Part II

Towards the Second Plastics Revolution

(1970-2015)

A Car Free Sunday was held in the Netherlands on 4 November 1973 in response to the oil crisis in that year.

6. A black page

'The year 1975 will undoubtedly go down as a black page in the history of the plastics industry. After a period of strong growth between 1965 and 1973, the oil crisis was a turning point, not just in terms of economic development, but also in terms of the use of plastics ...'[1] The 1973 oil crisis triggered a panic reaction in the plastics industry. Businesses began to build up their stocks, fearful as they were of an impending shortage of raw materials for the production of plastics. A huge rise in demand was followed by a steep decline, with 1975 as the lowest point. The principal factors underlying the frenetic swings in demand were economic stagnation, the rising prices of plastics and the more frugal use made of plastics. 'There can be no doubt,' commented the Dutch trade journal *Plastica*, '... that the series of events during and after the oil crisis had a tremendous impact on the Dutch plastics market.'[2]

A period of uninterrupted growth had come to an end. The annual growth rate of 33% that the Dutch plastics industry had posted between 1963 and 1968 levelled off slightly in the following years, to 19%. The oil crisis seemingly put the lid on economic growth. Confidence was superseded by uncertainty. Manufacturers found it hard to work out what exactly the international political situation, an unpredictable oil supply, rising oil prices and stockpiling would mean for them. The same applied to the impact of inflation, rising unemployment and falling disposable incomes on plastics consumption: it was hard to know what this would be. In the words of Wim Bogers, DSM's CEO:

> 'Just a year ago, we'd got all our chess pieces into position, ready for an offensive campaign to secure the continued growth of our company. And then we were taken by surprise ... We may well have to swim against the current in the years ahead. And that generally means making less progress than you would like.'[3]

A ripple in the pond

At the same time, it was amazing to see how quickly the old order was restored in certain respects. In hindsight, the 'black page' was merely a ripple in the pond, the slightest of hiccups in the largely rising trend of plastics production and consumption. It was the same again fairly recently – in 2008, the year of the credit crunch. The fact is that both global production and global consumption have remained on the rise right up to the present day. The same applies to the Netherlands, albeit that there has not been a repetition of the spectacular growth witnessed in the 1960s. The Netherlands remains a major plastics exporter, with the rest of Europe (notably West Germany) as its principal customer.
After an initial rapid rise in per capita plastics consumption, consumption has continued to show a gradually rising trend. Construction and packaging continue to form the prime markets,

Part of the Shin-Etsu complex near Rotterdam, 2017. This Japanese company is the largest producer of PVC in the world.

followed by electronics, household articles and transport.

However, there has also been discontinuity in addition to continuity. The following chapters examine five changes that have taken place:

- The shift in the balance of power among plastics producers
- The changes affecting the plastics processing industry
- The changing research landscape
- Trends in plastics technology
- The debate on plastics and sustainability

Box 7

NRK, the Dutch Federation of the Rubber and Plastics Industry

One of the drawbacks of the heterogeneity of the plastics industry is that it does not lend itself easily to organisation. For this reason, the history of the Dutch Federation of the Rubber and Plastics Industry (NRK) consists of a series of changing alliances of industry groups. It was founded in 1945 by a number of processors of synthetic resin. Not long after, a special Thermoplastics Processing Division was created as a home for injection moulding companies. Another division was subsequently set up for raw materials producers, as well as one for machine manufacturers. In 1998, the NRK merged with the Dutch Association of Rubber and Plastic Manufacturers, with the result that its ranks were swelled with rubber, adhesive and sealant suppliers. The Federation was restructured in 2010, when it was decided that the raw materials producers, the machine manufacturers and the adhesive and sealant suppliers should henceforth each go their own way.

Today, the NRK acts as an umbrella organisation for 20 industry associations and divisions. A total of 470 companies are members, most of them either medium-sized or large companies, i.e. employing at least 10 people. Given that the industry itself consists of around 1,300 businesses, the figure suggests a rather low membership level. The picture is somewhat distorted, however, as the vast majority of businesses (890, or 68%) in the industry are small firms (less than 10 employees).

The 20 industry associations and divisions all represent the specific interests of their own members, while the NRK itself caters for the interests of the industry as a whole. Its fields of interest include training and innovation, working conditions, compliance (i.e. the statutory requirements with which production plants need to comply), the business climate and the status of small and medium-sized firms. For example, the NRK has for the past 25 years endorsed an industry-wide energy-saving covenant with the government. It recently launched a project for implementing the international ISO 26000 standard, which provides guidelines on how businesses and organisations can operate in a socially responsible way.

Public information has been one of the major concerns of the NRK ever since its foundation. This was already evident in 1947, when the first 'plastic corner' was opened as part of a major trade fair. Since then, the Federation has been involved in other trade fairs, has published periodicals and acted as a centre of expertise that is able to field questions from members of the public. Today, the NRK issues a trade journal called *Netwerk*, is a co-organiser of a conference for the rubber and plastics industry, and takes part in wide-ranging social debates on topics such as sustainable development, recycling, 'smart' products, CO_2 emissions, litter and plastic waste in the oceans.

7. Plastics producers: making strategic choices

TenCate Grass (Nijverdal, Netherlands) produces synthetic grass fibres, 2007.

DSM and Shell were the big Dutch plastics producers. Akzo was a Dutch producer of synthetic fibres and some plastics. Alongside these companies, a number of foreign manufacturers were also active in the Netherlands, the main ones being Hoechst (from West Germany), ICI (based in the UK) and Dow Chemical, DuPont and General Electric Plastics (GEP), all three of which were US firms. Even before the oil crisis hit, plastics producers in the Netherlands had already been facing two intractable problems, which the crisis only served to exacerbate: growing competition and the constant threat of overcapacity.

Fiercer competition

Most of the competition came from within Europe. The creation of the European Economic Community (EEC) resulted in the formation of a ‘common market’ that offered new opportunities but at the same time heightened competition with West Germany, France, the UK and Italy. Rising wages in the Netherlands in the 1960s undermined the country’s ability to compete with Italy, for example. Nonetheless, most plastics producers still managed to earn a reasonable profit – thanks to expansion of scale and the discovery of new markets.

Although there was initially very little competition from outside the continent, it gradually began to make itself felt as time progressed. In the 1970s, the US and Japan exported relatively small volumes of plastics to Europe. In later years, they were joined by other countries, including Thailand, South Korea and Taiwan. More recently, the ranks of plastics exporters have been swelled by India and China.

Risk of overcapacity

All these countries gradually expanded their capacity for the production of standard plastics. With the technology now regarded as mature, starting up production was much easier than during the infancy of plastics. At the same time, the need to align supply with demand was a constant headache. This problem had already been seen in the second half of the 1960s and during the oil crisis, and surfaced again during the 1980s. 1981 and 1982 were difficult years for the chemical industry. The year 1983 heralded the start of recovery and a period of strong growth for the European plastics industry. Existing production capacity was put to optimum use and plastics producers throughout the world sought to massively step up their capacity. Plastics manufacturers in the Netherlands enjoyed a fantastic year in 1985, posting record sales of polypropylene in particular. However, the tide began to turn in around the year 1990, with polypropylene being the first plastic to be hit. Prices plummeted, and other plastics followed suit.

The North complex at the production site of Royal DSM in Geleen (Netherlands), 1991

During the 1960s, the plastics producing industry became a cyclical industry because of substantial increases in capacity per production unit. This meant that shortages arose during times of economic prosperity, and manufacturers sought to quickly expand their production capacity.[4] During an economic downturn, on the other hand, there was a surfeit of supply, forcing manufacturers to quickly suspend or halt production. Fierce competition also led to a long-term trend of falling prices.

Diversification

So how did plastics producers in the Netherlands respond to these problems? Diversification was one of the main initial responses. Companies decided to focus on products at different stages of their life cycles, i.e. not just mature products that were capable of bringing in money, but also new, promising high-margin products in which investments still needed to be made. These new products might be the results of in-house research, but equally they could follow from mergers and acquisitions. The latter was generally the preferred course of action, as it also enabled the acquiring company to gain easy access to both a new market and the necessary expertise. In short, diversification was the dominant management philosophy among big companies during the period around 1970.[5]

Shell had already embraced diversification some time before then. This was not so much because of the cyclical nature of the plastics industry as on account of Shell's desire to reduce its dependence on oil. Having already invested in plastics and in agricultural, industrial and basic chemicals, it moved into nuclear energy, coal, forestry and metal mining in the 1970s.[6]

For its part, DSM had started building up a chemical business alongside its existing coalmining operations before the war. The new business concentrated initially on two main products, ammonia and fertiliser, before extending its scope after the war to include plastics and the raw materials required for the production of plastics. Around 1970, the company was all set to make a 'great leap forward', to use the Maoist term with which the strategy was described in internal company documents.[7] The idea was to close down the mines: the future lay in the chemical industry, it was thought, and there was sufficient funding available to implement the new strategy, thanks to natural gas revenues and specific-purpose grants. In 1969, the then CEO, Antoine Rottier, declared that 'the most urgent need for DSM in the years ahead is to pursue an aggressive policy of expansion so as to gain the respect of our competitors and other large concerns'. The main sources of expansion were to be plastics (including PVC and synthetic resins) and the raw materials required for their production.

DSM also sought to diversify by pursuing both forward integration, i.e. in the direction of the end product, and backward integration, i.e. in the opposite direction – towards the raw materials. The main form of backward integration was participation in natural gas activities, while acquisitions in the plastics processing industry and markets that were critical for sales of plastics provided the main forms of forward integration. To give a few examples, DSM acquired a shareholding in the *DAF* motorcar production plant in 1967, *Macintosh Confectie* (a clothing manufacturer) in 1971, and the company *Isolatiesteen* in 1972. It also fully acquired *Curver* (a plastics processor) and *Van Egteren Bouwnijverheid* (a construction company) in 1972. Some of these participations and acquisitions were helpful in securing employment for the former employees of the coalmining operations.

AKU had already made various attempts at diversification in the 1960s, for example by trying to produce plastic piping in addition to synthetic fibres. However, this had not proved a success and it was not until AKU merged with *Koninklijke Zout Organon* ('Royal Salt Organon') in 1969 to form the Akzo group that it truly managed to diversify.[8] AKU's main role in the new group lay in the production of synthetic fibres. *Koninklijke Zout Organon* was itself a conglomerate of a number of different companies and sought to achieve synergy with plastics and synthetic fibres primarily in its paints, coatings and adhesives business lines. These eventually merged to form Akzo's coatings division. Koninklijke Zout Organon also produced the bulk product VCM (vinyl chloride monomer), the raw material for PVC.

A difficult strategy to manage

In practice, however, diversification proved a difficult strategy to manage. For a start, combining different management styles and corporate cultures often proved a tough challenge. Another problem was that senior management generally did not know a great deal in detail about the wide variety of subsidiaries accommodated within the group. Wildly optimistic expectations at the outset resulted in correspondingly bitter disappointments and feelings of deep frustration later on. Alliances were disbanded and companies sold off. Shell was a case in point, losing USD 500 million when it decided to move out of nuclear energy at the end of the 1970s.[9] Other activities, such as tin and coal mining, followed suit.

But this was not the only problem in relation to plastics.[10] The cost price of plastics depended – and indeed still depends – primarily on the price of oil. Companies like Shell that had access to cheap oil had an advantage over other plastics producers. Fiercer competition and smaller profit margins on bulk plastics in the 1980s only served to give such companies even more of a competitive edge. An additional factor entered the equation in the 1990s, when the European Union outlawed cartels and price-fixing agreements, thereby squeezing profit margins in the chemical industry yet further.

At the same time, shareholders also became more vocal, calling for higher returns and a reversion to the core business. The spotlight shifted to market leadership, the thinking being that market dominance would enable a company to control prices and hence to influence its profit margins. Conglomerates needed to be split up, it was claimed: their stocks generally performed less well than those of specialist producers and demerging them would produce capital gains. It was the age of venture capitalists and private equity funds. The upshot was a complete restructuring of the chemical industry – and the plastics producing sector in particular.

Shell

Shell continued to invest in plastics in the 1980s and 1990s, albeit with varying degrees of success. Keen to jump on the PET bandwagon, Shell joined forces with Mossi Ghisolfi (M&G Chemicals) in 1989 to build its first factory for the production of polyethylene terephthalate (PET). When the business failed to build up a leading share of the market, Shell decided in 2000 to sell its share to Mossi Ghisolfi.[11]

Production of another polymer, polyketone, which Shell had developed entirely on its own and which was marketed under the trade name of Carilon, came on stream in 1994. Shell reckoned that the main markets for Carilon would be the automotive industry and the market for electrical equipment.[12] The product turned out to be a flop, however, due to the excessively high cost of production and the fierce competition it experienced with other plastics. Shell was unable to recoup the huge sums of money it had invested in the production facility; nor did it find any buyers for its patents or its factories.[13]

Then, in 1998, Shell decided to stop producing vinyl,[14] selling off its VCM and PVC production plant in France as well as its shareholding in Rovin, a joint venture with AkzoNobel that owned the VCM and PVC production plants in Botlek and Pernis in the Netherlands. AkzoNobel also announced that it would be withdrawing from the VCM/PVC market. The new owner of this business was the Japanese chemical group Shin-Etsu.

