one, nep removal increasing with increasing carding power. The subsequent gilling operations can reduce vegetable matter slightly but can also create neps. The configuration of the high-production semi-worsted cards, which are generally covered with rigid metallic wire, depends upon fibre type and characteristics, such as length and fineness, as well as upon the production rate required. A semi-worsted card typically has only one swift, with four or five sets of workers and strippers and usually twin doffers to ensure high production rates.\(^1\) Depending upon applications, they can be supplied with morel rollers, a burr roller on the licker-in, with a fancy, with an intermediate doffer and with one or two delivery doffers.

Carding is followed by two to three drawing operations, mostly using chain gills, preferably three if no roving operation is involved, so that a majority of trailing hooks enter the spinning frame as leading hooks. The first and/or second passages can be autolevelling. The sliver is then either attenuated further into roving or spun directly on a ring frame, where drafts can be as high as 300 in a multiple (e.g. three) drafting zone, the main drafting taking place in the final double apron drafting zone.\(^34\)

Correct fibre lubrication, for low fibre-to-metal dynamic friction, good fibre-to-fibre static friction and antistatic properties, is important. The optimum fatty matter content lies between about 0.7 and 1.2%.\(^35\) A regain of about 19.5% appears acceptable for carding. Atmospheric conditions of 23 to 24°C and 70 to 75% RH can be regarded as suitable for the processing of wool, while for spinning it is 21 to 25°C and 55 to 60% RH.\(^35\)

Elliott et al.,\(^35\) building upon the work of Richards and Batwin to develop the concept of ‘Total Carding Power’, describe a computer model based upon published empirical and theoretical studies, for simulating the semi-worsted processing of wool, which predicts how changes in scoured wool properties and processing variables affect yarn irregularity, breaking strength and bulk, spinning performance, card waste and card mixing power. They assumed that most fibre breakage occurred when fibres were withdrawn from tufts during opening. Maddever et al.\(^36\) reported on an Expert System which can be used to determine a suitable objective blend specification for the manufacture of wool carpet yarn by the woollen or semi-worsted routes, the fibre property specification depending upon the processing route, product specification and technical data.

### 6.5 Woollen processing system

#### 6.5.1 Introduction

The woollen system represents the shortest processing route for staple fibres, essentially entailing only two primary stages, namely carding and spinning, although there is an important preliminary stage involving blend-
ing, opening and lubrication. Yarns ranging in linear density from about 30 to 2000 tex can be spun on the woollen system. A woollen yarn is defined\textsuperscript{37,38} as a yarn made from any fibre processed on a card with at least two parts, and at least one intermediate feed, a condenser dividing the card web into slubbings or rovings, which are subsequently spun at drafts of up to 1.6 (or at most 2). Because spinning follows immediately after carding, the fibres are not very well aligned, and woollen yarns tend to be characterised by their bulkiness, low density, less orientated fibres, softness, low twist and hairiness. A ‘woollen yarn’ would normally refer to 100\% wool, whereas a ‘woollen-spun yarn’ would refer to a yarn spun on the woollen system but which contains other fibres.

Virgin wool represents a relatively low proportion of the total fibres processed world-wide on the woollen system, the bulk being materials such as noils, re-used and reprocessed wools, man-made fibres, cotton etc. It is a very versatile system and represents one of the major systems for processing noils and other forms of fibre waste and recovered fibres into yarn, although capital and labour costs relative to its productivity impact negatively on its competitive position, particularly for medium to fine yarns. The continuing trend towards lighter-weight fabrics has also impacted negatively on the woollen system, although the move towards a more informal or casual form of dress favours it. Purely from an economic point of view, woollen processing compares unfavourably with semi-worsted processing. Nevertheless, these systems generally process widely different fibres and also produce yarns very different in character. The advantage of the woollen system is that it can handle natural and man-made fibres of almost any type, fineness and length, it being stated that any fibre can be processed, ‘provided it has two ends’. In the case of wool, the woollen system handles from lambswool, 19\,\text{\textmu}m or even finer, to Shetland and crossbred wools 35\,\text{\textmu}m and coarser. In the main, fibres ranging in mean fibre length from about 25 to 80\,mm\textsuperscript{33} are processed on the woollen system. The wool processed on the woolen system is also referred to as carding wools (e.g. crutchings, locks, lambs and skirtings), generally having staple lengths ranging from about 30 to 50\,mm. Woollen carding generally requires a low level of vegetable matter, vegetable matter adversely affecting carding and spinning, and it is important that only wool with little, if any, vegetable matter is processed on this system. This can be achieved by carbonising, a large proportion of wool processed on the woollen system being carbonised. Atmospheric conditions of 65\% RH and 20\,\textdegree C are normally acceptable for processing wool on this system.

