1 Introduction

1.1 General Remarks [1–3]

Natural fibers, especially wool and natural silk, have existed for several thousand years, soon to be followed by cotton, flax and the like. Their processing and usage have continuously been developed. Within one hundred years the chemical fibers and within only fifty years the synthetic fibers have improved their standard from originally being "substitute products" to recently providing about 50% of the total fibers consumed. It was a long way from the first ideas by *Hook* (1664) and *Réaumur* (1734) to the first chemical fibers [4] that were produced by *Nicolaus de Chardonnet* (1884). In 1898 in Oberbruch near Aachen, *Paul Fremery*, *Bromert* and *Urban* produced the first cooper silk filaments that after carbonization were used as incandescent filaments in light bulbs. The first fully synthetic fiber would be produced based on an idea by *Klatte* (1913) from polyvinyl chloride. *Staudinger* [6] succeeded first in 1927 under laboratory conditions to spin a fully synthetic fiber from polyoxymethylene and later from polyethylenoxide from the melt [7]. 1938 *Carothers* developed the first polycondensation fiber that was produced as Nylon by the company DuPont de Nemours & Co. Just one year later *Schlack* [10] proved that lactam can be polymerized, what resulted 1939 in Berlin-Lichtenberg in the first Perlon® fiber production. Soon IG-Farben-Industrie obtained a license for the melt spinning process for Nylon and transferred it to Perlon. After 1934 research was conducted in Germany that allowed the first semi-technical production of polyacrylonitrile fibers (PAN) during 1940 to 1943 [12, 13]. Almost simultaneously and independently of the German developments similar work was done at DuPont, so that the patent registrations almost have the same dates. Already 1950 DuPont started in the Candem plant full scale production of polyacrylonitrile fibers, what was not possible in Germany until much later. The commercial production of polyester follows around 1950 after an invention by *Whinefield* [52], and so does polypropylene around 1958 as developed by *Natta* [15]. These are the fibers that today are produced worldwide in tremendous quantities.

The development of specialty fibers began 1937 with polyurethane by *O. Bayer* et al. [14], followed by a wide range of fibers. Only Nomex® [16] and Kevlar® [17], both by DuPont, will be mentioned here. The development of high-grade carbon fibers did not begin until 1966 with the oxidation and carbonization of PAN filaments. More on this topic can be found with *Klare* [18] and *Elias* and *Vohwinkel* [19].

Many of the developed fibers could not be commercialized, e.g., fibers from polyaminotriazoles, where the pilot production was discontinued around 1965. The production of PA 7 in the USSR was discontinued due to the insufficient supply of oenanthe acid. PA 4 was too difficult to spin. Quiana® was commercialized in 1968, but in view of investments in the range of DM 600 million and the significant funds of DuPont it was discontinued in 1977, because the fiber was too expensive [20].

1.2 Conditions for the Production of Textile Fibers

Textile yarns or technical yarns and fibers have to fulfill certain characteristics that are primarily determined by the end use, and in the case of textile products also by climatic conditions. They need to be inexpensive, and it must be possible to produce them in sufficient quantities and consistent quality. In the fiber state it must be possible to blend them with other fibers.

The properties of textile fibers are primarily determined by their chemical structure, their degree of polymerization, the orientation of the chain molecules, their crystallinity, the packing density, and the cross links between individual chain molecules. In general they consist of threadlike long chains of mixed cells or stretched macromolecules etc. that are arranged more or less parallel to the fiber axis and pass through crystalline and amorphous areas. Figure 1.1 shows three models:

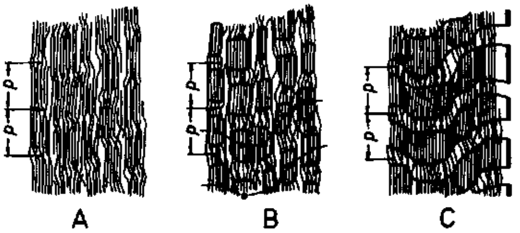


Figure 1.1
Schematic diagram of a super molecular fiber structure (according to *Hess* and *Kiessig* [21, 22]
A) Five fibrils with neighboring amorphous and crystalline regions of period *P*
B) Developed from A) to a para-crystalline macro grid (according to *R. Hosemann*)
C) Change to a para-crystalline layer grid with chain refolds

(A) amorphous and crystalline areas are arranged along the length of the fiber with the period P; (B) shows the same model in a further development towards the para-crystalline macro grid and (C) the transformation to the para-crystalline layer grid with chain refolds [21, 22]. These stages can be shown by X-ray or by differential thermo-analysis (DTA) or similar methods [23]. Cotton for example has about 60% crystallinity, viscose rayon only about 40%. The degree of crystallinity is also dependent on the temperature. PA 66 has about 75% crystallinity at 20 °C, about 52% at 85 °C, about 40% at 100 °C, and about 0% at 120 °C.

In the melt, the chain molecules have almost no orientation. When they cool during the spinning process they become a little pre-oriented. For solution spun fibers, e.g., hydrate cellulose, this pre-orientation can already be increased during the coagulation in the spin bath. Melt spun fibers, however, require a specific draw process—either in a continuous process after cooling under the glass transition temperature, or in a second separate process at a suited temperature. This drawing and orienting change the tenacity and elongation of the fibers considerably: For viscose rayon for example the tenacity increases from 1.5 to about 6.3 g/dtex (Super-Tyrex®) with a reduction in breaking elongation from about 30% to about 10%. The tenacity of PA can be arranged by drawing between values of 3 and 10 g/dtex with an elongation between 40% and 10%. Likewise this can be done with other synthetic fibers. Only filaments from liquid crystals are wound during melt spinning in a fully oriented state. Thus the fiber producer can vary orientation, tenacity and elongation depending on the material and process.

Fiber tenacity also depends on the degree of polymerization of the chain molecules. *Staudinger* [24] found that for native cellulose there is no change in tenacity with $P \geq 500$; between 500 and 200 the tenacity drops significantly with the degree of polymerization, and for $P \approx 200$ disappears. *Marsh* [25] found that high polymer fibers need a degree of polymerization of $P > 80$ to have any tenacity at all; it then increases significantly until $P \approx 250$, and increases insignificantly to $P < 600$ and not at all beyond that point. For this the distribution of chain length is important [26] as well as for many other properties. The distribution of density is also relevant for the properties: Viscose rayon has a significantly denser packed zone near the shell; the packing density of PA 6 increases with increasing draw ratios [27].

The average degree of polymerization (= average molecular weight/molecular weight of the base molecule) for cotton is around 3000, for normal cellulose 600–800, high quality cellulose and cotton linters 800–1300, viscose fibers 250–700, cupro fibers 500–600, acetate 220–300, polyamide 100–180, polyester 130–220, acrylic fibers 1000–2000, PVC fibers 1300–1800 [51], and can reach for high molecular PE for gel spinning about 160,000.

The formula schematics in Fig. 1.2 for PA 66 and in Fig. 1.3 for natural silk are an example for how much specific synthetic fibers look like natural fibers. For more examples see [30]. The main valences respond to the links along the length of the fiber. They contribute the majority of the fiber tenacity; this was already expressed by the dependence on the degree of polymerization. But the side valence links across the fiber direction provide the stability of the network. When these links are missing or loosened by heat and/or swelling a shifting of the chains can happen [27]. These cross links influence the hand and drape of textile materials. When comparing the schematics of PA 66 and natural silk it can be noticed that the cross links always appear between the oxygen atoms of the carboxyl groups and the NH-groups of the neighboring chain. For PA 66 every 100 chain atoms only have 14 amid groups and thus 14 hydrogen bridges = side valence links, whereas for natural silk each 100 chain atoms have 50 hydrogen bridges. PAN also has for each 100 chain atoms 50 hydrogen bridges. For PET the cross links are of a different nature due to the rings included in the chains: The ester group is linked through side valences to the neighboring CH_2-groups [28]. Due to the spherolites formed during the spinning of polymers the relation is more complex than shown here in the most simplistic idealization. Details can be found in [23].

Consequently and according to the studies of *Ulrich* [29] the following conditions make a fiber useful for production and industrial use as a textile material:

1. Raw materials must be available or produceable in sufficient quantities and for reasonable prices.
2. Existing methods must allow processing of these raw materials to polymers and then to filaments or fibers without high cost or damage to the environment.
3. The intermediate and final products must have sufficient continuity in terms of quality and quantity.
4. The final price of the yarn made from the fibers or filaments must be bearable for the market.
5. The fiber has to be either endless and possibly capable of being textured or must be capable of being processed in a mechanical spinning process, and must fulfill the following requirements:
   a) The resulting yarn has to show sufficient tenacity and elasticity, and the inital elastic modulus may not be too low.
   b) For textile applications the staple length should not be too low and somewhat uniform or within a desired distribution. For paper like products, reinforcements, and flock fibers, uniform staple lengths are required.
   c) The fibers have to provide a certain degree of friction among each other.
   d) Flexibility and elasticity are relevant for the mechanical spinning and subsequent processes.
   e) The fiber (dpf) determines the lowest titer of the yarn as well as the hand, breathability, comfort etc.

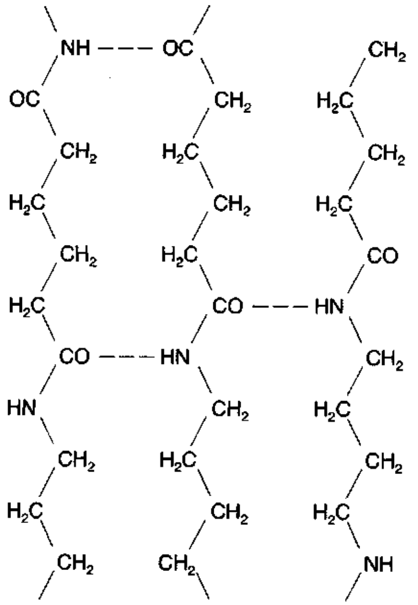


Figure 1.2 Schematic diagram of the structure of polyamide 66 (according to *Brill*)

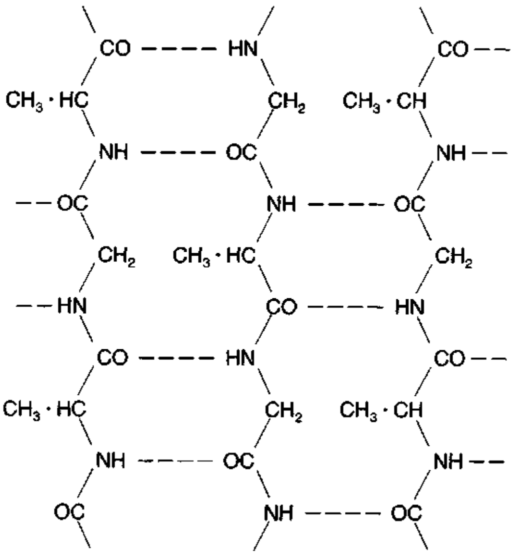


Figure 1.3 Schematic diagram of natural fiber structure: Silk (according to *Brill*) with polypeptide chains in the crystalline regions

Preface

One hundred years of chemical fibers, and of these more than fifty years of synthetic fibers, do demand an inventory of the required technologies. While there is literature for the chemistry of the chemical and synthetic fibers, as well as for the processes and the textile testing technology, it is hardly possible to find comprehensive descriptions from installation, equipment and machinery manufacture through production of synthetic fibers and filaments and the manipulation of their properties.

