ underwear, fruit and vegetable bags, geotextiles, medical textiles.
References