### 6.5.2 Pre-carding

Good opening and cleaning of the wool prior to carding are beneficial, the pre-carding operation generally involving blending, opening (willeying) and
lubrication (oiling and antistatics). The blending operation, crucial for achieving quality woollen yarns and products, can be either manual or automatic, generally employing ‘sandwich’ (horizontal) layers and ‘vertical slice’ removal. Bin blending is still widely used for wool although various improved feeding and bin-emptying methods (e.g. automatic and continuous) have been introduced, with continuous inclined step blenders of increasing importance. It is vital that the components of the blend be similar in their degree of openness, composition and density. WRONZ applied the concept of linear programming (computer blending) for optimising wool blends for spinning carpet yarns, taking into consideration the relevant wool characteristics, such as diameter, length, bulk, medullation, colour and vegetable matter content.39

The Fearnought (coarse metallic toothed roller) type of machine, automatic or hand-fed, for example, is widely used for opening and blending, particularly at the final willeying (opening) stage prior to carding. It imparts a carding (fibre working) action, tufts being partially opened by the action of the fast moving cylinder and slower moving worker teeth, there often being four workers. Some fibre cleaning also takes place. Oiling/lubrication, generally takes place here, preferably at the exit, which is more effective, does not lead to the contamination of the Fearnought and does not interfere with its cleaning efficiency.

6.5.3 Lubrication (oiling)

The effectiveness and efficiency of woollen carding, and in particular fibre breakage, are dependent upon various factors, notably fibre lubrication. It is critically important that the wool is optimally lubricated prior to carding in order to minimize fibre breakage, fly waste and static electricity, provide additional fibre cohesion and facilitate drafting, condensing and spinning. Between about 5 and 10% of oil is usually applied, either as a straight oil or preferably a 50/50 oil/water emulsion, the card generally being key in the even distribution of the lubricants/additives.

Lubricants are used to:40

- Reduce static, fibre breakage and friction against the condenser rubber
- Lubricate the fibres for drawing and twisting
- Increase fibre cohesion
- Control the rate of build-up of trash on the card.

The essential requirements of a wool lubricant are as follows:

- Must have good lubrication and anti-static characteristics in carding and spinning within the temperature ranges experienced
- Should not discolour the wool
- Should not impair the strength of the fibre
• Must not cause rusting or corrosion of the clothing (surfaces) with which it comes into contact
• Should not reduce the life-span of the leather aprons or condenser tapes
• Should form a stable and uniform emulsion with soft or moderately hard water
• Must remain stable in storage under various conditions of temperature
• Must be easily removed by scouring
• Should not cause or support spontaneous combustion
• Should not have or create an objectionable odour.

A further requirement today is that the lubricants should be environmentally friendly (e.g. bio-degradeable).

6.5.4 Carding

Because of the very shortness of the woollen processing route, the carding stage is critical and the woollen card is very sophisticated, particularly when relatively fine yarns are being produced. The card web needs to be uniform, both in terms of fibre blend and density (mass), across its width and along its length. The card needs to separate (individualise) and mix the fibres and this requirement largely determines the number of carding units.\textsuperscript{42} The production of a woollen card is greatly dependent upon its width, which can vary from 1 to 4 m (typically around 3 m), and the fineness of the fibre being processed, increasing the card production rate tending to cause a deterioration in slubbing and yarn quality and nepiness. Neps increase as the wool becomes finer, carding rate increases and number of swifts decrease. Over the years there has been little real improvement in the basic productivity of the worker, stripper, swift and doffer actions, increased production largely coming from the increased width of the card.