The first book "Synthetic Fibers" was published in 1954 with about 160 pages and a world production of about 200,000 t/year at that time. The revised second edition from 1964 with 950 pages covered the total area of production through processing. The annual production of synthetic fibers had increased to 1.7 million t/year by then. Today, approximately 20 million t/year are produced accounting for about 45% of the world fiber production. The technical progress connected to this also requires a new edition which addresses only the first third of the topics covered in the 1964 book on 900 pages.

Further reasons for the new edition are: At the European universities only Chemnitz and Zurich maintain a department for the design of machines and equipment for the production of synthetic fibers. Textiles taught within the framework of mechanical engineering departments of other universities focuses primarily on textile engineering, while the training of the engineers is left to the specific industries. Thus this becomes an issue for about 1200 fiber production companies and over 1000 machinery makers, without having a comprehensive overview available. Many of the design elements are also unknown in the general mechanical engineering. Drive problems, auxiliaries preparation and conditions for auxiliary plants, as well as mathematical–physical and process technological items are explained in many examples.

The corresponding electro and micro-processing technology, automation and computer-integrated manufacturing are not covered in this book, as this would exceed the given frame.

This book is separated into a part on material specific processes, the corresponding installations, machines, and process data. In a further part the designs and calculations are introduced, also for different materials and varying function parameters.

The second to last chapter on fiber properties and their manipulation by Mr. Peter M. Latzke reflects a change in thought over the last 20 years: While the fiber user back then used to receive data sheets on the specific properties of a shipment, today's fiber producers have to keep all agreed upon properties constant for all future shipments and influence their production accordingly to stay within given tolerances. Production control thus has been replaced by process control that simply supervises the production parameters. Accordingly, quality systems have been specified in DIN, ISO, etc. Finally, the numerous conversion factors are shown and the fiber property ranges demonstrated according to a fiber table by Kleinhansl. Following the wish of practitioners to show most connections in measurable sizes, the author uses numerous drawings, diagrams, tables, and formulas and only a limited number of photos. He does want to point out though, that the installations, machines, and parts in the drawings have been built and installed in praxis.

This book provides a large number of diagrams, data, and companies names, but it does not expect to be complete or exclusive. There are certainly more companies producing similar or equal products; they should not feel neglected. Very often production is done according to individual ideas and guidelines, which can also result in optimum products.

1.3 The Most Important Fiber Raw Materials

Table 1.1 shows most of the presently used fiber materials that can be categorized by:

- Synthetic Fibers:
  - Polymerization Fibers
  - Polycondensation Fibers
  - Polyaddition Fibers
- Chemical Fibers (from natural polymers)
- Inorganic Fibers
- Natural Fibers
  - Animal Fibers
  - Vegetable Fibers

The selection and terminology reflect mostly to the Textile Identification Act and the respective regulations in the European Community.

Table 1.1 The Most Important Synthetic, Chemical, and Natural Fibers, Their Raw Materials and Production Methods

1. *Fibers from synthetic polymers*
   a) polymerization fibers
   b) polycondensation fibers
   c) polyaddition fibers
2. *Chemical fibers (from natural polymers)*
3. *Inorganic fibers*
4. *Natural fibers*
   a) animal fibers
   b) vegetable fibers
   c) mineral fibers

P = production
M = modification
S = specific characteristics
T = end-uses, trade names

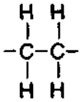
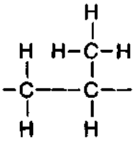
1a) Polymerization fibers		
Polyethylene (PE)  $-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-$ $K = 2$ $M = 42$; $DP > 62{,}500$ $T_M = 107 \ldots 138°C$ $T_G \approx -100°C$ $(-20\% - 30°C)$	– LLDPE and HDPE are well spinnable and drawable (figure 5.6) due to short and few side chains (figure 2.89)	Chapter 2.4, see fiber table Chapter 11
Polypropylene (PP)  $-\overset{H}{\underset{H}{C}}-\overset{H-\overset{H}{C}-H}{\underset{H}{C}}-$ $K = 2$ $M = 42$; $DP > 45{,}000$ $T_M = 160 \ldots 165°C$ $T_G \leqslant 5°C$	– P: only well spinnable and hot drawable with > 97% isotactic parts (Chapter 2.4.1.3)	CH 2.4.1; see fiber table Chapter 11

Table 1.1 The Most Important Synthetic, Chemical, and Natural Fibers *(Continued)*

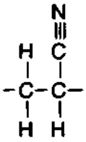
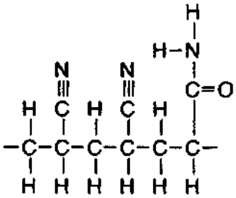
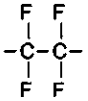
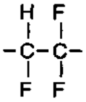
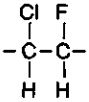
Polyacrylonitrile (PAN)  $-\overset{H}{\underset{H}{C}}-\overset{N\equiv C}{\underset{H}{C}}-$ $K=2$ $M=53$; $DP > 1070\ldots2500$ $T_M >$ T (decomposition) $T_G=0°C$ (≈95°C, dry)	– P: polymerization of ≥85% ACN + comonomers, precipitation, drying, solving dry or wet spinning and aftertreatment, especially for staple fibers. Also continuous polymerization in solution for direct wet spinning possible (e.g., in $ZnCl_2$/water)	Chapter 2.5, see fiber table Chapter 11
Modacrylic (PAM)	– P: ACN-portion 50…84% (According to ISO), rest comonomers, e.g.:  $-\overset{H}{\underset{H}{C}}-\overset{N\equiv C}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-\overset{N\equiv C}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-\overset{H_2N-C=O}{\underset{H}{C}}-$	Chapter 2.7; see fiber table chapter 11
Polyvinylchloride (PVC) $-(CH_2 \cdot CCl_2)-$ $K=2$ $M=97$; $DP \approx 800\ldots1000$ $T_G=75°C$ $T_M=160 \div 200°C$ and	– P: Acetone + Chlorhydroxide → vinylchloride → polymerization to polyvinylchloride: possible post chlorinating with tetrachlorcarbon	Chapter 2.6; see fiber table chapter 11
Polyvinylidene chloride (PVDC)	– P: Ethylene or vinylchloride → vinylidene chloride etc. – M: e.g., "Saran"	
Polyfluoride (FL) e.g.,  $-\overset{F}{\underset{F}{C}}-\overset{F}{\underset{F}{C}}-$ $M=100$; DP: $10^3\ldots10^5$ $T_G=127 \div 140$ $T_M=327 \div 342$ (decomposed: 399°C)	Polytetrafluoroethylene (PTFE)  $-\overset{H}{\underset{F}{C}}-\overset{F}{\underset{F}{C}}-$ Polytrifluoroethylene (PTFE, e.g., "Hostaflon")  $-\overset{Cl}{\underset{H}{C}}-\overset{F}{\underset{H}{C}}-$ $M=82$ Polyvinylfluoride	Chapter 2.9, see fiber table chapter 11
$K=2$	$M=80.5$	
aliphatic fluorocarbon fibers	– P: e.g., polymerization of tetrafluoroethylene; special spinning processes	
Vinylal	Paraffin polymers with OH-groups on every second C-atom of the main chain, partially acetyled; e.g., polymerization of vinyl alcohol and solving in water – wet spinning.	

Table 1.1 The Most Important Synthetic, Chemical, and Natural Fibers *(Continued)*

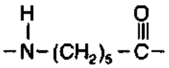
Trivinyl	Paraffin polymers with nitril groups or one or two Cl-atoms at every second C-atom; e.g., mixed polymerization of acrylonitrile and two other vinyl components, e.g., vinylchloride and vinylidenchloride with 50%; solving in acetone and wet spinning.	
Elastodien	Paraffin polymers with methyl branches and sulfur bridges to neighboring chains; e.g., polymerization of isoprene and dienes with or without vinyl monomers; or starting with natural latex; cutting vulcanized thin rubber plates into narrow stripes or extrusion of latex emulsion (Latex) respectively benzene-rubber solution through spinnerets; wet spinning; vulcanization of the coagulated and dried filaments.	
1b) Polycondensation fibers		
Polyamide 3 (PA3) $-CH_2=CH(OC\cdot NH-$ $-CH_2\cdot CH_2)_n-NH_2$ $K=4$ $M=71$ $T_M=165°C$	– P: Head-tail polymerization from acryloamide with alkaline catalysts or from chlorcyan and N-carbosulfamide acid chloride + olefins → sulphochloride groups → β-lactam (III) for polymerization. – T: thus far no technical production and application	
Polyamide 4 (PA4) $-NH-(CH_2)_3-C:O-$ $K=5$ $M=85$ $T_M=200-265°C$ $T_G=76°C$	– P: Polycondensation at 265°C → vacuum drying → melt spinning drawing; very difficult, because $t_{spin}=t_{decomposition}-2°C$ – S: good textile properties, but to date not commercial due to P; $\gamma=1.25\ g/cm^3$	Chapter 2.2.2
Polyamide 5 (PA5) $-N\cdot H-(CH_2)_4-C\cdot O-$ $K=6$ $M=99$ $T_{M,\ theoretical}=300°C$ $T_{M,\ in\ praxis}=259°C$ $\text{for n}\ \frac{30°C}{m-cresol}=0.25$	– P: only successful in laboratory scale. – T: none – S: $\gamma=1.2$	
Polyamide 6 (PA6)  $-\overset{H}{\overset{\vert}{N}}-(CH_2)_5-\overset{O}{\overset{\Vert}{C}}-$ $K=7$ $M=113;\ DP>100-200$ $T_M=215°C$ $T_G=40\ldots42°C$	– P: Crude oil → benzene → cyclohexanon → ε–aminocaprolactam → pressure free polycondensation at 275°C…260°C during about 18 h with an approximate yield of 88%; past condensation possible; possible to melt spinning; up to about 40 dtex final denier with air quench, for ≥65 dtex spinning titer (≥0.08 mm diameter) with water quench; can be drawn	
Polyamide 7 (PA7) $N\cdot H-(CH_2)_6-C:O-$ $M=113;\ DP>100$ $T_M=233°C$	– P: Ethylene (at 100 bar with radical formers) → tetrachloralkane → ω-chloroethane acid → ω-amino oenathe acid → pressure free polycondensation → PA7; can be melt spun and drawn; almost no monomers or oligomers – S: good properties for textile and technical applications, $\gamma=1.10\ g/cm^3$ – T: very short production around 1960 discontinued due to high raw material cost	Chapter 2.2.3, see fiber table chapter 11

Table 1.1 The Most Important Synthetic, Chemical, and Natural Fibers *(Continued)*