Shell remained active in polymers during this period, albeit exclusively in polyolefins. In 1993, it launched a joint venture – named Montell – combining its own polyethylene and polypropylene business with that of the Italian company Montedison. Not long afterwards, Shell took over full ownership of the business and, in 2000, concentrated all its European polyolefin activities in a company called Basell, which was incorporated as a joint venture with BASF. Despite becoming the largest European manufacturer of polypropylene, with an annual output of 3,600 kilotonnes,[15] Basell nonetheless failed to meet the profitability targets set by the Shell management[16] and was sold in 2005 to Access Industries, a company owned by the Ukraine-born American billionaire Len Blavatnik.[17]

By the end of the previous century, Shell had wound up more or less all of its polymer business.[18] It announced that it would be pursuing a new strategy known as the 'cracker + 1' strategy: this meant that output would have to be just one reaction away from the cracker producing ethylene, propylene, or whatever.[19] Shell wanted to invest more in oil and gas exploration, production and refining. Today, apart from producing fuel, Shell supplies the familiar basic chemicals and a small number of derivatives. It also produces one or two plastics, such as polyethylene and polypropylene, albeit not in the Netherlands but much further afield, in places such as Nanhai, China.[20]

The exhibits at the international ROKA Food Fair in Utrecht in 1980 included disposable plastic milk bottles.

DSM

DSM's history follows much the same pattern. DSM withdrew from plastics processing and the production of PVC and acrylonitrile butadiene styrene (ABS) in the 1980s and 1990s. In 2002, it sold its facility for the mass production of polyolefins to the Saudi Arabian company SABIC and, in 2010, it sold its elastomer (synthetic rubber) production facility to Lanxess, a German chemical group.[21] In 2015, it set up a separate company to handle the production of caprolactam, the raw material for the production of plastics that DSM had been manufacturing for the past 60 years. DSM took a 35% shareholding in the new company, with the remaining 65% being owned by a private equity fund called CVC Capital Partners.[22] DSM decided to concentrate on the production of specialty chemicals, mainly for the foodstuffs and healthcare markets. Although it remained active in plastics, its role was limited to advanced engineering plastics and resins.[23] Going by newspaper reports, further splitting up of the company is conceivable.[24]

Akzo

After acquiring the Swedish firm Nobel Industries in 1994, Akzo rebranded itself as AkzoNobel. By that time, it had already ended most of its activities in synthetic fibre production in the Netherlands. In 1998, the AkzoNobel group acquired a UK company called Courtaulds, a leading producer of coatings and fibres. The two companies' synthetic fibres wings were merged under a new name, Acordis, before being sold to CVC Capital Partners a year later.[25] Thus, polymers for paints, coatings and adhesives continued to be produced in the Netherlands. AkzoNobel later decided to concentrate on coatings and evolved into the world's biggest paint manufacturer. However, there is no intrinsic reason why the company should necessarily remain in its present form forever. Splitting up AkzoNobel into separate chemical and coating divisions would be a logical move.[26]

Foreign companies move in

Although bulk plastics and synthetic fibres are still produced in the Netherlands, very few *Dutch* companies are involved in this. The big 'traditional' plastics producers – Shell, DSM and AkzoNobel – have all withdrawn from the business. Shell still supplies raw materials for plastics. DSM now concentrates on engineering polymers and fibres and AkzoNobel deals only in coatings.

Today's bulk producers are now all foreign companies: although General Electric, Dow Chemical and DuPont were already bulk producers in the 1960s, the bulk production landscape has undergone a tremendous change during the past few decades. With a production capacity of over 3 million tonnes, new kid on the block Shin-Etsu is now the world's leading PVC manufacturer, with production facilities in Botlek and Pernis in the Netherlands.[27] In 2007, the owner of Basell, an investment company called Access Industries, bought a US firm called Lyondell. The resultant business, LyondellBasell Industries, now owns a range of production facilities in the Netherlands.[28] It is one of the biggest chemical companies in the world, ranking sixth in the top 100.[29]

Another newcomer, SABIC, acquired General Electric's plastics division in the town of Bergen op Zoom. This was after it had bought DSM's bulk production business in 2002.[30] The move signalled SABIC's entry into the engineering plastics market, and also meant that it became a direct competitor of DSM. SABIC, too, has rapidly evolved into one of the world's leading chemical companies, and is ranked no. 5 in the list of the top 100 chemical companies.

In a deal again involving CVC Capital Partners, the Japanese chemical and pharmaceutical company Teijin bought a former AkzoNobel subsidiary producing superstrong fibres.[31] Another former AkzoNobel subsidiary, Diolen Industrial Fibers, was relaunched in 2009 following insolvency in 2008.[32]

The 'merger of giants', i.e. of Dow Chemical and DuPont, announced in 2015 is highly characteristic of the dynamism of the chemical industry. The merger is likely to affect the two companies' production sites in the Netherlands, including those in Terneuzen and Dordrecht.

The quest for profitability

During the past few decades, both chemical companies and the private equity funds investing in them have sought to attain market leadership as a means of controlling prices and profit margins. The Japanese company Teijin, for example, has made clear its desire to become the world's leading producer of strong aramid fibres. Having added AkzoNobel's Twaron aramid fibre to its armoury, it found itself in an excellent position to achieve this aim and mounted a challenge to DuPont. It is now also threatening DSM's position as the market leader in strong fibres.

In its search for profitable destinations for its oil revenue, SABIC, the state-owned Saudi chemical company, has deliberately decided to invest in petrochemicals and bulk plastics: '... You need to have your own cracking plants if you want to control costs throughout the production chain. The more of the chain you have in your control, the better you're able to respond to fluctuations in market demand. In other words, if you don't have your own raw materials, you can't make enough profit throughout the production chain...'[33] Thanks to its acquisitions, the company now also has access to advanced technology. Firms such as LyondellBasell and Shin-Etsu are seeking to become market leaders by dominating the markets for specific bulk plastics such as polypropylene and PVC.

In other words, the plastics landscape in the Netherlands has completely changed. As *Het Financieel Dagblad*, the leading Dutch financial daily, wrote in 2004, 'the Association of the Dutch Chemical Industry (VNCI) really ought to change its name to the Association of the Chemical Industry in the Netherlands (VCIN)... as the Dutch chemical industry has largely been transferred to foreign ownership over the years ...' [34] The Association's chairman claimed there was nothing wrong with the situation, however. Indeed, he said that the Dutch chemical industry was in an outstanding state of health: 'We have deep-water ports and a huge hinterland, with hundreds of millions of fairly wealthy consumers all living within a range of one thousand kilometres ...' Apart from the advantages of the location, the industry also benefits from an outstanding knowledge infrastructure and the presence of a highly qualified workforce.

Does this mean that the Netherlands has the situation well under control? The petrochemical market remains in a state of turbulence. Refining capacity, for example, is being transferred from Rotterdam to the Middle and Far East, where companies can produce more cheaply and at less distance from a growing market.[35] Moreover, the shale gas revolution in the US during the first decade of the century has turned the international oil and plastics markets upside down.[36] At the outset, US petrochemical companies caused huge problems for the European chemical industry by dumping bulk plastics on the European market. Following the recent steep decline in the price of oil, however, it has now become more attractive to produce bulk plastics in Europe, and in the Netherlands in particular. The question is: can Dutch policy-makers influence these processes?

The chairman of the Association of the Dutch Chemical Industry is not sure whether they can: '...[a *Dutch policy-maker*] would find it much easier to call someone in a local town than on the other side of the world, in Houston or Riyadh. You're on the same wavelength for a start. The thing is, though, we're going to have to start dealing with people there. Like it or not, that's where the decisions are taken nowadays.'[37]

This is something they know all about in the southern Dutch province of Limburg. In 2006, to the bitter disappointment of the provincial council and the Dutch government, SABIC decided to cancel its plans for investing EUR 1.3 billion in new chemical plants. 'Of course it's a regrettable decision...,' the Dutch State Secretary for Economic Affairs commented after flying to Riyadh to throw his weight behind the investment, '... SABIC is already a big investor in the Dutch economy and has had a huge social impact. This project would have generated many hundreds of jobs and would have provided thousands of man-years of work for the construction industry. I hope that the decision only meant postponing the investment and not a definitive no.'[38] In the event, SABIC decided to buy a refinery in the UK. The question is therefore: is the petrochemical industry in the Netherlands no more than a plaything for foreign companies?

The battle for Twaron

In the 1960s, the American chemicals giant DuPont developed a ‘superstrong’ fibre – ‘as strong as steel and as flexible as rubber’ – and put it on the market in the 1970s under the trade name Kevlar. Car tyres formed a key market for Kevlar, which was meant to provide an effective alternative to steel for reinforcing radial tyres.

The Dutch chemical concern Akzo (now AkzoNobel), recognizing the fibre’s potential, decided to face up to its powerful rival and embarked on a deveopment path of its own for the superstrong fibre. However, Akzo had a huge amount of ground to make up. The project was plagued by confusion at the outset about the type of polymer that DuPont was using for the fibre. In 1971, however, Leo Vollbracht and a team of fellow-researchers discovered that the polymer in question was PPD-T.[i]

When DuPont subsequently announced plans to start semi-commercial production and produced evidence at the same time that its fibre did indeed possess exceptional properties, Akzo decided to substantially strengthen the size of its research team. The main problem was that, although Akzo’s researchers now knew which particular polymer DuPont was using, this did not necessarily mean that they were able to reproduce the fibre. Only when DuPont’s patents for polymer spinning were published in 1972 did they succeed in producing a lab-scale imitation of Kevlar with more or less the same properties. They called their product ‘fibre X’, and later renamed it as ‘Twaron’. The big question was: would Akzo be able to circumvent or contest the spinning patents? After a detailed examination, the firm’s patent office decided to contest DuPont’s patents on the grounds that they were based on existing knowledge.

Thanks to the fact that the researchers also managed to find a new way of making the PPD-T polymer, Akzo finally acquired its long-sought-after patent on its own proprietary production process. The patent subsequently shot up in value when it emerged that the solvent used in DuPont’s production process was carcinogenic. Although the news prompted Akzo to open negotiations with DuPont, the talks proved fruitless.