Uniform feed, by a feed hopper, to the card is very important in terms of productivity and web and yarn quality, notably evenness. Feed can be manual, semi-automatic or automatic. The hopper feeds the tufts of fibres to the card, the aim being as uniform a feed of fibres as possible (in terms of both composition and weight), often achieved by weighing or otherwise monitoring and controlling the tufts and their rate of supply to the card. Automatic hopper feeds can provide either ‘weigh’ (gravimetric) or volumetric ‘chute’ delivery, with or without control systems, the latter entailing monitoring, correcting and controlling. There has been a significant move to chute feed-hoppers, hopper-fed via spiked lattice or automatically from a bin. Examples of advanced feed control systems are the \textit{Tathams Microweigh 2000} system for a weigh hopper feed and the \textit{Microfeed 2000} and \textit{HDB Servolap} for volumetric chute hopper feeds. Double hoppers, microprocessor-controlled hoppers and volumetric feeds with autolevellers
provide good long-term evenness, although some medium- and short-term variation remains.41

The composition of the woollen card (Fig. 6.8) depends upon the type of fibres to be processed, as well as the range of yarn linear densities to be produced, the card generally consisting of between two and seven units, typically four, each with a swift. The two-card set, with an intermediate feed, is becoming increasingly popular.

The major differences between woollen carding sets are as follows:

- Number of Sections
- Number of Swifts
- Number of Workers per Swift
- Type of Intermediate Feed
- Type of Condenser
- Type of Card Clothing

As shown in Fig. 6.8, a typical woollen card essentially consists of two parts or sections, namely the scribbler (breaker card) and carder (finisher card), there typically being two or three cylinders (swifts), each with a doffer (and four or five pairs of worker and stripper rollers each) in each section. The density of card clothing pinning increases along the machine, thereby increasing the opening of the fibre tufts correspondingly. Typically, the carding unit is made up of a breast section clothed with metallic wire with two workers and strippers; this is where the opening and disentangling of tufts commences. From the scribbler the sliver is fed, crosslapped (cross-
fed) to improve blending, to the next section, i.e. to the carder. Various combinations of metallic and flexible card wire are supplied with woollen cards, the combinations depending upon the nature of the fibre being processed. Because of the high levels of oil used, flexible wire clothing, as opposed to metallic wire, was traditionally used on woollen cards, but there has been a significant move towards rigid metallic wire (garnett) clothing, the early part of the card (feed and breast sections) having been metallic for many years. Metallic wire is used extensively for synthetics and well-scoured coarse wools, semi-rigid or fillet wire being more popular for relatively ‘greasy’ and fine wools, although even in the case of fine wools there is a move towards metallic wire, particularly for the scribbler section (A G Brydon, private communication).

After the scribbler, the fibrous web can be passed through crush (‘Peralta’) rollers. The Peralta hardened steel rollers (precision ground and perfectly set) at the end of the scribbler section, crush vegetable matter, such as burr, in the open fibre web, the smaller crushed particles being easier to remove. The much finer fibres are not damaged to any significant extent.

On a woollen card there are typically around 15 to 30 positions where a carding or working action (closely set point-to-point) takes place, which breaks down the tufts into individual fibres, a typical fibre passing through such an action between 100 and 300 times. Fibre separation (working) generally takes place where two card-clothed surfaces, set closely to each other and the teeth pointing towards each other, move at different speeds. The stripping action occurs when a faster moving roller, with the clothing tips pointing in the direction of movement, removes all the fibres from the backs of the teeth of a slower moving roller.