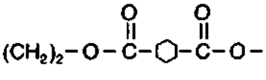
Polyamide 8 (PA8)	$T_M = 209°C$; $\gamma = 1.08\ g/cm^3$	
Polyamide 9 (PA9)	$T_M = 200°C$; $\gamma = 1.06\ g/cm^3$ No applications	
Polyamide 10 (PA10)	$T_M = 188°C$; $\gamma = 1.04\ g/cm^3$	
Polyamide 11 (PA11) $N \cdot H-(CH_2)_{10}-C \cdot O-$ $M = 169$, $DP \cdot 100$ $T_M = 190°C$	– P: Castor oil (over 5 steps) → aminoundecan acid → polycondensation from aqueous suspension over 3 steps in a tube, then evaporation, polycondensation, then reaching the condensation equilibrium: $\eta_{265°C \approx 600...100\ P;\ \gamma - 1.04}$ kg/cm^3; can be spun and drawn like PA6 – S: Similar to PA6 and PA66, but only minimum moisture absorption, dimensionally stable – T: Zippers, ropes; too expensive for textiles	
Polyamide 12 (PA12) $N \cdot H-(CH_2)_{11}-C{:}O-$ $M = 183$; $DP > 100$ $T_M = 179°C$	– P: Butadiene-trimerization → 11-aminoundecan acid → Laurinlactam → almost 100% polymerization; direct spinning possible – T: especially for coarse deniers and wires; no textile applications yet; $\gamma = 1.01\ g/cm^3$	Chapter 2.2.5.5
Polyamide 46 (PA46)	– P: from 1,4 diaminobutane (DAB from ACN and watercyanid) and adipic acid	Chapter 2.2.5.1
Polyamide 66 (PA66) $NH-(CH_2)_6-NH-CO-$ $-(CH_2)_4-CO-$ $K = 14$ $M = 226$; $DP > 80...200$ $T_M = 250...252°C$ $T_G = 42°C$	– P: hexamethylendiamin adipate in aqueous solution is polycondensated at approx. 285°C and spun continuously or via chips and then drawn – S: well dyeable similar to PA6; partially better properties than PA6 $\gamma = 1.14\ g/cm^3$	Chapter 2.24; see fiber table chapter 11
Polyamide 610 (PA610) $NH-(CH_2)_6-NH-$ $K = 18$ $M = 254$; $DP > 100$ $T_M = 215°C$	– P: with Sebacic acid (from castor oil), rest similar to PA66; polycondensation at 245...260°C – S: best wet tenacity PA	Chapter 2.2.5.2
Quiana $T_M = 260...275°C$ $T_G = 135°C$	– P: polycondensation from Bis-(4-amino-cyclohexyl-)-methane (from Anilin and formaldehyde) and dicarbonic acid with 9...14 C-atoms – S: excellent textile material: best crease recovery – T: Production (DuPont) discontinued due to high cost $\gamma = 1.03...1.04\ g/cm^3$	
Polyester (PES)	– Common name for polymers from dicarbonic acid or dicarbonic esters and glycoles	
Polyethylene terephthalate (PET)  $K = 10$ $M = 192$; $DP > 100...200$ $T_M = 257...264°C$ $T_G = 70...75°C$	– P: from DMT + EG via transesterfication or from TPA + EG via direct esterification to diethylene glycol (DEG) and polycondensation at ≥285°C to PET; spinning via continuous melt processing or via chips dried to ≤0.004% H_2O; hot drawable – S: excellent for technical use and textile yarn, staple fiber	

Table 1.1 The Most Important Synthetic, Chemical, and Natural Fibers *(Continued)*

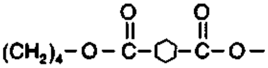
Polybutylene terephthalate (PBT)  $K = 12$ $M = 284$; $DP \geq 100 \ldots 200$ $T_M = 225°C$ $T_G = 440°C$	– P: similar to PET but from butylene glycol + DMT or −TPA; polycondensation temperature about 250°C – S: good textile properties; can be dyed carrier free – T: higher cost than PET	Chapter 2.3.7
Polyurea	– linear macromolecule with repeating functional groups (–NH–CO–NH–) – P: polycondensation of urea with aliphatic diamines; melt spinning	Chapter 2.8.7
Aromatic polyamides (Polyaramides) with meta structure (molecules in ring arrangement) $T_{(Decomposition)} = 371°C$ $T_G = 280 \ldots 290°C$ M = 192; DP = 220...260	– P: m-phenylene diamine and isophthalic acid chloride is solution polymerized in DMAC, neutralized and directly dry spun. – S: $\gamma = 1.38$ – T: Nomex (DuPont), Conex (Teijin)	Chapter 2.11.2, Fiber table chapter 11
Aromatic PA with parastructure $M = 278$; $DP = 550$	– P: phenylene diamine and terephthalic acid chloride are polycondensated and disolved in concentrated sulfuric acid and wet spun – S: $\rho = 1.44$ – T: Kevlar (DuPont), Twaron (Akzo)	
Super absorbent products (SAP)	– P: from hydrogen-aryl and -alkal and/or hydrolyzed polyacrylo amides – S: moister absorbency of up to 230g/g fiber, salt water absorbency of up to 50g/g fiber – T: disposable diapers	see chapter 2.12.5
Polyaryletherketones $M = 288$ (PEEK)	– P: condensation of acid chlorides under Friedel–Kraft conditions produces low molecular –(R)–O–(R)–COCl; with HF as a solvent and BF_3 as a catalyst high molecular compounds are formed for extrusion processing – S: see figure 2.124 – T: Victrex (ICI)	
1c) Polyaddition fibers		
Polyurethane (PUR)	– linear macromolecule from paraffin chains that are connected by the urethane group –NH–CO–NH– – P: polyaddition of diisocyanates and dioles, e.g. hexamethylene diisocyanate and 1,4 butandiol; melt spinning	
Elastan (EL) (also "Spandex") ≥85% segmented PUR	– P: polyaddition of a linear dihydroxy polyester (e.g. polyethylene glycol adipate) or a dihydroxy polyether (e.g. polytetramethylene etherdiol) with excessive diisosyanate and chain lengthening or cross linking with diamino compounds (e.g. diamines) in solvents (e.g. DMAC or DMF) for direct dry or wet spinning; also reactive spinning possible with a reaction of the prepolymer in the coagulating bath with diamin. Melt spinning in development, possible with similar yarn properties.	

Table 1.1 The Most Important Synthetic, Chemical, and Natural Fibers *(Continued)*

1.2 Chemical fibers (from natural polymers)		
Viscose rayon (CV) Hydrate cellulose $DP = 300-500$ (High tenacity: 400–500)	– P: Cellulose with a high o-portion is changed with soda lye to alkali cellulose and then with carbon disulfide to cellulose xanthogenate; Dissolving in diluted soda lye, maturing, and spinning into a sulfuric acid/water bath for coagulation; washed repeatedly and de-sulfured (if possible), dried. Continuous process and winding process produce Rayon filament, cut wet into staple and drying produces staple fiber.	See fiber table chapter 11
Cupro (CUP) Hydrate cellulose $DP = 300-400$	– P: Dissolving cellulose in cupperoxide ammoniac → wet spinning (funnel spinning process), washing, drying and winding or cutting – T: Only produced in four location around the world because more expensive than CV	See fiber table chapter 11
Modal (CMD) Hydrate cellulose $DP \Rightarrow 300$	– P: Modified viscose process with wet spinning	
Acetate $2\frac{1}{2}$ cellulose acetate $P_m = 250–400$	– P: Acetylizing of cellulose with acetic acid, partial saponification; dissolving in acetone; primarily dry spinning; endless winding or cutting to staple fiber	See fiber table chapter 11
Triacetate (CTA) Cellulose-3-acetate $P_m = 300–400$	– P: Acetylizing of cellulose with acetic acid → dissolving in dichloromethane → dry or wet spinning, drying and winding	
Protein fibers (casein) *Zein or other vegetable proteins* *PROT (Protein)*	– P: Casein precipitated with acid or lab ferment from milk and dissolved in soda lye → wet spinning → stabilizing → drying – P: Extraction of Zein (e.g., from corn flour) → precipitation and dissolving in soda lye or extraction of peanut press cake with diluted lye → dissolving and wet spinning etc. – T: For some time was wool substitute and blending fiber; not stabilized used as release yarn in knitting	
Alginate fibers metal alginates (ALG)	– P: Extracts from (sea) alga → alginic acid → dissolving in diluted soda lye → wet spinning and stabilizing in metal salt baths, e.g., NaCl	
1.3 Inorganic fibers		
Glass fibers (GF) primarily low alkali Bor silicate glass, e.g., about 52% SiO_2 about 11% B_2O_3 about 14% Al_3O_3 and about 17% CaO	– P: Melting of ground mixture of quartz sand and additives at 1400 … 1600°C; spinning by jet draw or jet blow or centrifugal process (all gravimetric or by rod draw process – T: Endless glass filament or staple (glass wool)	See fiber table chapter 11
Basalt fibers	– P: Clean whinstone by melting twice and pouring into cold water → cast into crucible from PtRh, melt and draw gravimetric to filaments at over 3000 m/min and wind; "rock wool" spun directly from first melt by jet blow or centrifugal process	Chapter 2.13.4

Table 1.1 The Most Important Synthetic, Chemical, and Natural Fibers *(Continued)*

Metal fibers *(MTF or MT)*	– P: Coarse rolled wire from metals or alloys are drawn in several steps through draw plates or draw stones with thermal treatment between steps until the desired fineness has been reached; e.g., for 1.4571 drawing up to a diameter of 1 μm is possible.	See fiber table chapter 11
Carbon fibers *CF* > 90% pure C	– P: Primarily from post drawn PAN fibers, but also CV or PVAL fibers 3-step process: Stabilizing (= oxidation) → carbonization → graphitization	Chapter 5.7; see fiber table chapter 11
1.4 Natural fibers **1.4a) Animal fibers**		
Wool (WO) *keratin*	– fineness: 2–50 dtex see figure 1.4	See fiber table chapter 11
Alpaca (keratin) Hair (wool) of the alpaca (type of camel)	– P: Shearing Earlier also re-used wool from rags, that contained vegetable fibers, which were removed by carbonization	
Lama (keratin) Hair (wool) of the lama (type of camel)	– P: shearing	
Camel (keratin) Base hairs of camels and dromedaries more than 10 cm in length, lightly curled, light red to yellow brown, or the beard hair dark brown to black	– P: Hairs fall out in bundles in spring – T: Best qualities for yarns for underwear, lower grades for "press cloth"; weather proof coat fabrics	
Cashmere (keratin) Hair of the cashmere goat, off white, low crimp, silky shine, very fine, beard hair coarser	– P: Combing out or pulling in spring – S: Very soft hand, appreciated as wool, also in blends with wool – T: Fine yarn ladies' dress cloth 3-ply filling yarn (Nm 50 to 60 worsted yarn, 40 ... 80 ppcm), knitting yarn	
Mohair (keratin) Up to 150 mm in length, strong, simple hair of the true angora goat	– P: Shearing (once or twice per year)	
Angora (rabbit) *(keratin)* Primarily pure white, fine and soft hairs; beard hairs coarser	– P: Several shears per year, or combing and pulling in spring and fall – T: Felts, very shiny mohair yarns, etc.	
Vicuña (keratin) Hair (wool) of the Latin American mountain lama (type of camel)	– P: Shearing after corralling	
Yak (keratin) Hair of the Tibetan ox	– P: Shearing	
Guanaco (keratin) Hair of the Latin American guanaco (mountain lama, type of camel)	– P: Shearing after corralling	

Table 1.1 The Most Important Synthetic, Chemical, and Natural Fibers *(Continued)*