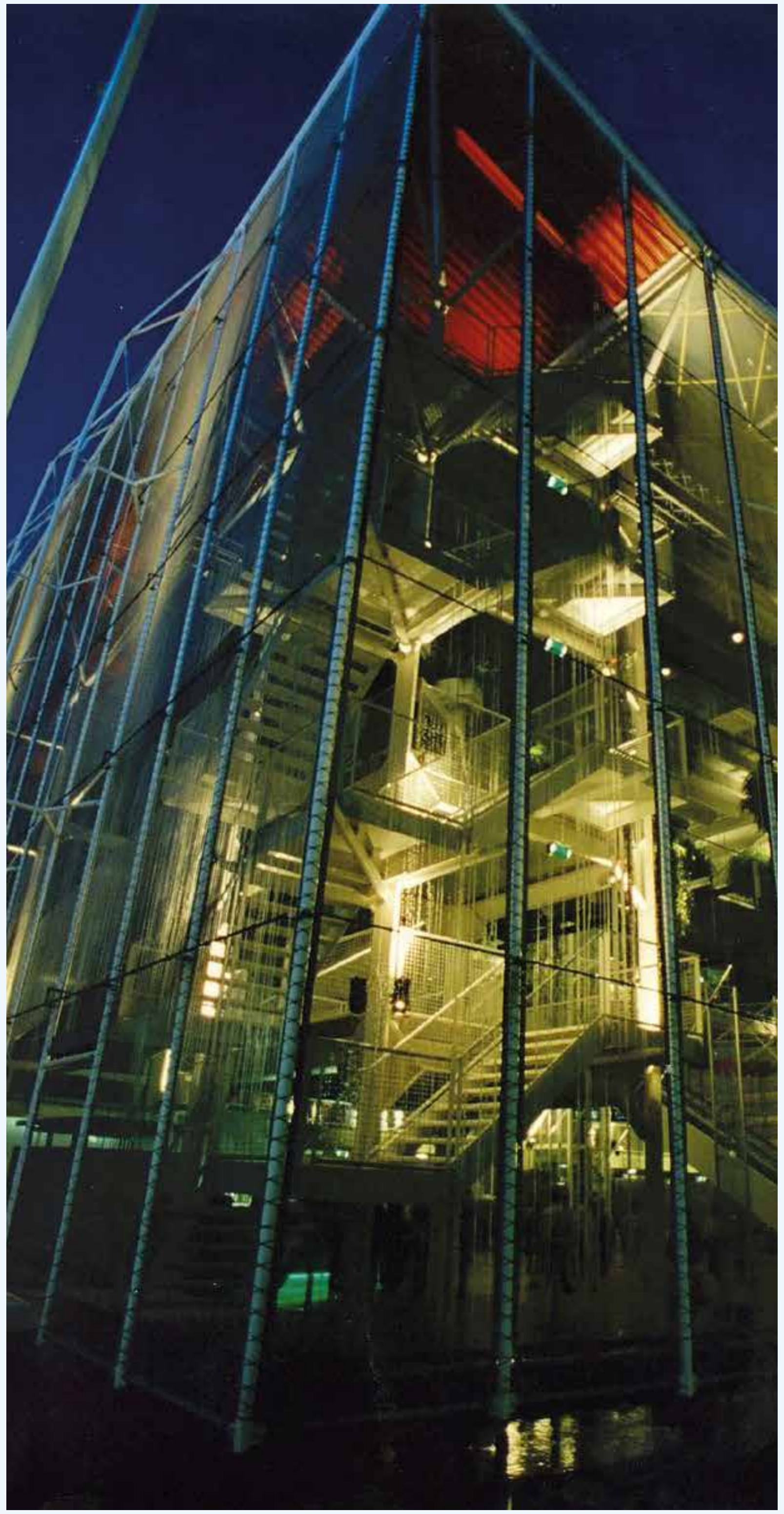
It was now the 1970s, and times were tough for the synthetic fibre industry. Overcapacity meant plummeting profits: Akzo incurred heavy losses and was forced to announce thousands of redundancies. The company continued with its R&D work on the super-strong fibre, but in fits and starts. At one point, there was even talk of the project being scrapped and the Dutch Ministry of Economic Affairs and the Netherlands Development Company were forced to step in with a rescue package.

Scaling-up the production process proved far more difficult than had been expected and the commissioning of the first production plant in 1985 was nothing short of a disaster. The official opening ceremony, which was to be performed by the then Prime Minister, Ruud Lubbers, had to be postponed.

The market had also changed in the meantime. The car tyre market proved to be less lucrative than expected. The use of steel as a means of reinforcing radial tyres continued to have its advantages. And the properties of the conventional viscose yarns used in diagonal-ply tyres remained superior to those of synthetic tyre yarns.[ii]

In short, Akzo needed to find other applications. Which it did indeed find: for example, in the replacement of asbestos in friction materials (as used in brake pads, for example) and in new materials for the aviation industry.

Nonetheless, the battle of patents with DuPont continued to hang over Akzo like a Sword of Damocles. Even after big investments had been made and production had been started, the battle remained unresolved, with both DuPont and Akzo taking turns to claim victory. Things came to a head in the winter of 1985-86, when the US International Trade Commission banned Akzo’s Twaron fibre from the US market. The decision was ratified by President Reagan, with the support of Congress. Two years later, however, Akzo won a court case in the UK, thus jeopardising DuPont’s position in Western Europe. The court ruling proved a tipping point for DuPont, which decided that the time had come to reach a compromise with Akzo.



The Dutch pavilion at the World Expo 1992 in Seville (Spain). The walls were covered with transparent Twaron fabric, allowing water to be trickled down the walls enabling evaporative cooling of the building.

[i] PPD-T: poly paraphenylene terephthalamide.

[ii] Viscose was less prone to deformation, which meant that these tyres were less susceptible to flatspotting, i.e. the flattening of the tyre that occurs when a vehicle has been standing still for a prolonged period of time and which affects the vehicle’s ride comfort.

SOURCES:
K.F. Mulder, *Choosing the corporate future. Technology networks and choice concerning the creation of high performance fiber technology* (PhD dissertation, Groningen University 1992).

8. Plastics processors: the quest for high-performance products

Children playing with plastic toys

So how did the Dutch plastics processing industry fare? The lack of data makes it difficult to paint a full picture of the development of the industry after 1970. Not only are the statistics produced by Statistics Netherlands (the Dutch central statistical agency) incomplete, they are also inconsistent, thus making it hard to compare different periods with each other. For example, the figures do not include companies producing plastic components for captive use, i.e. for use in their own products. Similarly, companies with a core business in another industry – such as furniture-makers and shipbuilders – are not covered. The same applies to plastics processing companies producing coatings: this is a heterogeneous industry that includes very disparate businesses, ranging from one-man operations manufacturing simple plastic products to huge companies using robots to assemble complex products. For this reason, we have decided to restrict ourselves to a general impression, starting with some national statistics.

The figures

In the 1960s and 1970s, Statistics Netherlands made an inventory of the plastics processing companies employing at least 10 people. It found there were 253 of such companies in 1977, compared with 160 in 1968. These 253 companies employed 12,200 people in 1968 and over 16,000 people in 1977. Their aggregate turnover was approximately EUR 2.8 billion, compared with EUR 1.6 in 1970 (all figures adjusted for inflation).[39] Although the oil crisis had meant tough times for the industry, it had nonetheless succeeded in expanding in the 1970s, in line with the growth in plastic production and consumption.

The vast majority of the 253 respondents (66%) were formally classified as medium-sized companies (10-49 employees). They employed 26% of the industry's workforce and produced 22% of its aggregate output (see Table 8.1). At the other end of the spectrum was a small group of big companies employing at least 200 people. These companies represented 5% of the population, employed 35% of the industry workforce and generated 45% of the aggregate industry output. It is worth noting that the two extremes, i.e. the firms employing 10-19 people and those employing over 200 people, posted the best results.[40]

Right up to the present day, medium-sized companies have continued to play a dominant role in plastics processing. Even more remarkably perhaps, a 2014 industry census revealed a large number of one-man bands: 475 out of a total of 1,310 businesses in the rubber and plastic products industry (see Table 8.2). At the other end of the scale were 20 companies employing more than 200 people.

An official count held between 1983 and 1994 (and using a different method of counting) pointed to a rising trend in the number of businesses in the industry. The number fluctuated between 1,000 and 1,350 during the following years, i.e. until 2006. The variations in the figures reflect the brief economic crises in the mid-1990s and again around the turn of the century. A longer-lasting crisis began after 2004 (and can be seen in Graph 8.1), reaching its nadir in 2009. A period of recovery followed in 2010 and 2011, apart from among firms processing plastics for the building & construction industry. It seems likely that the small firms felt the brunt of the swings in the fortunes of the industry. Dozens of small firms have been founded – and dozens disbanded – in recent years (see Table 8.3).

An unsuccessful attempt was made in the early 1980s to produce an adequate classification of companies in the plastics processing industry. A survey of 130 businesses resulted in a classification consisting of around 20 market segments, based partly on products (such as profiles and pipes) and partly on processing techniques (such as injection moulding, machining, resin casting, fluidized-bed dip coating and metallic coating).[41] However, it proved difficult to construct a coherent picture on this basis.

Industry associations

It is easier to gain an impression of the main segments of the plastics processing market by looking at industry associations that are members of the Federation of Dutch Rubber and Plastics Manufacturers (NRK). A number of these associations are centred on product groups such as plastic piping, plastic roofing, plastic windows and plastic packaging. However, a larger group of companies are represented by associations based on materials and technologies, i.e. plastic film, PVC, recycled plastics, bio-based plastics, rigid polyurethane foam (i.e. plastic blocks used for packaging objects such as washing machines), flexible polyurethane foam (used mainly for mattresses), thermoplastics (for injection moulding and thermoforming), expanded polystyrene (EPS, used for packaging and insulation, and as a light filling material in civil engineering and public works) and plastic composites, i.e. special materials for the automotive industry, the machine-building industry, civil engineering and the aerospace industry.

However, this list also fails to do justice to the huge variety of firms represented in the industry. After all, they also include a tiny, one-man business producing spoilers, sills and doors for motor sports (which manually laminates the parts before fitting them with inner frames and supplying them as unpainted end products),[42] as well as a small company making coffee tables, side tables, desks and other items of furniture out of Plexiglas.[43]

A narrow portfolio…

Not only the very small firms are able to survive by specialising in a particular niche. Big companies can also use specialisation as a means of building up a large share of both the domestic and the international market. Designing and producing plastic profiles for the window and door frame industry, thus enabling windows and doors to be made windproof, soundproof and waterproof, is one such specialisation. The firms active in this particular segment supply the Dutch, Belgian, French, UK and Irish markets.[44]

Another specialisation involves the manufacture of electric sliding roofs for the automotive industry. Combining plastics, metal components and electronics in a robotic production process is a specialisation mastered – and exploited on a global basis – by a mere handful of companies around the world.[45] Many companies in the plastics processing industry are specialists in some form or another. For example, they may specialise in certain products such as film (see also above examples), materials (such as PVC), technologies (such as injection moulding, thermoforming or machining) and markets (such as the automotive, building & construction or shipbuilding industry).

A company may be a specialist in certain respects but still have a broad portfolio. For example, a company may specialise in injection moulding, but nevertheless supply a fairly wide range of products in small, short-lived series consisting of just a few hundred products (such as casings for remote controls), alongside series consisting of millions of products produced over a number of months (such as ball bearings, suspension bushings, label holders, and so forth). It may sell its product range on highly divergent markets, supplying its customers on a round-the-clock basis. And yet there is no reason why a company operating along these lines should necessarily be a large company: provided it has a wealth of experience and top-quality machinery, it should be able to operate perfectly well with a workforce of less than 10 people.[46]

…or a broad portfolio

A company may have a broad portfolio by accommodating different business units under its roof. For example, in addition to production, purchasing, sales, quality control and service, it may also encompass a tool shop where punches and dies are made, a design department where products and moulds are designed, an assembly shop for putting together the end product, and a lab for research and testing.

These types of companies are generally medium-sized, i.e. employing between 50 and 200 staff, or big, i.e. employing over 200 staff. One of the oldest plastics processing companies in the Netherlands, Van Niftrik, is a good example of such a broad-portfolio company. Van Niftrik specialises in the injection moulding of all sorts of plastics for a wide range of applications. The company's strength lies in its ability to organise the entire process, from devising an idea for a new product in collaboration with a customer to delivering the finished product. This process

Transport of plastic public urinals in Amsterdam

A red plastic covering protects a bicycle saddle from rain in Amsterdam

applies even if the customer is located in a distant country, and includes all the various intermediate processes. The company employs around 300 people and is owned by an Austrian group called Voestalphine A.G.[47]

Heterogeneity of the industry

Apart from varying in size, market, product range and production technology, the companies in the plastics processing industry differ from one another in many other ways, such as age (many of them are less than 40 years old), ownership (many are private limited companies, in many cases family-owned, while others are public limited companies or part of a group) and origin, i.e. some started life as a plastics processor, while others began as a metal processing company, a tool-maker, a design agency or a mould maker. As a consequence of this variety, there are many different corporate cultures in evidence.

The heterogeneity of the plastics processing industry has its pros and cons. On the one hand, its heterogeneous nature is a reflection of its ability to operate flexibly on both the domestic and the international market. Thanks to its low threshold and the great opportunities it offers to young entrepreneurs, dozens of small-scale start-ups (1-9 employees) spring up in the industry every year. It does not generally require a huge amount of capital to set up a plastics processing business. Experience is more important than qualifications. However, it should be remembered that dozens of small companies go out of business every year.

The flexibility of the industry is also reflected by the diversity of strategies devised by companies for meeting the challenges in the marketplace. One of the big challenges facing the industry since the 1960s has been the formation of a single European market. Another, since the 1970s, has been the competition from low-wage economies such as Taiwan and, more recently, China. Yet despite these factors, Dutch plastics processors have managed to retain a sizeable share of the international market. Over 65% of their output goes abroad.[48]

One typically Dutch business strategy involves competing in the area of high-tech products. This is also true of the plastics processing industry. The design and production of electric sliding

roofs for cars (mentioned above in relation to specialisation) is a good example of this. Another example is compound injection moulding, in which a number of plastics with different functions are integrated in one and the same product, which has to fully comply with a wide range of detailed specifications, for example in relation to its melt temperature, tolerances, hardness and so on.[49]

A company may also decide to compete in the area of 'low-tech' products. In that case, it will try and derive a competitive advantage from its proximity to its customers, low transport costs, and cheap methods of production using fully automated machines and robots.