Fibre opening takes place at the interfaces between the feedrollers and licker-in, the swift and the workers, and the doffer and swift, being completed when the fibre reaches the last swift of the scribbler section. The main opening at the swift–worker interface is due to the combing action of the swift wires on the tufts of fibres held by the slower moving workers. Work by WRONZ has modelled fibre breakage on the basis of fibre tensile properties and the mechanics of tuft opening. In addition to fibre separation, during which process significant fibre breakage takes place, the carding operation is also crucial for blending (mixing) the fibres, the collecting power of the doffer playing an important role in this respect. According to Richards, the Delay Factor (D), or time constant, which is a measure of the average time that fibres take to pass through a part (excluding time on doffers), may be calculated as follows:

$$D = \frac{1}{f} \left( 1 + \sum np / (1 - p) \right)$$  \[6.12\]
where
\[ f = \text{collecting fraction of the doffer} \]
\[ p = \text{collecting fraction of the worker} \]
\[ n = \text{number of swift revolutions during which the fibre spends on a worker, stripper and swift from when it is picked up until it is released again.} \]

In the case of four workers this becomes:

\[ D = \frac{1}{f} \left( 1 + \frac{4np}{1-p} \right) \]

\[ C \text{ (Carding Power)} = \frac{1}{f} \left( 1 + \sum 1/1 - p \right) \]

C, a measure of the card–opening ability and determined by the average number of times a fibre passes through the setting region between swift and workers and swift and doffer, is the same as the average number of workings (t) received by a fibre as derived by Montfort. Carding power increases as the delay factor increases.

The Intermediate feed (intermittent or continuous) transfers the output of the one carding machine (section) to the next, the objectives being:

- to convert the fibres emerging from the one carding section into a convenient form for transfer to the next carding machine or section
- to reduce irregularities in the rate of flow of fibres through the card
- to improve fibre blending
- to produce a uniform shade where fibres of different colours are involved

Examples of the different types or combinations of feeds are:

- Pull-away Centre-Draw and Cross Feed
- Wide Side-Draw and Cross Feed
- Pull-away Centre-Draw
- Scotch Feed (finer yarns)
- Parallel-Fibre Feed (bulkier fibre and coarser yarns)

The pull-away centre-draw, reciprocating overhead and Scotch feed is considered to offer a simple, yet effective, operation. The Scotch feed is popular as it is simple, versatile and convenient for small lots. The wider cards have resulted in a move away from the side-draw Scotch feed system to centre-draw cross-feed and broad-band or parallel-fibre feed systems.

The Condenser divides the web of fibres emerging from the last (final) carding machine into a number of continuous ribbons, consolidates these ribbons into cylindrical, twistless slubbings and winds the slubbings onto individual cheeses positioned side by side on condenser bobbins (posi-
tioned in a creel) for transfer to the spinning frame. There are two different methods of condensing, namely by Ring Doffers or by Tape Condensers, the latter being more common. Ring Doffers (single or double) separate the web into ribbons by a carding action, producing strong, straight and uniform slubbings while Tape Condensers (Series or Endless) separate the web into ribbons by a tearing action. Tape condensers can be offered with single (fine yarn), tandem/double (medium yarns), or triple (coarse yarns) rub arrangements. Tape condensers are generally manufactured with four or six heights (tiers), the latter increasing the production and number of ends, or the end spacing, and package size. Condenser rubbing leathers, used for condensing the narrow strip of materials, are made in various designs; leather aprons have largely been replaced by either grooved or smooth fabric/rubber/synthetic aprons. A well-rubbed slubbing has good cohesion and wraps onto the condenser bobbin well and unwinds easily and cleanly during spinning, different creel assemblies being used for mule spinning and ring spinning creel assemblies including Ordinary, Traverse and Tandem. Doffing of the condenser bobbins can be either manual or automatic, being one of the most costly operations in woollen processing. Automatic doffing can increase card productivity by up to 12%.