Hair (keratin) Other animals (especially horse hair)	– P: Shearing or cutting of tail hair – T: Upholstery, filling materials, etc.	
Silk (SE) *(Natural or Mulberry silk)* $P_m \approx 2500$	– S: Fibroin (silk substance 70…80%) → Sericin (silk bast, 3 layers, 19…28% → fat substance (0.5…1%) → mineral components (0.5…1%)	See fiber table chapter 11; schematic in figure 1.3
1.4b) Vegetable fibers		
Cotton *(CO, also Bw)* Native cellulose $M = 162.14$ P_m (raw) ≈ 7000 $P_m \approx 6500$	– Fineness depending on origin 1… ≈4 dtex; figure 1.4	See fiber table chapter 11
Flax, linen (LI) Bast layer of the up to 1 m long flax plant fiber length 600…700 mm yield 45…55% cellulose $P_m \approx 8000$	– P: Pulling of the plant (linum usitatissimum) when starting to yellow; after drying and removing the seed bolls, retting removes the bast fibers from the wood, breaking and hackling → tow → line	See fiber table chapter 11
Hemp (cellulose) Bast fiber of the hemp plant (cannabis sativa) of up to 3 m height Color: off white, silver or pearl gray, greenish or yellowish, lighter is usually better	– P: Similar to flax, but also pulled when green between breaking and hackling usually some scutching or cutting – M: Bast hemp is broken hemp; pure hemp after removing impurities; strand hemp is broken and scutched, stone or spin hemp is ready to be spun, ground hemp is made by peeling the bast from the stem – S: Much higher tenacity than LI (and LI higher tenacity than cotton) – T: Coarse yarns, twisted or plied or braided ropes, tars depending on origin, Galician, Polish, French etc. split hemp is particularly fine	
Abacá (cellulose) Leaf stalk fiber (from the leaf stem) of the fiber banana, musa textilis, also Manila) fibers are yellow-white or brown, shiny, stiff, and weatherproof	– P: Manual or mechanical pulling of the fiber bundles (possibly after rotting) from the leaf flesh, drying and hackling; or by use of a defibreur – M: Long hemp yarns $\mathrm{Ne} \geq 0.65 = \mathrm{Nm} \geq 0.39$ spun, hemp tow yarns $\mathrm{Ne} = 0.39 \ldots 10$; finest fibers by stamping in a mortar for fine fabrics – T: Ropes, netting, cable wrap, saddle thread, twine	
Alfa (cellulose) Leafs (stalks of the esparto grass (stipa tenacissima)	– P: Two year old stock dried after harvest, boiled to destroy the chlorophyll, retting in running water, separate from other matter with wooden clubs	
Coco (cellulose) Fruit fiber between the shell and the core of the coconut	– P: After braking the outer layer solving of the fibers from the inner nut, months of retting in a mixture of fresh and salt water, removing of the fiber coat by beating, scutching and pressing; drying, hackling. The combings are pulled by gear teeth and are cleaned, bleached, dried and mechanically spun. – S: Highly resistant to weather and mechanical wear – T: Rope, twine, mats, runners, foot mats, etc.	

Table 1.1 The Most Important Synthetic, Chemical, and Natural Fibers *(Continued)*

Sisal (cellulose) Leaf fiber of the agave sisalana (Mexico) fiber yellow white, shiny, resistant against humidity	– P: Mainly mechanical pressing to separate the flesh from fibers and rinsing, centrifuging, and drying – T: Twine, rope, coarse fabrics, crimped for upholstery
Jute (cellulose) Bast fiber of the East Indian jute plant (corchorus capsularis and oliotorius) fibers of 2–3 m length lighter color: better brands	– P: Harvest by cutting above the water level, water retting, removal of the bast coat by hand, washing and drying – M: Best type: Serajgunge (fine fiber, good color), Narajgunge (slightly lower quality), Daisee (very fine, but undesirable dark), Dacca (hard, brittle, but pure color), Dowrah (coarse, hard, short, wood like and dark brown); cuttings are mechanically separated roots, lowest grade jute – S: Yarns of 0.06…4.2 Nm – T: Woven fabrics (burlap, carpet backing, wall coverings, etc.) ropes, cable
Kenaf (cellulose) Stalk bast fiber of the kenaf plant (hibiscus cannabinus)	– P: Cold water retting, similar to hemp
Ramie (cellulose) stalk bast fiber of the ramie plant (bohemia nivea, member of the nettle family $P_m \approx 6500$	– P: The 1.2…2 m stalks are separated from wooden portions (no retting possible) → stiff gummed bast → degumming by soaking in caustic soda, then washing, bleaching, drying – M: Chinese type white, Indian type greenish – S: Softer and more flexible hand than flax, very fine, elastic, shiny, high tenacity – T: Rare, in linen, lace, etc.
Broom (cellulose) From the South European broom (spartium coparius)	– P: Chemical retting from the stalks of the plant – S: Fine, brownish, soft, but high tenacity – T: in blends with flax and hemp tow for ropes and coarse fabrics, with reed fibers can be blended for coarse woollen yarns
Asbestos Magnesium or iron silicates weathered minerals serpentine (chrysotile) and hornblende (amphibole) Processing illegal due to risk of cancer. Only natural mineral fiber	– P: Mining (surface or underground); gentle separation of the fibers from stone – M: Depending on mining site: Canada (Thedford and Black Lake) Siberia (Perm and Irkutsk) and type: Crocidolite or blue asbestos, Chrysolite or white asbestos, Amosite and Tremolite asbestos – S: High resistance to heat and acids, low heat and electric conductivity high splittable and splits by itself until floating in air and hazardous to lungs and breathing. – T: Past: Insulation material, in blends with cement for construction felts. – Due to cancer risks the production and use in no longer allowed

Further detailed properties of selected fibers can be found in chapter 11 “Fiber Table” at the end of this book.

1.4 Economic Development

Between 1900 and 1960 the production of chemical fibers increased from practically zero to about 3 million tons p.a. (i.e. an annual increase of about 50,000 tons. Then it increased to about 21 million tons p.a. until 1990 (i.e. an annual increase of about 600,000 tons p.a.). In 1946 the activities of the synthetic fiber industry were limited to three corporations with a total production of 21,000 tons p.a. on a semi industrialized scale and remained tied to the chemical fiber industry until 1960. In 1960 its worldwide production was 700,000 tons p.a. After that the fast growing production was partially independent of the chemical fiber industry and reached about 18 million tons p.a. in 1990, an average annual increase of about 580,000 tons. Figure 1.5 (graphs d–e) shows that the increase from 1960 on was almost exclusively due to synthetic fibers, while the production of chemical fibers and natural fibers remained almost constant—see also Table 1.2 [30, 33]. Also the number of production facilities for synthetic filaments and fibers increased from 511 in 1965 to about 1300 in 1985 (Table 1.3), while there were only 166 chemical fiber plants left.

The expansion of the synthetic fiber industry did not happen continuously. It was interrupted by several recessions around 1973 and 1981 as well as in 1991/93 (Fig. 1.6), where in some cases the production capacities even had to be reduced.

This overall development was caused by:

- the tremendous increase in the world population from about $3 \cdot 10^9$ in 1960 to about $5.3 \cdot 10^9$ people in 1990, or an increase around 1990 of 1.8% p.a.;
- the continuously increasing demand for textiles by individuals from about 5 kg/year and person in 1960 to about 8.0 kg/year and person in 1990 (Fig. 1.7). There are however significant regional differences from about 1 kg/year and person in Central Africa to about 24 kg/year and person in the USA;
- since 1980 the increased demand in home furnishings and technical textiles;
- the limits in agriculturally useable area that limits the increase of natural fiber production.

Figure 1.7 also shows that the per capita consumption since 1960 could only increase because of the synthetic fiber production (curve c).

This allows some conclusions with respect to the annual investment volume of the synthetic fiber industry. If the average lifetime of an existing production facility is assumed to be 20 years, 5% need to be re-invested annually, i.e. today for about 1.1 million tons p.a. Investment for expansion needs to be added, and according to Fig. 1.8 these additional capacities range from 0 to 1.6 million tons p.a. This

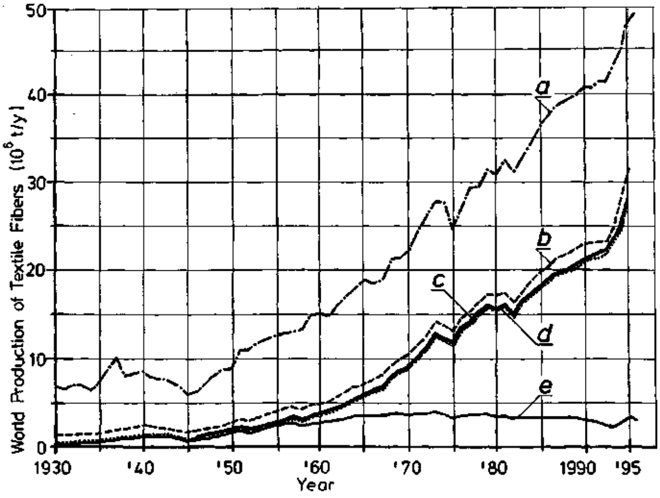


Figure 1.5
World production of textile fibers
a) Total
a)–b) Cotton
b)–c) Wool
c)–d) Silk
d)–e) Synthetic filaments and fibers
e) Chemical filaments and fibers (mainly hydrocellulose and acetate)

Table 1.2 Global Production of Different Textile Fibers (1000 t/a)