Drawbacks

One of the drawbacks of heterogeneity is that the industry does not lend itself easily to organisation, which is also why policy-makers find it hard to deal with this category of companies. A total of 470 companies are members of the Dutch Federation of Rubber and Plastics Industry (NRK) (see Box 7: 'NRK, Dutch Federation of Rubber and Plastics Industry'), which thus represents about one third of the companies in the industry. No figures are available on the type of companies that are members of the NRK, but these are likely to consist mainly of the medium-sized and larger companies, i.e. employing at least 10 people. There were approximately 430 of such companies in 2014. Compared with other industries, only a small number of issues are covered by collective agreements. There is no collective agreement that all companies in the industry are obliged to observe. Nor is there a fund for training and development. The job classification system for the industry contains no more than four job grades. There is no tradition of collective training, and industry representatives have for some time now expressed concern about the level of education and training among the workforce. This is a typical example of an issue that has proved fairly difficult to deal with. Let's take a closer look at it.

The training challenge

The main form of education that is relevant to the plastics processing industry is vocational education, particularly at secondary level but also at higher professional level. For a long time, the production and processing of plastics did not figure on the curriculum of mainstream technical education. The situation changed in the 1980s, when both colleges and private individuals designed a wide range of courses. However, it was not clear whether these courses were of the standard required by the industry and whether they met the industry's training needs. Moreover, an industry-specific training course, such as in the metal industry, failed to materialise.[50]

In the early 1990s, a committee set up to advise the Ministry of Education and Science and the Ministry of Economic Affairs named technical education as being the key priority of government policy on materials technology (including plastics, metals, ceramics and functional materials). The committee expressed concern about the possibility of a future shortage of qualified technical personnel. It claimed that there were not enough students and teachers, that training courses were not of a sufficiently high status and that the teaching resources were inadequate. The committee pointed to a disconnect between the colleges of vocational education and the demands of the current and future labour market. It identified 'integration' as a key concern:

> 'Integration is needed in order to consider the interrelationship between a number of disciplines, i.e. materials science, design and engineering, manufacturing techniques and maintenance techniques, and also so as to view them in relation to the various stages of the material cycle, i.e. extraction, manufacture, application, use, reuse and finally waste.'[51]

Following the publication of the committee's final report, large sums of money were invested in curriculum development, teaching equipment and teacher training.

Despite this, training has remained a problem. It is now 25 years later, and the imminent shortage of trained staff is still a topical issue. A policy document published by the Dutch Federation of the Rubber and Plastics Industry in 2014 referred to the inflow of qualified staff as being 'far from adequate'.[52] It also noted that the average age of staff working in the industry was high and that there was a risk of this gradually rising in the years to come. Certain employers were found to show little interest in staff training, and very few employees took initiatives to update their skills and expertise. New initiatives were sorely needed.

The policy document also made another interesting point, almost as an aside, which is that staff acquire most of their skills and knowledge on the job. The acquisition of knowledge through textbooks and standard courses is an important aspect of vocational education: students acquire a basic knowledge of plastics and learn the basic skills they need in order to operate the relevant machines. At the same time, the formal knowledge acquired in the educational system is not the most important form of knowledge. People pick up the necessary skills in practice, by working under the watchful eye of experienced craftsmen. Expert knowledge of the processing of plastics is both company-specific and person-specific. It is stored in the brains and hands of craftsmen, is transferred face-to-face from one person to another and is built up over many years of practical experience.

Artisanal

In that sense, the plastics processing industry retains something of an artisanal character. To say this is not to disparage the sector: on the contrary, the small-scale, craft-oriented nature of the industry is simply a reflection of the state of the market. It is an industry which is characterised by heterogeneity and which derives its inherent value from its specialisations. Without exception, every single plastics processing business seeks to carve out a niche for itself on the strength of its specialist expertise:

> '...specialists in injection moulding, both exclusively of plastic and of plastic in combination with metal components, with output ranging from high-performance technical products to bulk products...'
> '...specialising in the machining of high-performance plastics with the lowest possible tolerances...'
> '...designing the mould is a matter of high precision: both moulds and specifications are trimmed to within several hundredths of a millimetre...'
> '...we are proud of our products... over 50 years' experience with thermoforming and vacuum forming...'
> And so the list goes on.[53]

It is worth pointing out that, while many plastics processors are small-scale craft industries, the vast majority nonetheless make use of highly sophisticated machinery and tools.

This description of the work of the operator of an extruder, i.e. a machine in which plastic is forced through a die, is a neat illustration of the craftsmanship in the industry:

> 'An operator needs to have many years of experience before he can ensure a streamlined production process. The fact is that there are all sorts of variables: he can vary the speed of the feed screw in the extruder, heat – or cool – the extrusion zones, and change the speed at which the extrudate is pushed through the die. If the plastic heats up too quickly, it may coagulate into a lump. But if it heats up too slowly, it may not assume the right shape in the die. And then there are all the tiny pipes that blow exactly the right quantity of air into the die so as to form the cavities of the profile in question, of which there may be as many as five. This all takes place at a speed of 6 metres a minute if the profile is a complex profile, and up to 24 metres a minute in the case of simple profiles. After leaving the die, the profile, or extrudate, is pulled through a water bath, during which the operator has to regulate both the pulling force and the cooling speed. If he gets this wrong, the profile will reach its final length too quickly, which means that it will be either too soft or too hard, or too thin or too thick...'[54]

Innovation

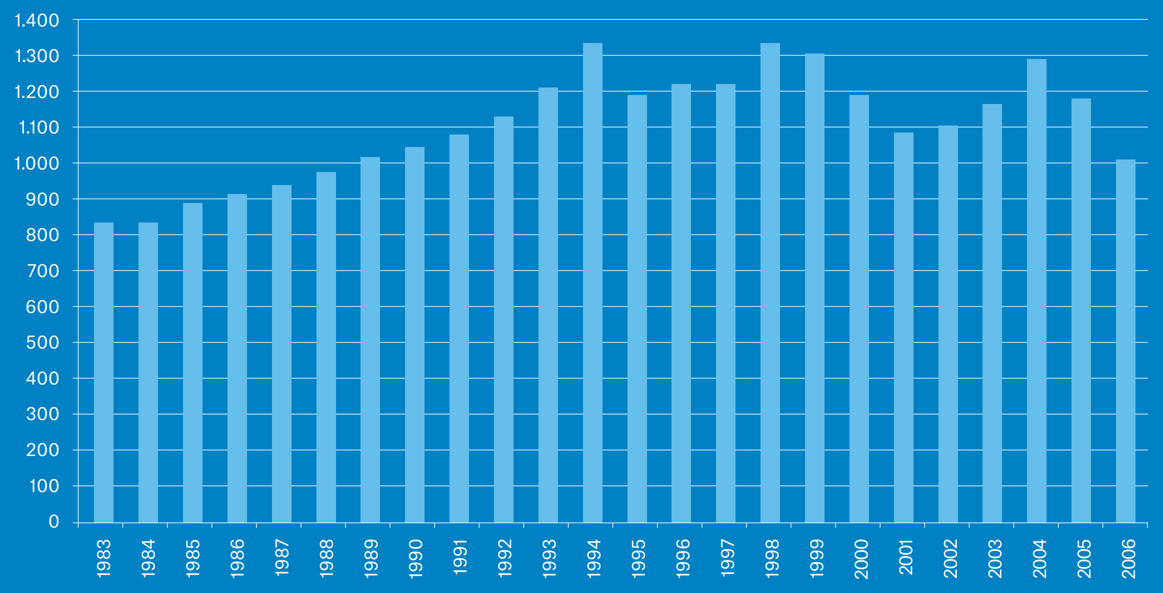
Education and training was not the sole concern of the policy-makers. The industry's capacity for innovation was another recurring issue. Around the year 1980, both the Dutch Federation of the Rubber and Plastics Industry and the Ministry of Economic Affairs were worried that the plastics processing industry was starting to fall behind. The wage costs in the industry were on the rise and were now among the highest in Europe. West Germany, France, Italy and Belgium were all proving serious competitors. Dutch plastics processors could not be described as forming an 'advanced' industry in the sense that they were manufacturing products that were either new or scarce in the rest of Europe. True, a small number of companies produced specialist products and were well-known names on the international market – companies such as the manufacturers of plastic piping. The future for the Dutch plastics processing industry lay in the production of technically more advanced plastic products, the stakeholders concluded. However, a decision to concentrate on this market would need to be supported by business audits, market research and quality assurance. The workforce would have to receive better training. And companies would need to invest in new technologies.[55]

Research facility at Eindhoven University of Technology which was used for polyolefins research, 2006.

Ten years later, the committee that had been set up to advise the Ministry of Education and Science and the Ministry of Economic Affairs and which had identified technical education as the key priority of government policy, also came to a sobering conclusion:

> 'Only a minority of the businesses ... are making active efforts to enhance their own knowledge of materials ... A closer analysis reveals a wide gap between large and small companies. Most of the bigger companies are aware of the vital role played by materials and can afford to take an active interest in developments in the field. However, there is a risk of small and medium-sized firms in particular failing to keep up with the pace of innovation in relation to materials...'[56]

GRAPH 8.1 Number of rubber and plastics processing companies, 1983-2006



SOURCE: CBS, Historie economische demografie, 25 Rubber- en kunststofverwerkende industrie (SBI 1993), 1983-2006, *StatLine* (The Hague/Heerlen, 13 November 2014)

The committee expressed a view that was widely accepted in the heyday of the big companies and their research labs. Although these companies were regarded as forming the vanguard of innovation, this perception was not entirely accurate. As we have already seen, a 'plastics platform' had come into being after the Second World War at the heart of which were the plastics producing multinationals, the TNO Plastics and Rubber Institute and the big machine engineering firms, many of which were foreign-based. These organisations had both the laboratories and the highly trained staff that were needed to perform research into new plastics, to experiment with new applications and to design new machines for processing plastics.

In fact, the plastics processing industry was already innovative in that it made use of the new materials and machines (see Table 8.5). Although the committee recognised this innovative aspect of the industry, it regarded this as an inferior form of innovation. While there were a small number of genuinely innovative companies,'... most of the other companies were *mere* users of the knowledge bound up in the equipment and materials that they bought...' [our italics].

Nevertheless, the use of new materials and equipment was an essential aspect of innovation. Moreover, the plastics processing companies designed a huge range of new products in collaboration with the plastics platform and end users. Innovations were built on a combination of professional expertise and craftsmanship. This is an aspect largely ignored by the committee (see also Box 6: 'The First Fully Plastic Garden Chair'.)

The results of new production methods, including the acquisition of new machinery and equipment, are clearly reflected by the changes in labour productivity among plastics processing companies. While the size of the workforce rose by around 10% between 1970 and 2005, output rose by over 400% during the same period (see Table 8.4).

A study of the capacity for innovation among businesses employing no more than 100 people ranked the chemical, rubber and plastics industry as the most innovative industry (see Table 8.5). The study covered the period between 2002 and 2005 and was based on 13 indicators that said something about the efforts made by such companies to innovate, about the results of their efforts, and about their plans for the future. In the words of the final report, 'while the big boys [in the chemical, rubber and plastics industry] such as Akzo and DSM have a long-established reputation as progressive, innovative companies, the SMEs operating in the same industry are by no means laggards. The players in the chemical, rubber and plastics industry are all operating in a highly turbulent environment in which today's products are out of date tomorrow. Competition from low-wage countries is squeezing prices, which is why many firms are tending to concentrate on complex, innovative, high-value products and are keen to work in close cooperation with other companies...'[57]

Difficult though it is to establish precisely how innovative a particular industry is, it seems reasonable to conclude that the Dutch plastics processing industry is one of the country's most innovative industries.