Two systems are available to increase the length of slubbings (by up to 50%) on the condenser spool, thereby extending the time cards, and spinning frames can run between creel changes. They are the Tatham’s Denspak Creel System and the High Density Spooling (HDS) System. The latter was first shown at ITMA in 1987, utilising friction in a groove and a difference in the surface speed of the bobbin/spool and the rubbing apron to create controlled tension and drafts (about 6% actual), enabling increased card production. It also has a beneficial effect on spinning performance and yarn properties.

Optical- and capacitance-based devices are used to automatically monitor the evenness of the slubbings or rovings at the output of the card, between the rub apron and the package. One such system (Rovingtex), using a capacitance measuring system, has an alarm should the values exceed preset limits. Open and closed loop automatic controllers are used to correct variations in card web mass per unit area. Automatic setting of the machine when changing slubbing weight (linear density) is also available. The use of electronics for control and automation has been one of the main areas of development, it now being possible to electronically programme and control the main functions of the woollen card.

Significant fibre breakage takes place during carding, the amount of fibre breakage depending upon factors such as fibre entanglement, fibre lubrication (friction), fibre strength, fibre length, fibre crimp, fibre regain and the severity of the carding action.
6.5.5 Woollen spinning*

Although ring frames dominate woollen spinning, the mule frame still occupies an important position. The ring frame produces about 2.5 times per spindle more than the mule frame and occupies about a third of the floor-space per spindle. The mule can, however, spin lower twist, bulkier, softer, more even and less hairy yarn, and can handle more difficult fibres and blends than the ring frame. Mule spinning enables finer yarns to be spun than ring spinning, due to the lower tensions involved and the advantages of spindle drafting over roller drafting, drafts often being about 5% higher. Mule spinning, however, is more labour intensive and requires greater operator skills than ring spinning.

It is generally accepted that commercial woollen spinning limits are about 100 fibres (125 being more typical) in the yarn cross-section, compared to 40 for worsted spinning, Lee22 suggesting a minimum of 120 per strand for two-ply yarn and 200 for singles yarn. In woollen spinning, draft (normally at least 1.2 but less than 1.6, with a maximum of 2) is usually effected against twist, its main function being to straighten rather than to relatively displace the fibres.

6.5.5.1 Ring spinning

A false twist device in the drafting zone close to the front rollers, inserting about 80 to 160 turns/m (typically 40% of the spindle speed), reduces the strand irregularity by preferentially drafting thick places with low twist, since twist generally runs into thinner places thereby increasing inter-fibre cohesion. Drafting is affected by the orientation of the hooks in the slubbing, best being when the slubbing is fed with the majority of hooks trailing, a draft of around 1.5 appearing to be desirable. Collapsed balloons (e.g. using a spindle top extension probe or finger or else a modified spindle top) have become popular and rings with diameters of up to 300 mm are used, traveller speeds peaking at around 40 m/s.

Automation in ring spinning, e.g. automatic doffing of full packages, fitting of new tubes, replacing slubbing packages, joining of slubbings, underwinding, stopping and restarting, represent notable developments.

Automatic doffing reduces labour and improves productivity, and so have end-break detectors and monitors that allow rogue spindles to be identified, 3 to 4% of such spindles often being responsible for 30 to 40% of end breaks. Information on traveller, roller and spindle speeds enables yarn production and twist to be determined by monitoring systems, such as the Uster

*Note: See also Section 6.6 Spinning
Ringdata. Electronic console adjustment of the various spinning operations and parameters is also possible.

6.5.5.2 Mule spinning

This system of intermittent spinning was invented by Samuel Crompton in 1774, the self-acting mule being patented by Roberts in 1825, and is now virtually only used for spinning fine woollen yarns (woollen mule) from woollen slubbings. The mule frame, utilising draft-against-twist, comprises two parts: a fixed part (headstock) and a moving part (carriage) that moves backwards and forwards on rails (although in some cases, the carriage remains stationary while the headstock moves, while in others, both systems move). The operation of the woollen mule consists of the following five stages (Fig. 6.9):

i) Slubbing Delivery: The carriage moves forward at approximately the same speed as the slubbing is delivered and the spindles rotate at a slow speed to insert twist into the slubbing.