Year	World population	Rayon and acetate			Synthetic							Natural fibers									Synthetic total[7] %a[6]
		filaments	fibers	total	PET-	PA-	PAN	Olefins	others	total	%[5]	Cotton	%	Wool	%	Raw	Silk	%	Total	%[5]	
					fibers and filaments																
1890	–	–	–	–	–	–	–	–	–	–	–	2720	79	726	21	12	0.3	32458	100	3458	
1900	1.550	0.9	–	0.9	–	–	–	–	–	–	–	2165	81	730	19	17	0.4	3912	100	3913	
1910	1.686	5.4	–	5.4	–	–	–	–	–	–	–	4320	84	810	15.7	23	0.4	5153	99.9	5158	
1920	1.811	14.5	–	14.5	–	–	–	–	–	–	–	4470	84	808	15.2	27	0.5	5305	99.7	5320	
1930	2.070	205	3.2	208	–	–	–	–	–	–	–	5480	81	1000	15.3	52	0.8	6532	96.9	6740	
1940	2.295	541	585	1126	–	5	–	–	–	5	0.1	6230	73	1135	13	59	0.7	7424	86.8	8555	
1945		402	200	602	–	17	–	–	–	17	0.3	4320	72	1040	17	11	0.2	5371	89.7	5999	
1950	2.516	872	739	1611	≈ 10	70	–	–	~2	82	0.9	6220	69.3	1060	11.8	19	0.2	7299	81.2	8992	
1955	2.757	1043	1252	2295	≈ 82	266	30	–	~10	388	3.1	8740	69.4	1263	10.0	29	0.2	10032	79.7	12715	−12.6
1960	3.019	1142	1465	2607	≈ 119	407	105	–	~70	701	4.7	10250	69	1440	10	30	0.2	11690	78.1	14998	−24.3
1965	3.324	1372	2074	3446	≈ 469	~1040	388	≈80	≈100	2077	11.0	11884	62.9	1484	7.8	32	0.17	13400	70.8	18923	−19.4
1970	3.693	1391	2194	3585	1635	1924	1010	338	140	5047	22.8	11784	53.0	1659	7.5	40.8	0.18	13484	61	22116	−10.0
1975	4.076	1148	2068	3216	3357	2462	1418	716	165	8118	32.9	11343	46.1	1578	6.4	45	0.18	13346	54.1	24680	−7.4
1980	4.453	1130	2392	3522	5066	3234	2048	1048	210	11606	37.9	13872	44.9	1599	5.2	53	0.17	15524	50.6	30652	−1.4
1982	4.586	967	2227	3194	5097	2913	1977	1048	260	11295	36.5	14738	47.4	1624	5.2	55	0.18	16417	53.4	30906	−9.0
1984	4.763	959	2428	3387	6065	3342	2352	1312	340	13411	39.4	15528	45.2	1672	4.9	55	0.16	17255	50.2	34053	−5.5
1986	4.917	934	2307	3241	6959	3411	2456	1723	380	14929	40.2	17181	45.6	1684	4.5	56	0.15	18921	51.0	37091	−7.7
1987	5.024	915	2371	3286	7581	3645	2478	1909	460	16073	41.6	17494	44.7	1731	4.4	56	0.14	19281	49.9	38640	−4.4
1988	5.112	950	2421	3371	8041	3793	2428	1994	520	16776	42.4	17552	43.9	1764	4.4	57	0.144	19373	49.0	39520	−3.6
1989	5.201	927	2415	3342	8425	3901	2340	2141	580	17387	41.9	18733	44.7	1933	4.6	66	0.16	20732	50.0	41461	−0.5
1990	5.292	864	2351	3251	8578	3812	2224	2227	640	17481	42.2	18714	49.2	1964	4.6	66	0.16	20744	50.0	41440	−3.0
1991	5.384	793	2068	2861	9208[1]	3617[2]	2466[3]	2300[4]	720	18311	443.4	18650	44.2	1934	4.6	67	0.16	20651	49.0	42162	−3.0
1992	5.477	676	2039	2715	9803	3612	2408	2280	760	18863	44.7	18758	44.5	1793	4.2	67	0.16	20618	48.9	42196	−3.0
1993	5.572	656	2029	2685	10209	3696	2388	2160	790	19341											−2.5

Remarks:
Filament (%): [1] 46 [2] 83 [3] 0.2 [4] [5]
Staple Fibers (%): [1] 54 [2] 17 [3] 99.8 [4] 98[5]
[5] including about 65,000 t foil yarns and fibers
[6] of total[7]

The numbers vary in the literature by about 5%, because the basis on production, demand, sales, or end-use are usually not defined; foil yarns and fibers are based on estimates.

Table 1.3 Number of Producing Firms by Production and Region

Year	Region	Acetate	Rayon	PAN	PA	PET	Others	Σ	PP*
1965	Western Europe	15	80	21	61	28	27	232	18
	Eastern Europe	9	47	13	30	13	6	118	3
	North America	11	20	9	42	22	19	121	38
	South America	8	14	2	23	15	1	63	1
	Asia	11	37	15	33	21	26	143	21
	Africa	–	3	–	3	1	–	7	1
	Total	54	201	60	192	100	79	684	82
1975	Western Europe	12	50	26	76	57	16	237	121
	Eastern Europe	–	26	7	12	10	3	58	10
	North America	9	10	10	50	55	18	152	74
	South America	8	13	4	39	33	2	99	45
	Asia	6	34	16	63	67	22	208	45
	Africa	–	2	–	2	3	–	7	1
	Total	35	135	63	242	225	61	761	296
1985	Western Europe	12	25	30	91	66	19	206	117
	Eastern Europe	–	33	10	19	20	3	52	18
	North America	8	7	12	44	44	10	125	104
	South America	8	9	6	60	50	4	137	52
	Asia								
	Oceania	6	56	21	85	131	19	318	61
	Africa	–	2	–	3	7	–	12	3
	Total	34	132	79	302	318	55	920	355
1990	Western Europe	7	21	18	71	56	14		118
	Eastern Europe	4	41	8	24	21	4		20
	North America	5	5	8	48	48	12		99
	South America	6	4	4	37	36	3		48
	Asia								
	Oceania	9	58	28	75	124	3		65
	Africa	–	3	1	8	15	–		4
	Total	31	132	67	263	300	36	829	354

*) Polypropylene spinning facilities, usually smaller capacities of about 10 . . . 100 t/24 h.

means that equipment manufacturers for the chemical and synthetic fiber industries have to adjust to deliveries between 1.1 and 3.7 million tons p.a. within an 8 to 9 years cycle. These numbers closely match those of engineering firms and equipment manufacturers [34]. In 1990 engineering firms built 39 installations worldwide with a combined capacity of 0.8 . . . 0.9 million tons p.a. Using average capacities of production units these capacities for 1990 equal 14 large staple fiber units with about 100 tons p.d. and 50 to 100 filament units with 20 . . . 10 tons p.d. and 36 compact spinning units of each 14 tons p.d. These numbers also allow the conclusion that there are approximately 280 staple fiber units and between 2200 and 1100 filament units currently producing.

Figure 1.8 demonstrates the production development from 1970 to 1990 by the three major polymers and for 1990 also by regions. Table 1.4 also shows the production development by regions, and Table 1.2

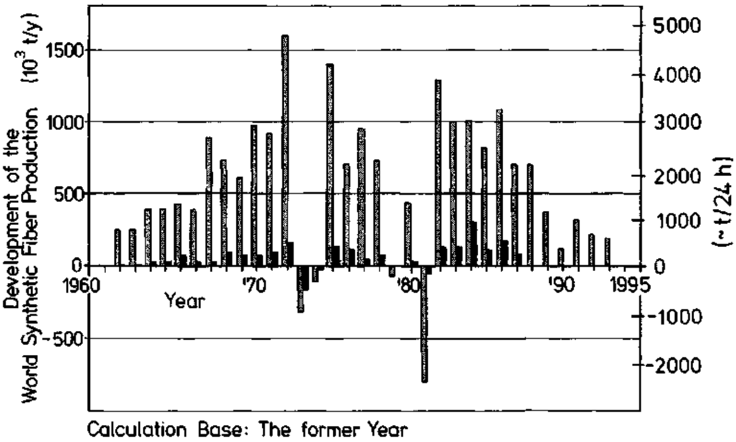


Figure 1.6 Annual increase or decrease of synthetic fiber production as an indicator for the annual investment rate

the breakdown by filament and staple fiber for the most important polymers. Not mentioned in Table 1.2 are polyolefines, where staple fibers and BCF make about 90% of the production.

The stagnation of synthetic fiber production in the highly industrialized countries does not mean that the industry is being reduced in those regions. Only the production of commodity items is being moved to the low cost countries, while in Western Europe, the USA and Japan more high tech fibers are being produced—low quantities relative to the total production, but with a high production value.

At the same time one tries to reduce production cost by using ever bigger units and more automation. This is only possible as long as companies in the rest of the world, e.g., Taiwan and South Korea, do not

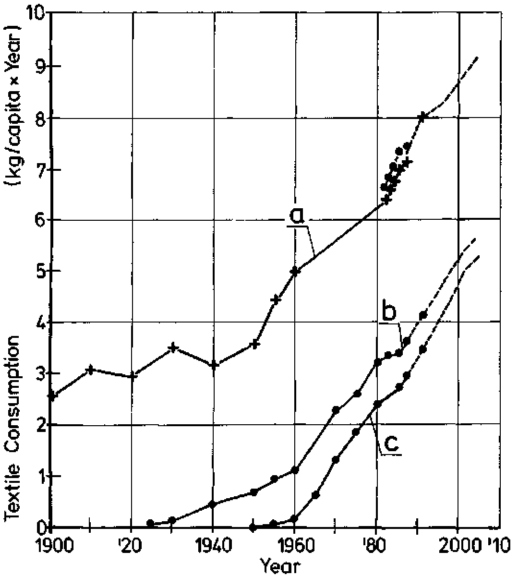


Figure 1.7
Average textile consumption in the world per person and year (since 1900 [38])
a) Total consumption
b) Chemical fibers (mainly cellulosic)
c) Synthetic fibers

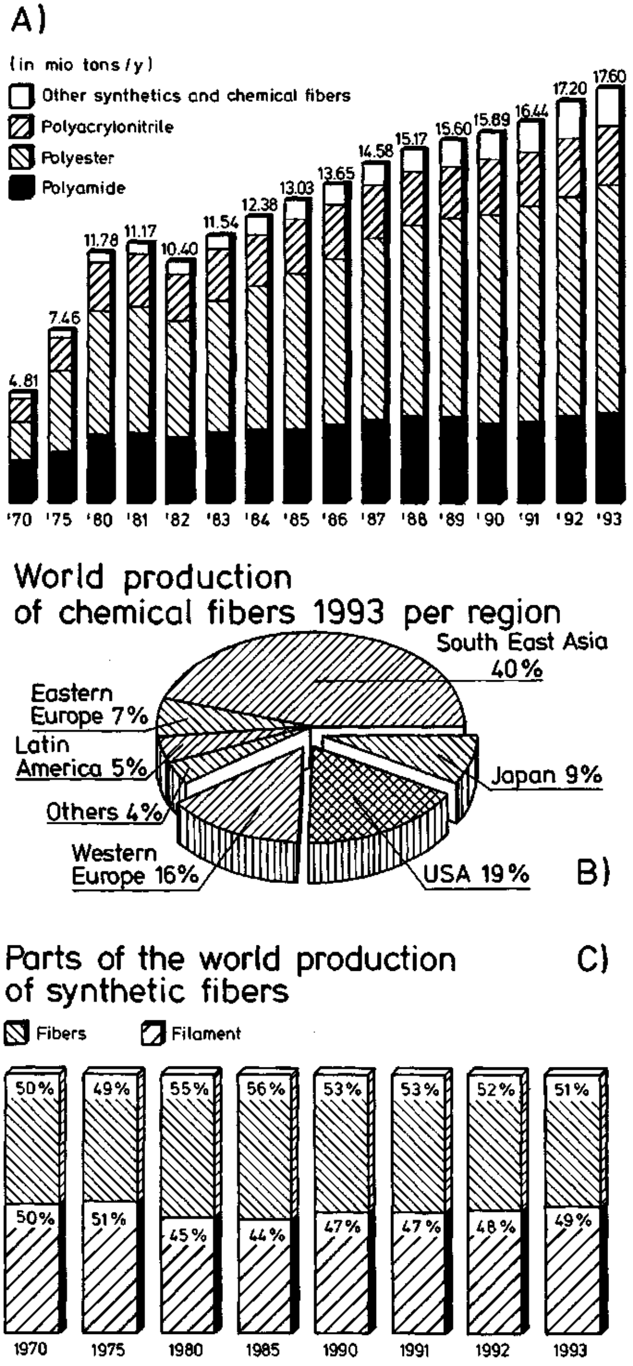


Figure 1.8 Break down of the global production of synthetic fibers and filaments
A) By fiber type
B) By region: USA 23%, Western Europe 18%, Japan 9%, all others 50%