TABLE 8.1 Size of plastics processing companies in 1977 (as % of total)

Size of company	As % of total number of companies (n = 253)
10-19 employees	26
20-49 employees	40
50-99 employees	21
100-199 employees	9
200 or more employees	6

SOURCE: 'Momentopname van de kunststofverwerkende industrie in Nederland', *Plastica* 34(1981) no. 4, 97

TABLE 8.2 Size of companies in the rubber and plastics producing industry in 2014 (as % of total)

Size of company	As % of total number of companies (N = 1310)	As % of companies with >= 20 employees (N = 432)
Sole trader	35	
1-9 employees	32	
10-19 employees	11	33
20-49 employees	11	33
50-99 employees	5	15
100-199 employees	4	12
200 or more employees	2	6

SOURCE: CBS, bedrijven; grootte en rechtsvorm, 22 Rubber- en kunststofproductindustrie (SBI 2008), 2007-2014, *StatLine* (The Hague/Heerlen, 13 November 2014)

TABLE 8.3 Number of plastics processing companies founded and closed down, 2007-2013

Year	Number of companies founded (1-9 employees)	Number of companies founded (10 or more employees)	Number of companies closed down (1-9 employees)	Number of companies closed down (10 or more employees)
2007	95	10	65	10
2008	105	5	65	10
2009	75	0	75	20
2010	60	0	55	10
2011	85	5	50	5
2012	55	0	60	5
2013	70	5	75	5

SOURCE: CBS, Oprichtingen, opheffingen, fusies en overnames, 222 Kunststofproductenindustrie (SBI 2008), 2007-2013, *StatLine* (The Hague /Heerlen, 13 November 2014)

TABLE 8.4 Index of production and size of workforce in the rubber and plastics processing industry, 1970-2005 (index number for 2005=100)

Year	Production index	Workforce index	Labour productivity index
1970	23	88	26
1975	24	85	28
1980	30	79	38
1985	35	79	44
1990	74	97	76
1995	80	94	85
2000	94	109	86
2005	100	100	100

SOURCE: CBS, nijverheid, productie, SBI, 2008, index 2005=100, 1953-2011

TABLE 8.5 Innovative capability of SMEs, by industry, 2002-2005

Ranking*	Industry	Score**
1	Chemical, rubber and plastics	8.21
2	Research and development	8.13
3	Computer services and ICT	8.09
4	Food, drinks and tobacco	7.98
5	Wholesale and capital goods	7.92
6	Machine manufacture	7.79
7	Management consultancy, PR and economic research agencies	7.72
8	Instruments and electrical and optical devices	7.69
9	Base metals	7.49
10	Wholesale suppliers of intermediate goods	7.46
24	Advertising agencies	6.72
25	Motorcar wholesalers	6.66
26	Fitting companies for the construction industry	6.61
27	Service-providers for the transport industry	6.60
28	Property management	6.57
29	The arts	6.54
54	Retail suppliers of textiles, clothing and shoes	5.23
55	Passenger transport	5.16
56	Civil engineering	5.13
57	Stock farming	5.10
58	Market and street traders	4.68

* The original table listed 58 different industries; a selection has been made for the purpose of this table.
** 10 = highest capacity for innovation; 4 = lowest capacity for innovation

SOURCE: J.P.J. de Jong en A.P. Muizer, *De meest innovatieve sector van Nederland. Ranglijst van 58 sectoren* (Rapport EIM Onderzoek voor Bedrijf en Beleid, Zoetermeer 2005)

9. The changing research landscape

Plastic rental pedal boats moored at Zuidlaardermeer (Netherlands).

During the period immediately after the Second World War, the institutions that took up the task of building up scientific and technological knowledge of plastics in the Netherlands were TNO (the Dutch Organisation for Applied Scientific Research) and the big multinationals (see Part I). At that time, the research infrastructure consisted mainly of the TNO Plastics Institute together with a number of industrial laboratories, i.e. at Shell, DSM, AKU and various foreign companies such as GE Plastics and Dow Chemical. Together, they formed the heart of the plastics platform, providing a solid base on which the plastics processing industry, the government, traders and consumers could rely.

The main changes that took place after 1970 were the gradual disappearance of certain industrial research activities, the changing role of industrial research and the rise of university-based research. These changes affected not just plastics as such, but also other areas such as catalysis and solid state physics. They heralded the start of a prolonged debate on the relationship between the universities and industry in all sorts of fields, including plastics. Fierce at times, this debate is still going on even today. The following have been among the recurring issues under discussion:

- What is the economic value of industrial research?
- What is the added value of public research centres, including the universities?
- What should the relationship be between the public research centres and industry?

Our analysis of these issues will naturally revolve around plastics, and more specifically around polymer science and polymer technology. We will start by sketching the general background of the changes in the Dutch knowledge infrastructure, before going on to look at the shifts in polymer research, notably at DSM and the TNO Plastics Institute. Next we will analyse the rise of university research and then return to the above three questions in our analysis of the Dutch Polymer Institute (DPI).

Industrial research under pressure

The changes taking place in the central research organisations of the big industrial companies were nothing short of dramatic.[58] After peaking in 1967, when it accommodated a total workforce of almost 1,600 people, DSM's Central Laboratory quickly shrank in size during the 1970s, ending the decade on a staff complement of around 1,200. The decline in research expenditure as a percentage of turnover was even more marked.[59]

Plastic devices are used in interventional cardiology.

The situation was more or less the same at Akzo, where the number of staff employed by the research laboratories in Arnhem fell by no less than 40 per cent, from 1,500 in 1970 to less than 900 in 1980. In the end, Akzo disbanded all its corporate research activities, which were completely separate from its divisions and production units.

At Philips, the Physics Laboratory (or NatLab, as it was generally known in the Netherlands), which had previously been a fully accepted part of the company, found itself facing difficult times. For the first time since the end of the war, it was required to economise: staffing levels subsequently fell from around 2,200 in 1975 to 2,000 in 1985. Relatively speaking, though, these were not big cuts. More importantly perhaps, they signalled the end of the laboratory's growth. Its continued existence was no longer taken for granted.

At Shell, a decline in research activities had already started in the 1960s. Severe spending cuts were made in the 1970s: Shell closed down its Plastics Laboratory in Delft and decided to concentrate its chemical research activities in Amsterdam.

Economic malaise

Why this squeeze on industrial research? One of the main reasons was the sharp increase in the cost of research on the back of rising wages in the 1960s.[60] Also, the multinationals themselves were having a tough time fighting off the competition created by the formation of a single European market. As a further problem, many markets had become saturated. Profit margins went into a steep decline as a result. The situation was worsened by the economic malaise of the 1970s and 1980s and research came under further pressure. Companies were compelled to put their expansion plans on hold – and that applied equally to their research labs. The generous budgets for research and development now came under fire.

Striking the right balance

However, the state of the economy was not the only cause of stagnation, contraction and closure. Companies were also beginning to review the status of their research laboratories.[61] The role of industrial research had not come under question during the period of post-war reconstruction and subsequent economic growth. The assumption was that it would produce countless innovations in due course. In later years, company boards subjected their relevance and value to a critical assessment. The big question was: were their research activities not gradually becoming divorced from their core business and targets? Was the balance between research on the one hand and development and production on the other really as it should be?

The answer was sought in the formation of matrix organisations, i.e. structural combinations of disciplines and application areas; project organisations, i.e. networks linking research, development, production and marketing; research coordinators, consultative committees and contract research. The idea was that this would help to integrate the central research lab with the rest of the organisation.

Urine bag attached to bed in a hospital ward

New terminology

In parallel with this trend, new terms came into circulation as a means of designating the various functions of research. Apart from 'fundamental research', the talk was now all about 'basic research' as a means of acquiring core competences; and 'exploratory research', the aim of which was to explore the technological potential of a given field of research. The new reality for all the research labs was that their legitimacy was no longer a given. No longer were they able to justify their continued existence by making the age-old claim that 'fundamental research automatically equates with innovation and progress'.[62]

The situation is neatly illustrated by the debate about the research activities at DSM's Central Laboratory. In 1974, DSM was divided into six divisions, including Plastics and Plastic Products. Two years later, the research at the Central Laboratory was reorganised in accordance with the principle of a matrix organisation. The researchers were not simply members of the lab's research departments, which organised the various disciplines of research. They were also members of project teams working on research projects that had been approved by the company divisions.

The battle for research at DSM[63]

Faced with both a reorganisation and imminent spending cuts, the management of DSM's Central Laboratory decided to gain a clearer picture of the potential conflict of interests affecting researchers by dividing the lab's research activities into a number of different categories. They designated the following three categories:

1. basic and support research;
2. pioneering research;
3. contract research.[64]

The 'contracted research projects' were adopted by the Central Laboratory in consultation with the divisions. These projects were funded by the divisions and revolved around the improvement of existing products and processes and the development of new products and processes. Together, they accounted for around 60% of the Central Laboratory budget in the 1970s.

Where disagreement arose, this mainly concerned the ‘basic and support research’, for which the Central Laboratory was solely responsible, and the ‘pioneering research’, which was the responsibility of the Managing Board.

Basic research

Times were tough for basic research in the 1970s. In a review of this period, DSM’s Corporate Research and Patents Department wrote that ‘basic and support research had a bad name in the company, as many staff claimed that it simply provided a means of plugging gaps and enabling researchers to pursue their personal hobbies… Discussions about the budgets for basic and support research tended to be emotional rather than rational…’[65]

Basic research consisted of a number of units, one of which was the Fundamental Polymer Research Department under the leadership of Ron Koningsveld. Various members of staff referred to the department mockingly as ‘our university’ and Koningsveld himself was known as ‘the professor’ because of the fundamental nature of the department’s research and its academic approach. Although the department had not been the subject of any criticisms or complaints until the 1970s, it had difficulty justifying its existence at a time when spending cuts began to bite and the emphasis shifted towards research commissioned by the divisions. Regular evaluations and reviews that were designed to align the department’s work with the needs of the company as a whole failed to convince the decision-makers of the value of basic research. The problem was compounded by the difficulty of measuring the results of the research, which centred more on the acquisition of relevant expertise and experimentation with expensive measuring instruments than on patents, prototypes and ideas for new products and processes. The researchers working for the department were interested first and foremost in becoming full members of the academic research community, keeping track of the latest scientific developments around the world, and placing their knowledge at the service of the DSM group. Some 15-20% of the Central Laboratory’s budget in the 1970s was spent on this type of research in the 1970s. It seems likely that this figure declined thereafter, placing pressure on the Central Laboratory in the early 1980s and preventing it from conducting basic research in support of new activities.

Pioneering research

Pioneering research had enjoyed its heyday in the 1950s and 1960s, at a time when DSM was keen to build up a chemical arm, and a plastics division in particular, largely through an in-house effort. The idea was for pioneering research to come up with ideas and options for completely new products and processes. The researchers explored the potential of a new chemical process on a laboratory scale, experimented with prototypes, and secured the results in the form of patents. An estimated 50% of the group’s research activities in that period was pioneering research. This included, for example, looking for ways of using urea as a raw material in the production of plastics.

When DSM subsequently decided to diversify by buying outside companies and technologies, the laboratory found itself working in support of the new policy. This led to a decline in the demand for pioneering research, and a shift towards more contract research on behalf of the divisions. Working in conjunction with the laboratory, the Plastics Division acquired a number of new technologies, including those for the production of PVC, ABS and polypropylene, all of which were proven technologies. The laboratory staff helped the company to master the technologies, build the necessary production plants and optimise production processes. Thanks to the policy of diversification, the Central Laboratory had to build more and more expertise in plastics processing. Thus, research into construction techniques and materials helped researchers to gain knowledge of the properties and processing possibilities of plastic composites. Here too, approved research was the main type of research.

A low-pressure (or high-density) polyethylene plant at the DSM site in Geleen (Netherlands), 1994

Although some pioneering research was still done, it was much less self-evident than it had been in the past. In the late-1960s, for example, researchers had identified a new type of strong polyethylene fibre that they believed might form an alternative to the strong aramid fibre made by DuPont and Akzo. However, research into the fibre was conducted out on a limb from the rest of the organisation in the 1970s, and came to a halt when one of the main members of the research team left to join Groningen University (see Box 9: ‘Dyneema, a superstrong fibre’).

Reversal of fortunes

Remarkably, there was a revival in pioneering research in the latter half of the 1980s. DSM reversed its decision to pursue a policy of wide-ranging diversification, and decided instead to consolidate its activities in bulk chemicals and to focus on knowledge-intensive products with a high added value. ‘The adverse economic conditions in recent years have compelled us to view research and development primarily as a cost factor … and less as a critical source of the company’s future growth and development in new areas’, to quote a strategy document published by DSM in 1984.[66] This situation was set to change – thanks in part to the combined effects of an economic recovery and an improvement in DSM’s operating profit.

A year later, the Managing Board decided to embark on a series of massive investments in what it referred to as ‘corporate development programmes’. The Ministry of Economic Affairs awarded DSM various grants and loans in support of the programmes, which were based largely on the pioneering research carried out in the past. Four of the eight programmes involved plastics: one was aimed at commercialising the strong polyethylene fibre; another sought to develop special composites; a third was aimed at developing high-performance plastics such as new types of nylon; and the fourth was a quest to find electrically conductive polymers.[67]

It is clear from subsequent reviews that the results were disappointing. Only a small number of research projects made it all the way to completion and subsequently to a form of

Airline passengers at Valencia Airport (Spain) have their luggage wrapped in industrial-strength cling film by way of protection.

commercial exploitation. This was because the corporate development programmes were in fact innovation programmes and, as such, both expensive and risky. They consisted of a mix of pioneering and applied research, each of which was totally different from the other. Pioneering research was laboratory research, generating laboratory knowledge and laboratory prototypes. In most cases, such knowledge and prototypes were not immediately usable in a practical setting. Applied research (or development), on the other hand, brought the researchers into contact with a new world: it opened the door to scaling-up, commercialisation, the construction of the first production plant, the production and the launch of the new product on the market. The incidence of failure was high. The main reasons quoted for the failure of corporate development programmes were insufficient technological progress, lack of proper alignment with divisional activities, and inadequate market potential. 'Research is a lottery with very few yes's and loads of no's,' a former director of the Central Laboratory explained.[68] His rule of thumb was that, out of every 100 ideas or prototypes generated by research, 20 would qualify for further development and just one would culminate in commercialisation.