ii) Drafting: At this stage the delivery rollers stop but the carriage continues to move and the spindle continues to rotate at the same speed, thereby causing a draft-against-twist of the twisted slubbing.

iii) Final Twist Insertion: At this stage the carriage is stationary at its most forward position but then moves slightly towards the stationary delivery rollers to compensate for yarn shortening due to the twist, and the spindles are now rotating at full speed to complete twist insertion (the faller wires out of operation).

iv) Backing-off: With the carriage stationary, the spindle now rotates in the opposite direction, thereby unwinding the yarn remaining on the spindle when twisting stopped. The winding faller is lowered and the counter faller raised so as to take-up the slack in the yarn, the winding faller being level with the nose of the cop.

v) Winding-on: The carriage returns towards the rollers to assume its original position at the start of the cycle; the spindles rotate to wind the yarn onto the cop under the guiding of the winding faller.

Today, electronic (computer-controlled), totally-automated self-acting Mule spinning frames are produced, modern examples attaining speeds of 15 to 18 m/min and featuring automatic doffing, fitting of empty tubes, yarn tension control, slubbing replacement and piecening, the complete cycle taking less than four minutes.

6.5.5.3 General

Woollen yarn properties can be predicted from the wool fibre properties, very much as is the case for worsted yarns. On the basis of their
processing trials on 68 wool lots, and using multiple regression analysis, van der Merwe and Gee\textsuperscript{47} established empirical relationships between on the one hand, carding and spinning performance and yarn and knitted fabric performance, and on the other hand, fibre properties. They showed that mean fibre diameter and its CV were the most important fibre properties influencing processing performance and yarn and fabric properties. The next most important property was fibre bulk resistance to compression followed by mean fibre length. An increase in either mean fibre diameter or
CV of diameter, more specifically the former, in most cases had an adverse effect on carding performance and yarn properties. An increase in bulk resistance to compression had an adverse effect on yarn and fabric strength, fibre breakage during carding, fabric abrasion resistance and spinnability but had a beneficial effect on yarn extension, bulk and hairiness and on cross-card variation. An increase in mean fibre length, within the ranges covered, generally had a beneficial effect. A ‘length after carding’ test has also been developed in which a small scale card and double draft gill system are used to convert the scoured wool into a sliver suitable for Almeter fibre length measurement.\textsuperscript{50} It correlates well with actual results.

### 6.6 Spinning

#### 6.6.1 Introduction

The ultimate aim of spinning is to produce yarn (i.e. a coherent and cohesive fibre strand) of the required linear density (count) and which has good evenness, tensile properties and a minimum number of faults.

Spinning can be divided into the following three basic operations:

- i) Attenuation (drafting) of the roving, sliver (semi-worsted) or slubbing (woollen) to the required linear density.
- ii) Imparting cohesion to the fibrous strand, usually by twist insertion.
- iii) Winding the yarn onto an appropriate package.

Spinning machines can be divided\textsuperscript{1} into two main groups, namely intermittent (e.g. mule) and continuous (e.g. ring, flyer, cap, open-end, self-twist, twistless, wrap-spinning). It should be noted that wool is not commonly spun on the open-end (rotor) spinning system, although a recent paper\textsuperscript{51} indicates progress in this direction, 42 tex to 111 tex yarns being spun successfully from 20.5\textmu{}m wool at speeds of around 100 m/min. Nevertheless, the wool has to meet very strict requirements in terms of residual grease levels (0.1 to 0.3\%) and fibre length; for example, an average fibre length of 30 to 40 mm is required for a 46 mm rotor diameter, with the longest 1\% of fibres not exceeding about 60 mm.

#### 6.6.2 Ring spinning

Because of its versatility in terms of yarn linear density and fibre type, and also the superior quality and character of the yarn it produces, ring spinning (Fig. 6.10) remains by far the most popular system for spinning wool, particularly for fine yarns, there being some 16 million long-staple ring spindles installed worldwide. It includes two-strand and compact/condensed type spinning.