Table 1.4 Global Synthetic Fiber Production by Region or Country

	1960	1970	1980	1986	1988	1990	Filament % (1990)
Western Europe		984.2		1893	1972.9	1822.7	38.3
w/o FRG	246	490.8		745	751.1	778.8	47.1
Eastern Europe		4152.9		660	695.2	821.1	49.4
w/o GDR	?	40.0		158.8	163.5	131.4	45.6
w/o USSR		1665.5		757.8	868.8	913.5	49.4
East Asia	–	6.1		219.5	281.0	400.3	
w/o Japan	129	968.7		1382	1381.0	1425.0	49.3
w/o South Korea	–	42.9		862.4	1115.0	1189.9	52.9
w/o Taiwan	–	40.8		1232.1	1430.2	1621.5	53.5
w/o India	–	15.6		220.7	321.6	430.9	60.1
w/o Indonesia	–	0		164.2	194.8	270.0	58.6
w/o PR China	–	11.1		747.4	1074.3	1309.4	38.6
Mid East, Oceania, Africa		26.5		207.1	232.7	219.7	50.8
America		120.2		193.7	197.5	212.1	
w/o USA, Canada	288	1571.5		3058.4	3244.2	3002.3	45.3
Mexico	–	46.7		296.3	345.9	323.3	40.8
Brazil	–	41.1		237.0	239.7	206.1	58.2
Others		156.8		1022.8	1141.1	1628.2	
Total	701	4876.3	10779	14058.2	15650.5	16497.4	46.4
For comparison (world total)							
Cigarette (acetate) tow production				362	422	462	
Glass fiber production				1449	1845	1826	

do the same. When increasing a plan production unit the production costs can be approximated from those of a smaller unit as follows:

$$K_2 = C_2 \cdot (\text{raw material costs}) + (C_2/C_1)^{0.6} \cdot K_1 \qquad (1.1)$$

K total cost — Index 1 smaller unit
C capacity — Index 2 larger unit

This means that the raw material costs increase proportionally with the capacity (neglecting improved terms in purchasing and transportation), but all other costs increase only with the 0.6 exponent to the capacity. If for example $K_2 = 2 \cdot K_1$, these costs will only increase by 52%. The fiber production in a 240 tons p/d. unit with 2000.-DM per ton raw material cost and 1000.-DM per ton other cost will reduce the cost per ton to 2760.-DM/t instead of 3000.-DM/t when doubling the capacity.

The useful size of a unit can only be determined when knowing all the facts about the regional conditions and the market. This is also true for the integration of such a unit into a larger corporate complex. Thus today unit sizes range from about 10 tons p.a. to 2 · 70,000 tons p.a. in the USA to a polyester plant in the PR China with 9 · 70,000 tons p.a. [36, 37] (now going to 18 · 70,000 t/a). The following overview may prove useful:

Unit size		Type of unit	Usage	Preferred countries for investment
kg/24 h	tons p.a.			
50...500	15...150	Filament unit	R&D speciality yarns	USA, Western Europe, Japan, PR China
200...2000	50...600	Speciality filament	Production	as above
7000	2200	Filament unit	Production	everywhere
4000...40,000	1300...13,000	Compact unit Small (preferred autoclave) Polycondensation and spinning unit	Fiber production Production	everywhere India, Indonesia South Asia, East Asia
80,000...160,000	27,000...54,000	Large (continuous) Polycondensation units and others	Large scale production	PR China, Taiwan, former USSR
400,000	130,000	as above	as above	USA

As continuous polycondensation units with 200...400 tons p.d. and a directly connected fiber spinning unit can only produce one standard product for a long time period, the problems shift from the technical production to the marketing side of this standard product. In the above mentioned example of the polyester facility in the PR China, however, the production represents only 0.5 kg per year and person.

Chip production and synthetic fiber production are part of the chemical sector, and the question needs to be asked, what percentage of the production of a chemical company or group of chemical companies should be for fiber production. If the production starts from the polymer chips it is practically independent and can be almost 100%, but usually those productions are connected with a specific textile corporation. For larger polymerization units, byproducts have to be used. Part of the polymer production can be sold in form of chips to the plastic industry or other spinning plants. For these combinations a fiber part of 30...50% of total sales proves to be useful. If on the other hand filaments and fibers are produced in large chemical corporations, the recessions of 1973 and 1981 showed that large corporations with more or less exclusive fiber production could not survive and had to merge with chemical corporations of similar sizes (e.g., Enka (AKU) b.v. with Zoon b.v. to become Akzo b.v.). Others were already part of a chemical corporation (e.g., Hoechst AG, Bayer AG, Rhône-Poulenc S.A. and others) and could cover the sometime losses from their fiber production that way. Also vertically integrated groups (like Beaulieux S.A. as a carpet producer) had better survival chances. This experience showed that synthetic fiber production should only amount to no more than 20% or even better less than 10% of the total corporate sales, so that losses from fiber production could be covered more easily. The large number of small production sites mainly survived by producing specialties that cannot be produced efficiently by the large producers either because the production quantity is too limited or the required flexibility is too high.

1981 *Falkai* [23] published a graph showing the relation between the sizes of the production units and the sizes of the factories for PAN fiber production (Fig. 1.9). The smallest economical wet spinning unit he sees at 5000...7000 tons p.a. (=about 24 tons p.d.), the smallest economical dry spinning unit at 10,000 tons p.a. (=30 tons p.d.), what should equal about 64 dry spinning chambers per machine. The smallest PAN fiber units must have considerably larger capacities than comparable melt spinning units, because they can only produce economically when recycling the solvents, spin baths, etc. Generally one counts on the use of about 75% solution and 25% dry substance. One also has to account for about 3...7% losses when recycling the solvents.

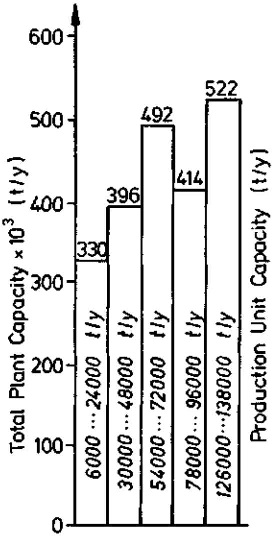


Figure 1.9
Production plant and production line sizes of a PAN plant (approximately 1980) [23]

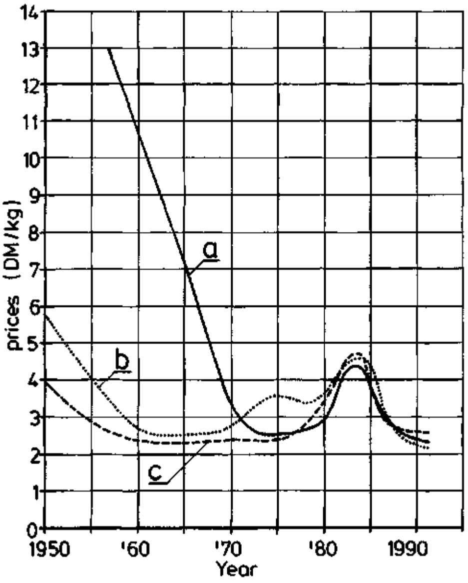


Figure 1.10
Approximate price development from 1950 to 1990 for
c) Viscose staple fiber
b) Cotton
a) Polyester staple fiber (cotton type)

1.5 Price Developments

Other than many commodities synthetic filaments and fibers have dropped in price since about 1950 except for a price increase during the oil crisis. This reduction in price is due to the considerable increases in capacity of the units without requiring significantly more labor. Labor intensive production has been moved to the low wage countries. An other factor is the fast worldwide communication that leads to

Table 1.5 Price Development of Monomers and Auxiliary Materials (DM/kg)

Year	Caprolactam	AH-salt	DMT	TPA	Ethylene glycol	ACN	Toluolene	Benzene	Dowtherm	Spin oil	$TiOP_2$ (AN atas)
1948	8.40	8.00									
1958	5.40	5.50	5.60		1.50	3.15			2.64…3.47	2.80…4.70	3.20
1964	3.60	4.00	3.00			1.20	0.21	0.258			
1968				3.00			0.193	0.246			
1978							0.321	0.402			
1988					0.76		0.472	0.664			
1989		3.00	1.23			1.25					6.00
1990	3.10…3.30¹⁾ 2.94²⁾		1.20	1.23¹⁾ 0.91…1.04²⁾	1.17	1.50		0.80	3.60…6.80		

AH SAlt = Monomers for PA66
DMT = Dimethylterephthalate
ACN = Acrylonitrile
TiO_2 = Dulling Agent
1) Germany
2) USA and Far East

Table 1.6 Development of Polymer Prices between 1958 and 1990 (DM/kg)

Chips, etc.	PAN powder	PA 6	PA 66	PET$^{1)}$ FGR	PET$^{1)}$ USA	PET$^{1)}$ lowest	PET $[\eta]=1.0$	PP
1958	3.80 . . . 4.00	7.00	7.40	7.60	7.00			
1988					2.38			$\leq$2.40
1989				2.30 . . . 2.45	2.00	1.90		2.04 . . . 2.29$^{2)}$
1990	$\approx$3.60	3.90 . . . 4.1	4.20	2.18 . . . 2.3	2.20	1.70	2.45	1.50 . . . 1.80

1) $[\eta] \approx 0.63 \ldots 0.67$
2) cheapest: 1.30 DM/kg from Far East

Table 1.7 Development of Yarn and Fiber Prices from 1936 to 1988

	1936	1948	1954	1958	1968	1978	1988	Region
Natural fibers								
Cotton, Egypt. cat.g	1.46	7.30	4.60	4.46				D
USA, middle	0.80	3.13	3.15	3.43	2.55	3.32	2.70	D
Wool, merc., 64 s	2.77	10.99	13.84	10.69				D
64 s	1.39	3.26	7.95	8.32				D
Japanese raw silk	5.51	13.51	49.91	46.24	–	–	–	GB
Flax, water-roasted	1.29	3.41	3.72	3.63	–	–	–	GB
Regenerated fibers								
Viscose fibers 1.5 denity $\frac{17}{16}''$	1.10	.1.02	2.59	2.59	–	–	–	GB
–	–	–			4.08 . . . 4.95			Japan
–	–	3.24	2.96	2.35	2.78	2.86		USA
–	–	2.95	2.95	–	–		–	D
Acetate fibers	–	–	4.70	3.91	–	–	–	D
Regenerated filaments								
Viscose 150/27 den pirn	3.46	5.46	6.35	5.98	–	–	–	GB
Acetate filaments	–	–	–	6.11	–	–	–	USA
Cupro 150/112 den	–	–	–	6.70	–	–	–	USA
Synthetic fibers								
PAN, dry spun	–	22.40	14.82	11.90	–	–	2.91 . . . 3.96	USA
wet spun	–	21.10	12.96	10.70	10.40	–		
	–	–	–	–	–	–	3.00 . . . 3.30	Western Europe
	–	–	–	–	–	–	4.16	Japan
	–	–	–	–	–	–	3.16	Korea, Taiwan
PET 3 den	–	–	14.82 . . . 15.56	11.67 . . . 13.10	4.75	2.67	2.75	USA, GB
1.5 den	–	–	–	–	–	–	3.12 . . . 3.21	USA
	–	–	–	–	–	–	3.50 . . . 3.90	Western Europe
	–	–	–	–	–	–	3.08	Japan
	–	–	–	–	–	–	2.98	Taiwan
	–	–	–	–	–	–	2.73	Korea
PA 6	–	21.20	14.75	12.90	9.40	–	3.58 . . . 4.37	
PA 66	–	–	13.80	11.90	9.50	–	–	
PP 3.3 dtex	–/–	–	–		7.80	–	~6.00	
6.7 . . . 7 dtex	–	–	–	–	–	–	2.60 . . . 2.30	