Relation to universities

The role played by DSM's Central Laboratory in relation to plastics hinged primarily on the economic conditions of the time and the policy pursued by the group as a whole. The economic recession meant spending cuts and a sharper focus on the relevance of research to corporate policy. The pursuit of diversification created a greater emphasis on approved research (i.e. funded by the divisions) – at the expense of basic and pioneering research. Although the opportunities for doing pioneering research resurfaced once DSM started posting better results, the scope for basic research remained limited.

This was due primarily to a constant factor during this period: the rise of the universities after 1970. They became increasingly active in the field of plastics and performed more and more research that would have qualified at DSM as basic research and to a certain extent also as pioneering research. This meant that companies such as DSM might just as well wind up some of their research activities. DSM managed to counterbalance this trend by creating a big network of part-time professors who worked both at DSM and at the Dutch universities. At the same time, the company also stepped up its funding of public-sector research.

However, this then generated a fresh question, i.e. how should DSM integrate the results of public-sector research into its strategy and innovation processes? As we have seen, innovation was already difficult enough in those cases in which most of the relevant expertise had to be mobilised in house. So how on earth would this work if some of the requisite expertise had to be sourced externally, i.e. from the public research infrastructure?

Before examining this issue, we will first look at another important change in the research infrastructure for plastics: the change in the status of the TNO Plastics and Rubber Institute.

The demise of the TNO Plastics and Rubber Institute[69]

The TNO Plastics and Rubber Institute (known by its Dutch abbreviation KRITNO) underwent a change of fortunes during the 1970s. The institute had just come to the end of a dynamic period in its history: besides enjoying wide recognition across the plastics industry, it had played a key role in the formation of the country's knowledge infrastructure, had performed collective research and had been granted numerous research contracts by private-sector companies. Despite succeeding in adjusting to the changes in the sector during this period, the institute nonetheless came to a sticky end.

Builders working on a DubbleDeck floor in Arkel (Netherlands). DubbleDeck is a new, environmentally friendly concrete floor system developed by a Danish engineer. The system consists of a steel lattice incorporating large, hollow plastic balls, enabling a 35% materials saving on iron and concrete. The system was also used in the construction of the 35-storey Millennium Tower in Rotterdam.

Just like the industrial research laboratories, TNO and the Plastics and Rubber Institute were hard hit by the economic recession during the 1970s and the early 1980s. A time of sustained, strong growth came to an end and was followed by a long period of stagnation. Yet the recession was not the only – or indeed the main – cause of the demise of TNO's Plastics and Rubber Institute.

The institute had felt the effects of heightened competition with the big laboratories operated by plastics producing companies such as DSM, Akzo and GE Plastics. In the 1960s, it had discontinued certain research programmes and shifted the focus of others. One of the fields affected was the synthesis of plastics, which received less attention as the institute switched the research spotlight to the processing of plastics. However, this was something that plastics manufacturers were now also doing more and more of, as they sought to provide a wide range of services to plastics processors. For example, they not only developed new and improved plastics for injection moulding companies, but also ensured that these plastics complied with the latter's specific requirements. They joined forces with their customers in developing new products, such as plastic garden chairs and plastic car bumpers.

The plastics processing industry had also matured in the meantime. A company such as WAVIN no longer needed to ask the Plastics and Rubber Institute for help in order to find the best way of extruding plastic pipes. Both WAVIN and other, similar companies had now set up big product improvement departments of their own. As a result, the institute gradually lost its value for the plastics processing industry. Its large collection of machinery and equipment rapidly became outdated and TNO did not have enough money to replace them. GE Plastics in Bergen op Zoom already employed a staff of around 50 for this purpose alone.

Design flaw

Another problem was a major design error in the way in which plastics research was organised at TNO. In the 1950s, basic research activities had been transferred from the Plastics and Rubber Institute to TNO's Central Laboratory. However, many big industrial firms remained interested in this type of research, which therefore performed well, without the institute being able to benefit from it. The organisational error was rectified in 1980, following which the institute's fortunes began to revive.

The change in the institute's fortunes was also the result of a decision to specialise – in dielectrics, for example. Among those interested in such research were Philips (with its electret microphones) and a consortium of companies making sticking tape and winding plastic film (where production lines would explode from time to time due to the build-up of static electricity during the winding process). Product development centred on carbon fibre-reinforced plastic products for use in space travel and the energy industry, among other applications. Another line of research was into the long-term behaviour of plastics; this involved studying the durability of the geotextiles used in the construction of the storm surge barrier in the Eastern Scheldt, for example. The institute also researched the fracture mechanics of plastic piping, including the crazing of PVC gas pipes, of which some 50,000 km had been laid underground in the Netherlands.

Advent of fine chemicals

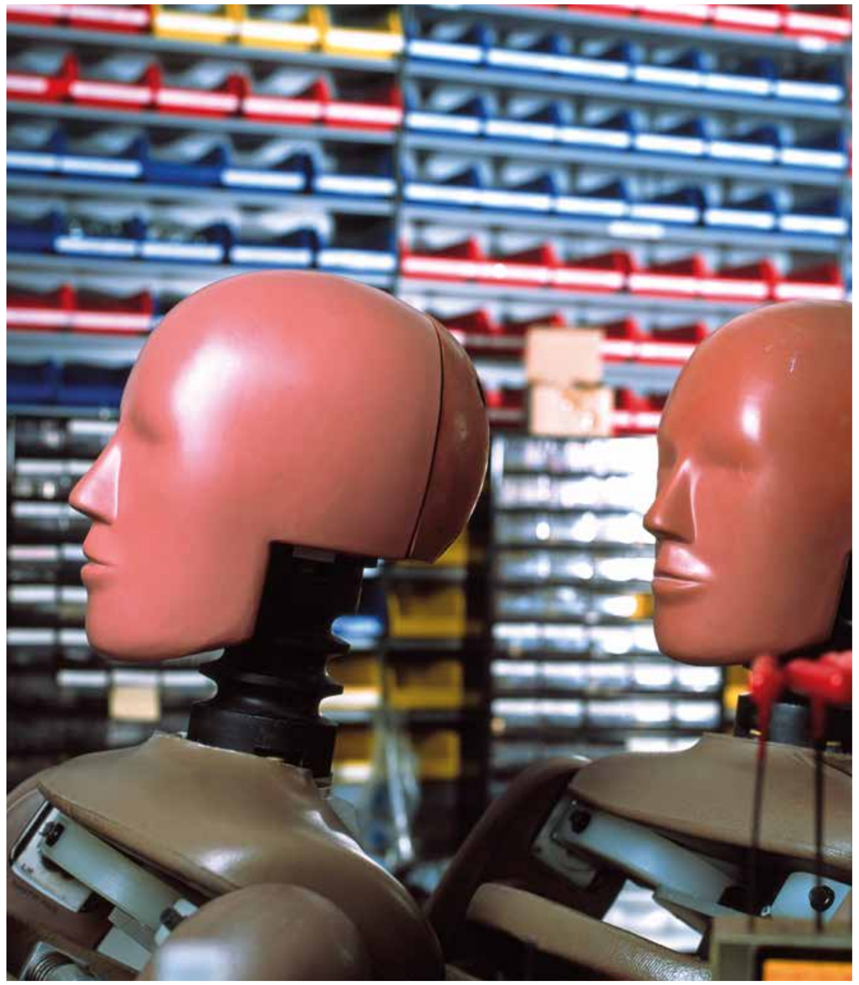
A new era for polymer technology began in the 1980s, partly due to the advent of fine chemicals, as the whole field of research into polymers started to spread its wings. New research topics arose, bringing with them a need for new forms of expertise. Universities, commercial companies and new research institutes all tried to fill the gap in the 'research market'. The Plastics and Rubber Institute played only an indirect role in this process – if at all. Notably, it was not involved in the foundation of the Dutch Polymer Institute in 1997.

The Dutch Polymer Institute pursued a generic programme of research into promising, specialist applications of plastics. 'What the Dutch Polymer Institute is doing is in fact a TNO-type activity,' asserted one observer, although the truth was that TNO had not been performing this type of research for some considerable time.[70] Curiously, the Plastics and Rubber Institute hardly participated in the Dutch Polymer Institute's research programmes. 'When the good people started to leave at the end of the 1980s, TNO simply collapsed.'[71]

The same trend was seen in the institute's role as a service-provider. In the 1990s, as the plastics producing industry began to wind up its services to the plastics processing industry, TNO failed to grasp the opportunity thus presented to it.[72] Eindhoven University of Technology did seize the opportunity, however, and set up a research centre called the Polymer Technology Group BV. Indeed, the universities as a whole began to do more contract research,[73] thus evolving into TNO's competitors. A former director of the Plastics and Rubber Institute claimed in 2011 that TNO was now 'a virtual non-entity' in the field of polymer research.[74]

The rise of the universities

Polymer science established itself as an academic discipline between 1945 and 1970. The main driving forces were the plastics producing multinationals in collaboration with TNO (see Part I of this monograph). During this period, companies such as AKU (later operating under the name of Akzo), DSM and Shell funded the vast majority of the research, postgraduate research posts and part-time professorships. With their industrial background, the professors in question were able to bring plenty of external research experience with them.



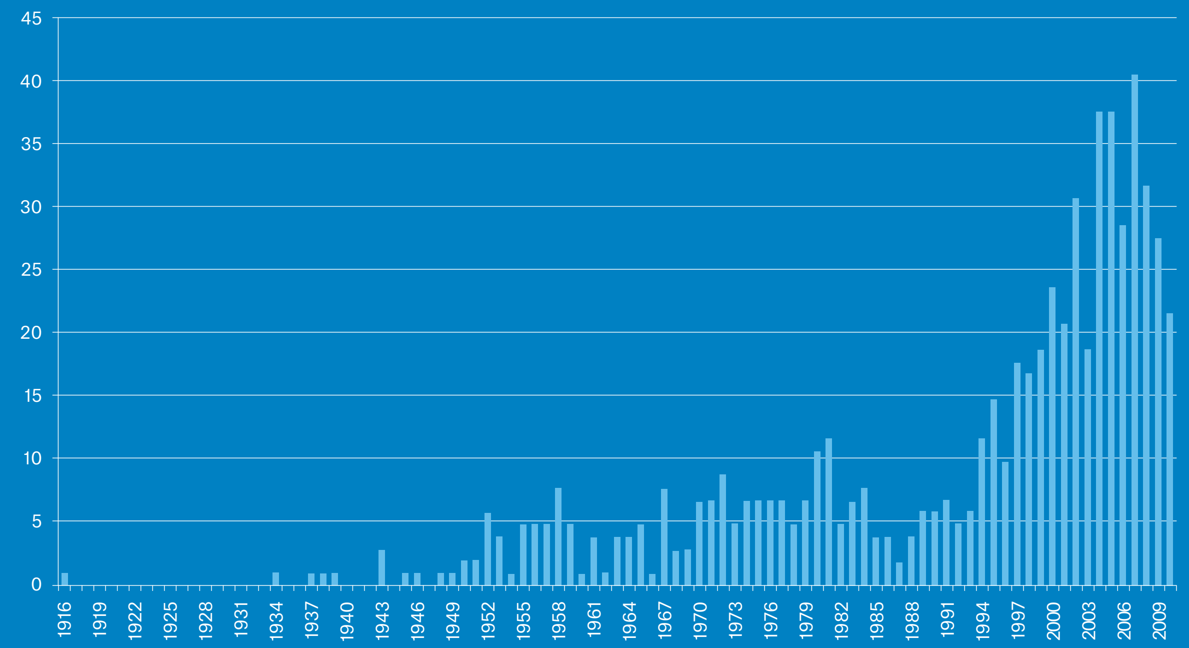
The so-called EuroSIDS (Side Imact Dummies) used in crash tests in Europe have a metal and plastic skeleton covered by flesh-simulating foam and plastic, with a PVC skin.