Table 1.7 *(Continued)*

	1936	1948	1954	1958	1968	1978	1988	Region
Synthetic filaments								
PA 6 15/1	–	114.00	64.50	48.50	30.10	–	–	
30/13 . . . 21	–	54.00	32.50	22.14	19.20	–	8.30 . . . 8.90	
840/140	–	–	13.70	11.10	8.10	–		
22/7 textured	–	–	–	–	–	–	12.40 . . . 12.90	Western Europe
BCF	–	–	–	–	–	–	~6.00	
PA 66 33 . . . 44 dtex	–	–	–	22.50	19.20	–	8.50 . . . 9.000	Western Europe
840/ den	–	–	14.20	11.10	8.10		6.30	
22/7 textured	–	–	–	–	–	–	8.50–9.45	Western Europe
BCF	–	–	–	–	–	–	~6.00	
PP BCF, spun dyed	–	–	–	–	–	–	5.00	
PET pirn/bobbin	–	–	–	18.60	–	–	3.72–4.40	
70 den								
100 den	–	–	–	–	–	–	–	
150 den	–	–	–	–	–	–	–	
1100 den	–	–	–	13.90	13.00	–	–	
POY 150 den	–	–	–	–	–	–	4.00 . . . 4.20	Western Europe
75 den	–	–	–	–	5.40	–	3.33 . . . 3.49	USA, Korea, Taiwan
Textured 70 den						7.35	6.31	Western Europe
100 den						5.88	5.05	
150 den						5.58	4.77	

underbidding of prices of intermediate and final products, especially from Far East countries. These low price materials are often of good quality because the companies work with the most modern production equipment.

Table 1.5 shows that prices of the most important monomers (Caprolactam, AH-salt, DMT, and TPA) have dropped from 8 DM/kg in 1950 to about 3 DM/kg in 1988, for acrylonitrile from 3.50 DM/kg to about 1 DM/kg. The same is true for the prices of polymer chips (PA and PET), according to Table 1.6 from about 8 DM/kg to 2.50. . .4.00 DM/kg. PP chips by now have reached prices of only 2.00. . .1.50 DM/kg or lower.

This price development of course influences the prices of the final products as can be seen in Table 1.7. Most of the commodity synthetic fibers today have prices between 3.50 and 5.00 DM/kg for standard titers. Non-textured filament yarns with more than 30 den are available for 8.50. . .10.00 DM/kg.

Table 1.8 Price Indices for Chemical and Natural Fibers in Germany [33]

Number	Year	1973	1978	1983	1986	1988	1990
581	Synth. filament yarns	101.0	84.5	95.5	100.4	889.7	96.8
580	Synth. staple fibers	77.8	73.4	90.5	100.6	91.7	90.7
579	Synth. filament yarns and staple fibers	90.3	79.4	92.9	100.5	90.6	93.8
578	Cellul. filament yarns and staple fibers	57.9	73.4	93.7	103.0	105.7	109.1
577	Chemical fibers, total	92.3	78.2	93.1	101.0	93.6	96.9
793	Textured yarns	110.8	87.2	97.2	104.1	93.9	102.3
118	Sheep wool	139.6	85.7	118.3	94.9	145.2	
116	Cotton	93.4	89.3	119.5	72.8	73.5	

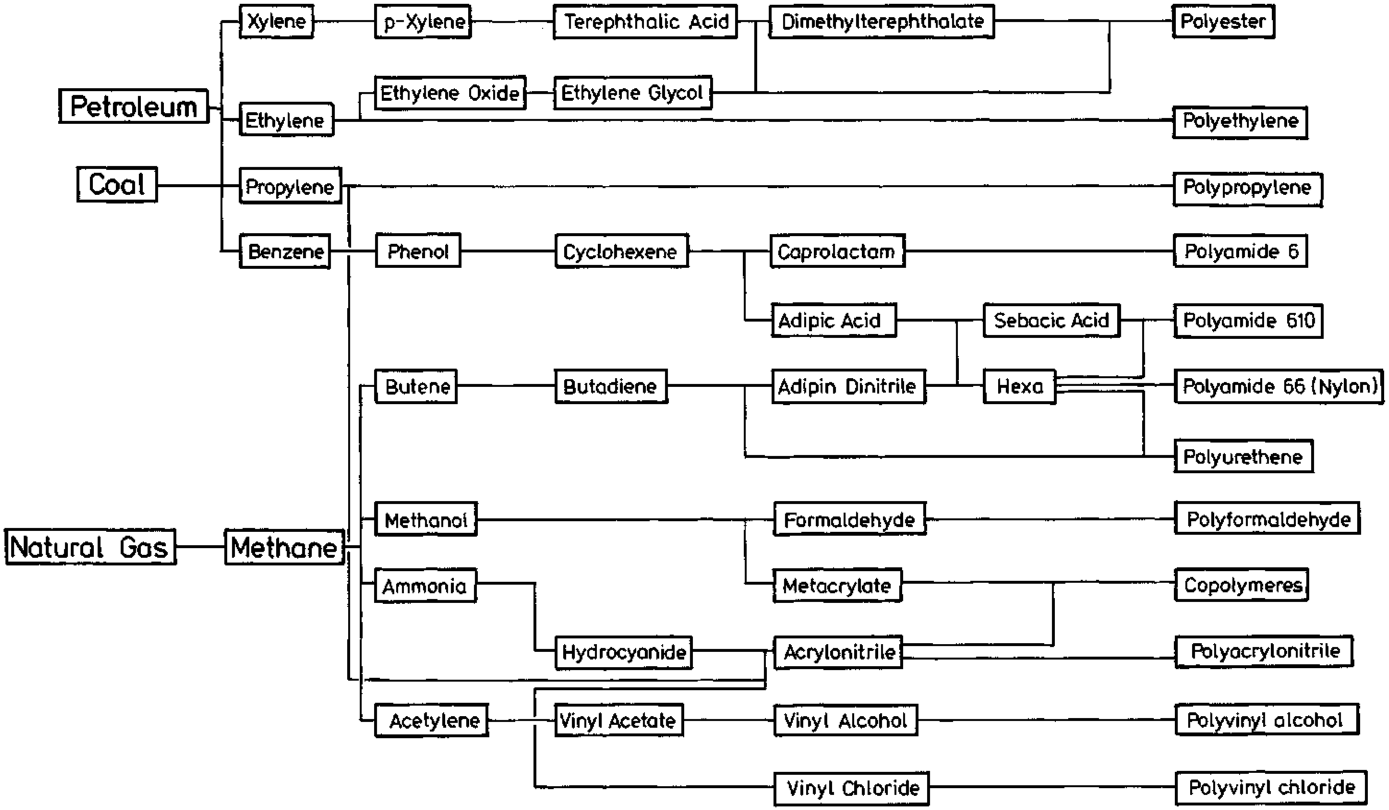


Figure 1.11 Raw materials and their intermediate steps to the polymer.

Textured PET multifilaments of 70 den are around 6.50 DM/kg and of 150 den only about 5.00 DM/kg if a good deal is available. PP staple fibers of 6 den can be purchased as low as 2.60 DM/kg and of 10 or 15 den as low as 2.30 DM/kg in large order quantities. Flat PP filament yarn den 1000 f 72 is offered for 4.10 DM/kg; BCF texturing is 0.50 DM/kg, and spin dyeing is depending on the dyestuff 0.40...0.80 DM/kg more expensive.

This price development can be seen in the comparison of polyester staple fibers, cotton, and rayon staple fibers in Fig. 1.10 and in Table 1.8 with the German price index for different fibers and yarns between 1973 and 1990.

1.6 Raw Materials

In 1964 *Fourné* [30] published a schematic graph on the natural raw materials leading to monomers and polymers that is still valid today. Certain quantitative shifts between petroleum, coal, and natural gas due to price increases of individual raw materials might repeat or reverse themselves today, e.g., from petroleum to coal, if mineral oil experiences a shortage or a price increase. Speculative thoughts about starting from sand, limestone, water, mineral salt, air, as it is theoretically possible, are not realistic at this

Table 1.9 Monomer Capacities 1988/90 (in 1000 t/a)[4] [39]

	Caprolactam	DMT	TPA	Acrylonitrile
EC	875[1]	1000[2]	935[3]	1275
Eastern Europe	950	631	60	550
USA, Mexico	600	2065	1845	1140
Latin America		80	100	150
Japan	475	335	1060	580
Taiwan			660	
South Korea			500	
India		145		
PR China		245	260	
Africa	130			
Others	270	123	?	305
Total	3300	4624 (4960)	530 (6550)	4000

Table 1.10 Global Monomer Capacities and Fiber Production

Monomer	Year	Capacity (1000 t/a)	Fiber production (100 t/a)
Caprolactam	1988	3129	3793
AH-salt		>3000	
DMT	1988	4715	8041
TPA	1988	7355	
ACN	1987	4000	2478
PP, PE	1988	≫2000	1994
		???	470
Total			16776

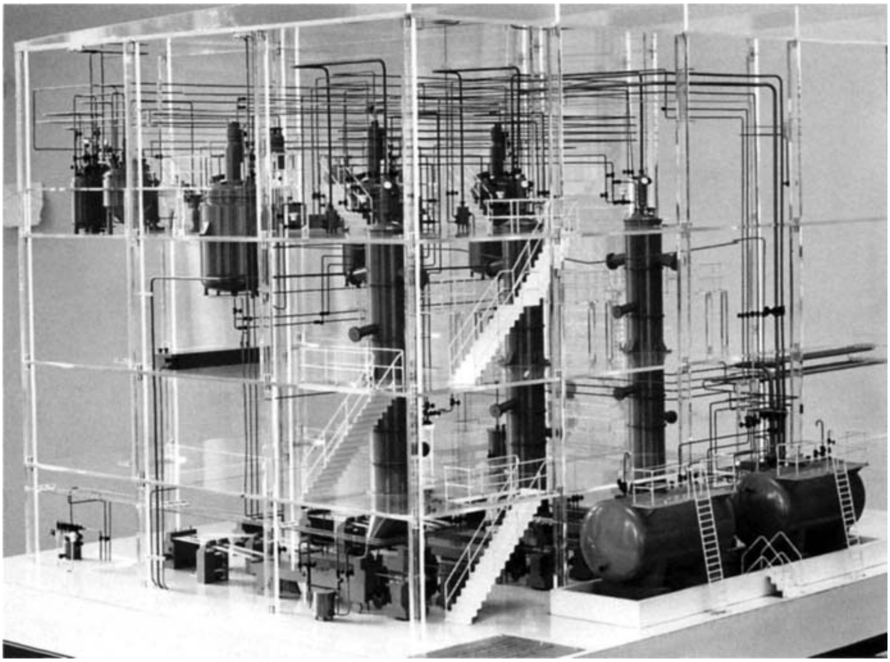


Figure 1.12 Model of a polyamide 6 polycondensation plant for approximately 40 tons/24 h chips [50]
Lower right: Storage bins for molten caprolactam;
Upper left: The preparation and mixing vessel; vertically: three VK tubes, each with approximately 10 m^3 volume; underneath: stringth quenching troughs (water quenches) with take-up and chip cutters

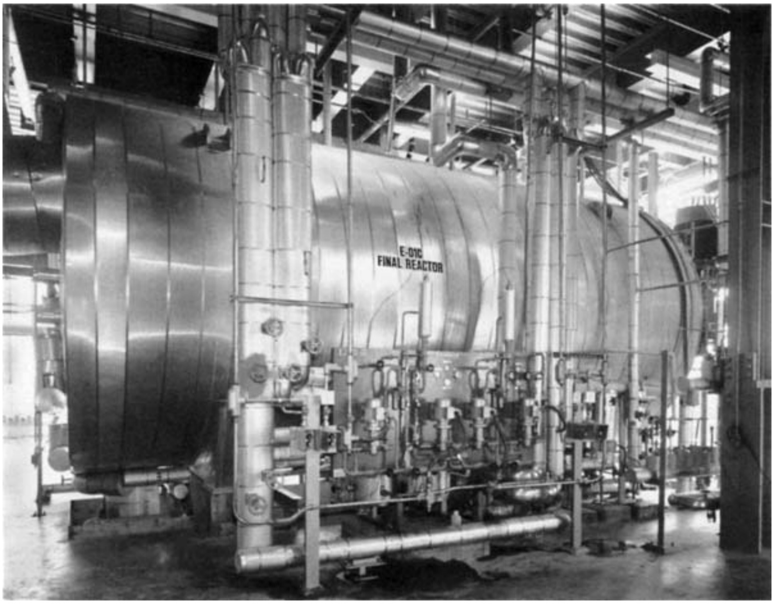


Figure 1.13 Polyester finisher for approximately 130 t/24 h [42]; inner volume approximately 40 m^3 corresponding to about 3 m diameter · 7 m length

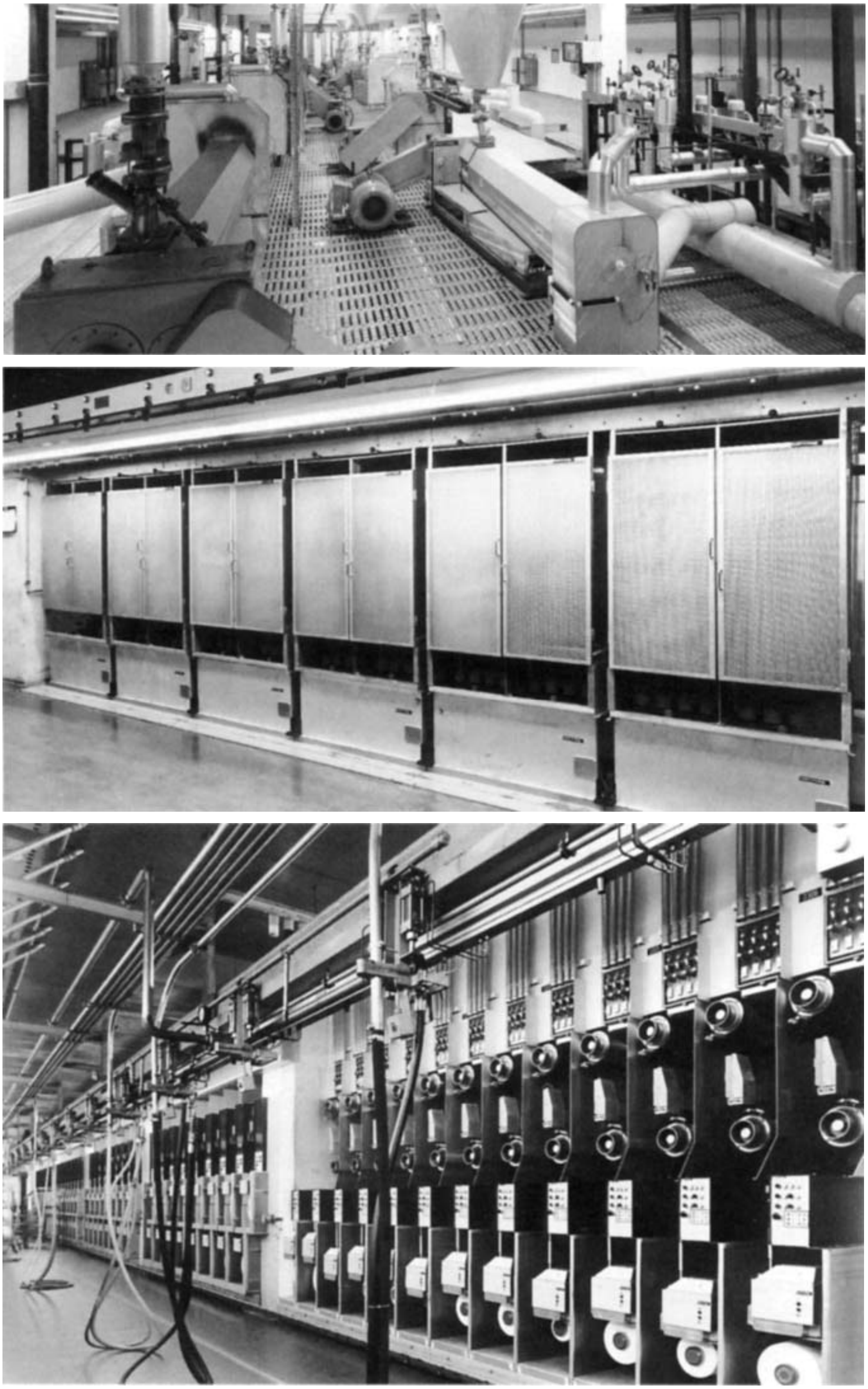


Figure 1.14 Three floor polyester filament spinning plant [44]; upper: Spinning extruder deck with insulated melt distribution piping; middle: Spinning heads with air quench chambers; lower: Ground floor with POY take-up machines (with godets)

Figure 1.15 Draw texturing plant with FK6 false twist draw texturing machines [44]

point of time due to the tremendous amount of energy required [23]. In 1979 only 6% of the mineral oil were used for the petrochemical industry and only 0.33% for the synthetic fiber industry. Within the scope of this book major shifts in the raw material supply are thus unlikely.

The required amount of raw petroleum (naphtha) for each one ton of PA is 2.7 tons, PAN is 2.3 tons, and PET is only 1.6 tons. Thus the synthetic fiber production in 1987 consumed about 30 million tons of naphtha with an annual rate of increase of about 5 million tons. One ton of mineral oil only contains about 20% of naphtha, which results in an annual increase in consumption of 25 million tons crude oil. This total consumption of crude oil might result in a return to more coal, which would result in a significant price increase.

Chemical fibers enjoy the advantage of natural raw materials that grow again, wood cellulose or cotton lint and rather simple auxiliary materials (NaOH, H_2SO_4, CS_2, CH_3COOH, $(CH_3)_2CO$, etc.) and are generally available, so that there should not develop any problems other than environmentally.

The world production of the most important monomers is shown in Table 1.9, where the increase of the TPA capacities is particularly striking [39]. Table 1.10 also compares the monomer capacities to the fiber productions.

Another important source of raw materials can be provided in the recycling of used textile materials. Waste generated during the production (3 . . . 10%) is recycled in some form already today. Recycling of used textile materials at today's state of technology is still a major problem—partially due to the lack of classification, partially due to the contamination, finishes, and dyestuffs etc.

Figures 1.12 to 1.19 shall provide a first impression of equipment used for the production and finishing of synthetic filaments and fibers, as described in more detail in the following chapters with the help of drawings. The texts under the figures should be self-explanatory.

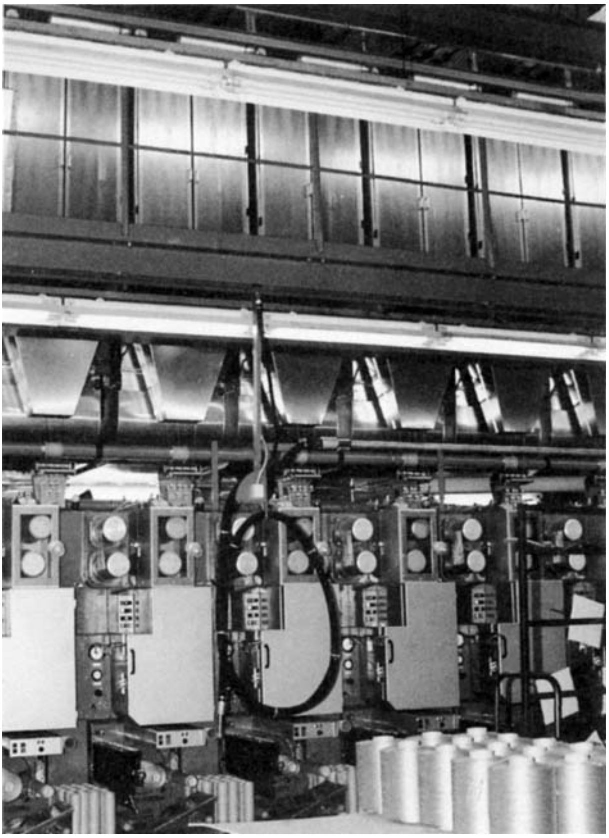


Figure 1.16
Carpet yarn spin-draw-texturing plant for BCF [45]

Figure 1.17 Two-staple fiber aftertreatment lines for approximately 200 tons/d capacity [43]

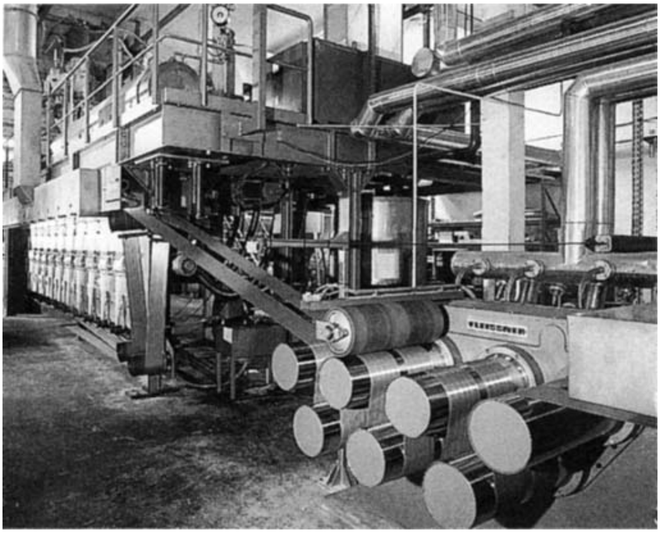


Figure 1.18
Compact spinning plant (one floor) for polypropylene or polyester or polyamide 6 staple fiber [49, 43]

Figure 1.19 Areal view of a complete production plant for polyester and polyamide 6 filaments, staple fibers, chips, synthetic thermo bonders and other specialties. Start of construction around 1950 from a wood saccharisation plant; extended and reconstructed in phases; photo of 1992 [48]

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