Trend in number of PhDs

The scale of research activities increased after 1970, a trend that is clearly reflected by the annual number of thesis defences. The number of defences averaged between five and ten during the 1970s (compared with the customary figure of between one and five during the 1950s and 1960s, see Graph 9.1). The number subsequently declined during the 1980s, hitting an all-time low of just two thesis defences in 1987. Things started to pick up again in the early 1990s, when there was a spectacular rise in the number of doctorates awarded, peaking at 41 in 2006. The number then declined again to 22 in 2010.

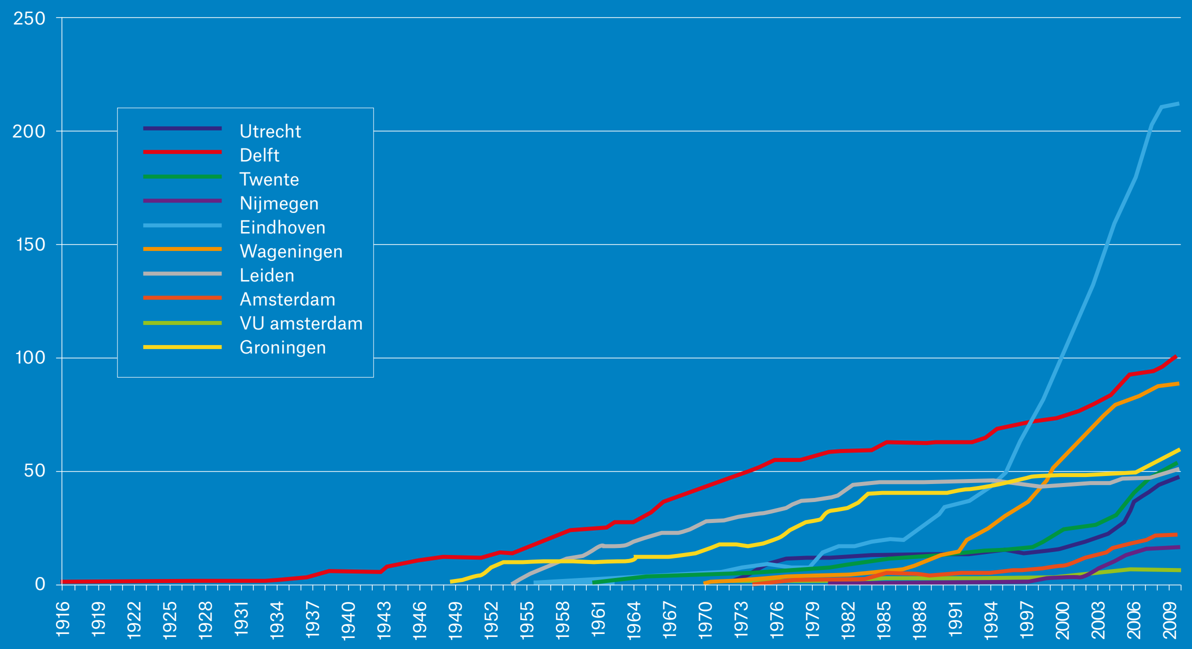
There are various reasons for these fluctuations. First of all, the multinationals continued to

GRAPH 9.1 Number of doctorates awarded each year for polymer research at Dutch universities, 1916-2010



SOURCE: Various university databases

GRAPH 9.2 Cumulative number of doctorates awarded for polymer research at Dutch universities, 1916-2010



SOURCE: Various university databases

invest in academic research in the 1970s, in part because they were in the process of winding down their own research activities. At the same time, polymer science came into its own as a university discipline. It had taken a great deal of effort on the part of polymer scientists to break the traditional mould at the universities. For example, it was not until 1979 that a 'work community' for polymer chemistry was set up at the chemical division (SON) of the Netherlands Organisation for Scientific Research (NWO).[75]

With polymer science now recognised as a fully-fledged academic discipline, the flow of university funding and research grants from the Netherlands Organisation for the Advancement of Pure Research (ZWO), the precursor of the Netherlands Organisation for Scientific Research (NWO), started to come on stream. At the same time, the universities began to place more and more emphasis on research, instead of concentrating solely on teaching. Nor was this purely academic research in the strictest sense: rather, there was a growing tendency to align research activities with current needs, both in industry and in society at large. Universities gradually transformed themselves from teaching institutions into research centres, and this trend is one of the explanations for the rise in the number of doctorates awarded for polymer research in the 1970s.

The situation changed in the 1980s, when both the government and multinationals decided to cap spending on university research – including polymer research. Both parties found themselves in financial straits and facing a need to curb their spending. Later on in this chapter, we will take a closer look at the period of rapid growth in polymer science after 1990.

There were also a number of big changes on the research front after 1970 (see Graph 9.2). Judging by the number of doctorates awarded, the leading Dutch universities in polymer research in the 1970s were the universities of Delft, Leiden and Groningen. They were joined in the 1980s by a second raft of universities: Eindhoven, Twente, Wageningen and Utrecht. Since the mid-1990s, the university awarding by far the largest number of PhD degrees has been Eindhoven, followed by Delft and Wageningen. Twente and Wageningen have been fast growers in this period. Until 2010, polymer research was firmly anchored in the Dutch universities, particularly at the three universities of technology, i.e. in Delft, Eindhoven and Twente, but also at Wageningen, Groningen, Leiden, Utrecht and Amsterdam. From 2010 onwards a decline set in, among others as a result of the government's innovation policy.

The Dutch Polymer Technology Foundation

The university research departments soon began to form national associations. The establishment of the Macromolecules Work Community at SON in 1979 was a big step forward, giving a big boost to the flow of research grants from ZWO (and its successor, the Netherlands Organisation for Scientific Research, NWO). In 1986, the universities of technology in Eindhoven and Enschede joined forces with the TNO Plastics and Rubber Institute and a number of industrial companies, with Shell at the forefront, to found the Dutch Polymer Technology Foundation (PTN). The Foundation's object was to coordinate training and research at the various research centres and to 'consult with industry'.[76]

While the Foundation gradually evolved into a national training centre, aligning university research with industrial research proved to be more problematic. Certain research departments, such as that in Groningen (one of the leading departments of the day), had already succeeded in obtaining a reasonable flow of funding from SON/NWO, and regarded close collaboration with industry as constituting a potential threat to 'unfettered research'. Consequently, they dissociated themselves from this aim of PTN.[77]

The fully automated production line of Record Industry, the world's biggest producer of gramophone records. The company, based in Haarlem (Netherlands), presses 4 to 5 million records per year. Vinyl is back and sales are soaring.

Collaboration between universities and industry

The year 1988 saw a fresh attempt at collaboration between the universities and industry, in the shape of the formation by the Ministry of Economic Affairs of a 'Materials Advisory Group' consisting of a mix of university professors and industry representatives. The Group's final report examined the issues of teaching and innovation in particular (see chapter 8), discussing university research in great detail and concluding that the universities were making remarkably little effort compared with industrial companies.[78] Indeed, the Group estimated that the scale of industrial research was 20 to 25 times bigger than that of university research. The Group also identified major shortcomings in fields such as polymer physics, modelling, plastics processing and polymer-based construction. The Group recommended close collaboration between industry and the universities and urged the government to intensify the scale of university research in all relevant fields, 'with a doubling of research volume in the long term being a distinct possibility.'[79]

The growth did indeed follow in the 1990s. NWO launched a 'priority programme' for materials research, with a budget of EUR 31 million.[80] The Ministry of Economic Affairs also contributed to the funding effort, by launching its 'innovation-centred research programmes' (IOPs) on polymer composites and IC packaging, as well as deploying other policy tools.[81] When the Minister of Economic Affairs announced a plan for setting up 'Leading Technology Institutes', the Dutch Polymer Institute was one of the first to be designated as such.[82] Launched in 1997 as a public-private partnership, the Dutch Polymer Institute pursued a demand-driven, generic research programme, in which industrial companies collaborated with university research departments under the Institute's supervision and with the Institute responsible for monitoring the quality of the research.

Polymer research infrastructure

Until recently, the public infrastructure for polymer research consisted of a number of university research departments, the PTN research school, and the Dutch Polymer Institute, which was itself an alliance of universities and industrial companies (both in the Netherlands and abroad) plus TNO. Another member of the infrastructure was the Polymer Technology Group BV (PTG), an independent subsidiary of Eindhoven University of Technology that was based on the university campus in Eindhoven and employed a staff of 20 researchers. PTG's work consisted mainly of carrying out analyses for SMEs and research projects for larger companies. It made use of university equipment and technicians.

The idea was that this infrastructure would plug the gaps that had been created by the changes in industrial research. Industrial companies were now performing virtually no basic research into polymers. Companies did take varying degrees of interest in pioneering and exploratory research, depending on their financial situation and corporate strategy. Development, i.e. applied research, was the dominant force in the formula.

As a result, policy-makers and research managers alike found themselves facing a dilemma: how could the public knowledge infrastructure help to boost the private sector's capacity for innovation? Until 1970, the big industrial companies had had in-house research departments that were capable of meeting the bulk of their research needs and which helped them to devise new products and processes. As we have seen, innovation-centred research proved difficult to manage. During the period after 1970, industrial companies tended to rely more on the public research infrastructure, which did not make things any easier. This is illustrated by the case of the Dutch Polymer Institute, which, during its 18 years as a Leading Technological Institute, played a key role in polymer research.

The Dutch Polymer Institute and the art of connecting[83]

As a Leading Technology Institute, the Dutch Polymer Institute (DPI) had the task of narrowing the gap between the supply of and the demand for knowledge in the field of polymers. The idea was that the institute would boost the academic contribution to polymer research and training, and ensure that academic research was aligned more closely with industrial needs. Finally, the institute was keen to improve the transfer of knowledge.[84]

The partner base of DPI consisted of private-sector companies (34 in 2010) and knowledge institutes (49 in 2010) from both the Netherlands and abroad. They were represented in a Council of Participants. A two-man Executive Board comprising a Managing Director and a Scientific Director was responsible for the institute's day-to-day management. DPI was funded by industry (which provided a monetary contribution), the research institutes (which contributed in kind by executing research projects) and the government (specifically, the Ministry of Economic Affairs), based on a 25-25-50 formula.

Structure of research

The areas of research covered by DPI were grouped into categories known as 'Technology Areas', which included Polyolefins, Performance Materials, Coatings Technology and Bio-Inspired Polymers.[85] A small office in Eindhoven provided the support needed for all of DPI's activities. In essence, it was the Technology Areas that formed the core of the institute's research platform. How did they work?

Each technology area had its own Programme Committee, which was responsible for setting the area's research agenda. The committee was made up of representatives of the participating companies, i.e. companies that had signed a partnership contract with DPI and made a financial contribution to the research budget for the area in question. Companies were free to participate in more than one technology area and could raise their level of control over a particular research programme by 'buying' more seats on the programme committee for the area in question.

Each programme was formally overseen by a staff member of DPI's central office, who was given the title of Programme Area Coordinator. Operating alongside the coordinator was a Scientific Chair, one for each Technology Area, who was responsible for supervising the programme from a scientific perspective. The policy was to recruit the Scientific Chair from outside the Institute.

The research projects coordinated by DPI were carried out by a large group of graduate researchers and a small team of postdoctoral researchers. Totalling 234 in 2010, these researchers were employed more or less exclusively by the research centres, universities in particular.

Peer reviews formed the main method of assessing the research proposals submitted by the research centres. There was also a Scientific Reference Committee, which was made up of a number of leading international scientists who each year assessed the coherence and scientific quality of the institute's research.

Organisational structure

The private sector was firmly anchored in DPI's organisational structure. The big chemical companies were well represented, with established plastics producers such as Shell, DSM, AkzoNobel and Dow Chemical taking their places alongside newcomers such as SABIC and LyondellBasell. There was also a wide-ranging collection of firms from all sorts of different industrial sectors: these included a manufacturer of synthetic fibres (Teijin Aramid), an electronics company (Philips), a tyre manufacturer (Michelin) and a dairy company (FrieslandCampina). Although the Institute had originally been set up by the Dutch Ministry of Economic Affairs as a means of supporting Dutch industry in general and the Dutch plastics industry in particular, the participation of foreign companies in its organisational structure not only made its network far more international in its make-up, but also injected more dynamism into its work.

Why were companies keen to join DPI? The companies themselves cited three main reasons.[86]

Access to international network

First of all, participation in DPI gave a company access to an extensive network of industrial and academic researchers, in both the Netherlands and abroad. Secondly, it also meant involvement in high-quality research projects that were capable of generating new ideas and theories. And thirdly, it provided access to a pool of highly qualified young scientists.[87]

Important as they were to private-sector companies, patents were not one of the main reasons for joining DPI. The bulk of patentable knowledge was developed by the industrial companies themselves, in many cases in collaboration with industrial or academic research partners. 'As far as we are concerned,' explained the research director of Teijin Aramid in Arnhem, a producer of high-performance fibres, 'the institute's added value does not lie in valorisation. Valorisation is something we can do ourselves. Participation in DPI is all about joining a network, acquiring new knowledge and adding to our existing knowledge. That's what makes it so valuable...'[88] DPI also acted as a platform that companies could use to get in touch with other parties (either companies or research institutes) and commission research projects.[89]

Companies did not necessarily expect research projects supported by DPI to result immediately in innovations. After all, innovation took place in-house in the companies themselves: this was the job of product development laboratories, technical departments, marketing departments – and indeed their management teams. The world of DPI was one of 'pre-competitive research', whereas the industrial companies were concerned with industrial research, designing and scaling-up production processes, setting up pilot plants and commercialising new products and processes.

Although DPI's research was not a direct source of innovations, a question raised at regular intervals was: how, in that case, did its research activities contribute to the innovation process? This had previously been a recurring internal issue within the multinationals themselves, in relation to their basic research activities on the one hand, and their development labs and production departments on the other (see the section headed 'Industrial research under pressure' above). It is worth bearing in mind that this was not an issue that related to DPI alone; it was also a common subject of debate in relation to the other Leading Technology Institutes.

By participating in DPI, companies hoped to gain an idea of the latest developments in the industry, as well as to find out about new ideas, current trends and technical feasibilities. The question is: was DPI's contribution to the industrial innovation process sufficient to ensure that these companies remained committed in the long term to the institute's research programme? In practice, the answer tended to vary from one company to another. As one industrial partner observed, 'You've got to be a very active participant if you want to get the most out of your participation.'[90]

Attitude of industrial companies

Some companies invested lots of time and effort in project meetings and in assisting the academic researchers. Others adopted more of an arm's-length approach. A professor described the situation as follows: 'Even if companies participate only to be informed about what is happening in the field, you would expect them to ask questions, to invite researchers to the company and ask them to explain their results to a larger group than the one or two people directly involved. But this hardly ever happens.'[91] The industrial researchers employed by the participating companies played a key role in this respect. Their quality and commitment were critical factors in the collaboration with the universities.[92]

There was also another aspect to companies' involvement in DPI. Commercial firms needed to come up with a new product just about every year, which meant not only short lead times for innovation projects but also that industrial researchers had to work in short bursts of concentrated activity. The question, therefore, was how to ensure that these industrial companies retained an interest in the type of long-term research undertaken by DPI.[93]

This was much less of a problem in an area such as Polyolefins, with its long research tradition. It was an issue, however, in relation to Performance Polymers, an area in which the industrial participants included DSM, Dow, SABIC and Teijin Aramid, and which was positioned much closer to the market.[94] In more general terms, the industrial companies tended to be rather more wary in the case of programme areas that had a relatively close bearing on the market.[95] The fact was that they often found themselves sitting next to their competitors at programme meetings. This problem could sometimes hamper frank and open discussions within a particular Technology Area.[96]

However, DPI also performed research in totally new fields, such as biobased polymers, in which considerations of market competition hardly played a role. There was a consensus among the industrial partners that DPI was the best vehicle for performing this type of research. It was not efficient for a single company to invest massive sums of money in virtually uncharted territory.[97] Research into plastic solar cells in the 1990s was a good example of this type of uncharted territory. In 2003, at a time when there was a risk of the relevant expertise being lost, DPI decided to fund a new six-year programme, known as the Organic Photovoltaics programme, thus preserving the knowledge infrastructure for the Netherlands.[98]

It was the job of the Scientific Chairman and the Programme Area Coordinator to make sure that the industrial partners remained interested in and engaged with the institute, and participated in the debates in the programme committees. They organised and ran the project meetings.[99] The steady growth in the number of industrial participants – from nine in 1997 to 21 in 2003 and subsequently to 38 in 2013 – suggests that they did indeed succeed in convincing them of the value of working together in a pre-competitive collaboration platform.[100]

In short, industrial companies participated in DPI in order to acquire relevant knowledge, deepen their knowledge of specific subjects and gain access to highly qualified, young scientists. Product innovation was not the main motivator for participation. Nevertheless, a 2005 report entitled *Evaluating Leading Technological Institutes*, commissioned by the Ministry of Economic Affairs, noted that DPI had made only a limited effort to ensure that newly acquired knowledge was quickly translated into new products, services and processes. Although the report added that this was not a problem in the case of DPI since industrial companies had a great absorption capacity for scientific knowledge, the government did expect action to be taken in this area.[101]

In 2006, acting in collaboration with the Ministry of Economic Affairs, DPI decided to set up a new body known as the DPI Value Centre. Targeted primarily at SMEs,[102] the new centre fulfilled a clear need, with some 40 companies signing up during the first six months of its existence.[103] Some needed feasibility studies; others wanted coaching, advice or workshops. DPI Value Centre also organised annual cross-technology area meetings, as well as an annual Polymer Innovation Day.[104]

Key performance indicators

In recent years, an average of 16 PhD theses and 135 other publications have been produced each year under the auspices of DPI. The institute has also been awarded an average of 10 patents every year. About half of the 44 or so researchers who leave DPI each year move to jobs with the institute's academic or industrial partners. DPI's academic publications have achieved a high Average Journal Impact Factor score for many years in a row. In terms of the citation impact scores achieved by public research institutes in the Netherlands, DPI was ranked second in 2005-2008, with a score of 2.19, making it the highest scoring Leading Technology Institute. This placed DPI on a par with the leading academic research groups in materials science in the Netherlands. Also, out of all the Leading Technology Institutes DPI had the largest number of patents to its name.[105]

Polymer research conducted by public-private networks has been shown to help build up valuable competences for the Dutch plastics industry. A study of Dutch polymer patents shows that, compared with foreign knowledge institutions, Dutch institutes see their scientific knowledge put to use more quickly – and more frequently.[106]

This is the context in which DPI's activities should be viewed. The institute's network has absorbed and enhanced internationally available knowledge, generated new ideas and adapted innovative designs to national needs. It has been young researchers who have done this work, 'human capital' that subsequently trickled through to the

Cross-border Event on Advanced Materials organised by DPI Value Centre, 2012

plastics industry, where they played a vital role in industrial innovation.

When the Dutch government introduced its new policy on leading industrial sectors in 2011, it abandoned the concept of Leading Technology Institutes. As a result, public-private institutes such as DPI are no longer funded directly by the government. The companies participating in DPI have decided that it should continue to exist as an independent, international institute for pre-competitive research funded primarily by its industrial partners. The latter will meet two thirds of the cost of the institute's research. The institute will obtain the remaining third of its funding requirement from a variety of alternative sources, such as the Ministry of Economic Affairs, EU incentive schemes such as Horizon 2020, and the Chinese and Brazilian governments.

DPI in its new form intends to extend its partner base to all parts of the value chain. To date, the bulk of its research has been performed on behalf of plastics producers such as DSM, SABIC and Teijin Aramid. In the new configuration, plastics processors such as Wavin and Bosch, as well as plastics users such as Mercedes and BMW, will also be involved in the development of research programmes. Together, they will have to search for a new generation of plastics and plastic products, and to find a solution to the environmental problems caused by the plastics value chain.

Dyneema, a superstrong fibre

Plastics consist of long macromolecules intertwined with each other rather like cooked spaghetti. In theory, if the macromolecules were to be untangled and laid out in neat lines next to each other, they would together form a strong fibre. Each individual macromolecule adds to the strength of the fibre. Although the theory had been around for a long time, it had proved impossible to put into practice.

The breakthrough came at DSM's Central Laboratory in Geleen, where Albert Pennings was working with Ron Koningsveld on the crystallisation of long polyethylene chains as undercooled solutions were stirred. In the early 1960s, he discovered that these macromolecules sometimes formed fibres consisting of parallel chains. When Pennings was subsequently appointed as a professor at Groningen University, he decided to continue with his research. One of his PhD students, Arie Zwijnenburg, spent weeks on end fishing threads out of a polyethylene solution that had been diluted with paraffin. There was not much intertwining between the molecules in this diluted solution. Zwijnenburg succeeded in pulling a polyethylene thread out of this solution – slowly, very slowly, just a couple of centimetres per minute. The result was the production of the very first strong polyethylene fibre, in 1976.

The big question, though, was how to turn this into an industrial process. The solution came three years later, in 1979. Two DSM researchers, Paul Smith (who was one of Pennings' students) and Piet Lemstra, decided to conduct further research into the problem. Using decalin as a solvent, they managed to produce a gel consisting of extremely long polyethylene chains. These could be drawn out more or less to their full length and then laid out parallel to each other in virtually straight lines. The result was an incredibly strong fibre.

The next challenge was how to scale-up the process. Han Meijer managed to dissolve the polymer in extruders at DSM's Central Laboratory, so that the process could then be performed on an industrial scale at speeds of hundreds of metres per minute. The superstrong polyethylene fibres were first commercialised in 1983, since when they have been marketed under the brand name of Dyneema. They are up to 15 times stronger than steel, and yet so light in weight that they float on water. The material is used in bulletproof vests, helmets, sportswear, fishing nets, sails, towing cables, surgical gloves and many other applications.

SOURCES:

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The plastic LED

'The Dutch Polymer Institute is one of the best examples in the world of successful collaboration between universities and industry' were the glowing terms in which Professor Paul Blom, Research Director at the Max Planck Institute for Polymer Research in Mainz (Germany), described DPI. He explained that the challenge facing DPI was to forge ahead successfully in the future, even without the support of its basic government grant (see chapter 9).

After studying physics at Eindhoven University of Technology, Blom first worked for Philips Research before taking on a professorship at Groningen University. He was then appointed as the Scientific Director of the Holst Centre in Eindhoven before assuming his current role, as the Research Director of one of the leading German research institutes, in 2012. Research into polymer systems with an electrical or optical function (such as plastic solar cells and plastic transistors) has been a recurring theme in his career. One of the subjects that have fascinated him constantly ever since his time with Philips is organic light-emitting diodes, otherwise known as OLEDs or plastic LEDs.

A plastic LED is made by placing a layer of special polymer between an anode and a cathode. The layer lights up when it is exposed to an electrical charge. Plastic LEDs are now used in small screens and displays. One of their main future applications is likely to be as a light source, where they should be able to generate big energy savings. One of the big advantages of polymers is that they are soluble in solvent, in much the same way as an aspirin dissolves in water. As the electronic component turns liquid, thin layers of film can be applied with the aid of a printer, rather as ink is applied to paper when a newspaper is printed. This should mean a massive reduction in the cost of producing the electronic components in question.
For the time being, however, this remains a matter of theory rather than practice. Researchers have yet to fully master the fundamental physical processes involved in transmitting electrical charges – as is needed in order to give a big boost to the efficiency of plastic LEDs. As someone who has been working on this problem for 22 years now, Paul Blom is familiar with every single facet. It was clear to him that he needed to collaborate with DPI. Blom was ideally placed to define a DPI research programme for organic polymer systems. After all, he still had useful contacts with the private sector thanks to his time with Philips, and he knew all about the needs of the industry. At the same time, he was also a key figure in the research world and was familiar with the main physical issues.

One of these issues involves the transport of charge carriers in the polymer layer, i.e. the electrons and holes. Light is emitted at the point where the electron and the hole come together, or 'recombine'. Research has shown that the transport of electricity depends, among other things, on the electrical field and the density of the charge carriers. Interestingly, in conductive plastics, the electrical charge is systematically lower in electron transporting layers than in hole transporting layers. Electrons have a tendency to mysteriously disappear, leading to a loss of charge and a lower light output. Research has shown that this is caused by 'defects' in the polymer layer.

How can these defects be localised and what exactly are they? Blom and other researchers recently summarised the results of 20 years of research in an article in a technical journal. Clearly, the problem has yet to be resolved. The researchers feel that they have almost cracked it and are very close to finding the answer – an answer that should prove of value not just to plastic LEDs, but also to plastic solar cells and other organic polymer systems.

SOURCES:

Paul Blom, interviewed by Harry Lintsen, 15 April 2016
M. Kuijk, Gert-Jan A.H. Wetzelaer, Herman T. Nicolai, N. Itina Craciun, Dago M. de Leeuw and Paul W.M. Blom, '25th anniversary article: Charge transport and recombination in polymer light-emitting diodes', *Advanced Materials* 26 (2014), 512-531

10. Trends in plastics and plastics technology

The Stedelijk Museum Amsterdam was reopened in 2012 after extensive renovations and the addition of a new wing (nicknamed 'the bathtub' because of its form), in which plastic materials played an important part.

In 1971, Bert Staverman, the then Professor of Physical Chemistry at Leiden University and the director of TNO's Central Laboratory, published an article reviewing the latest developments in polymer chemistry and plastics technology. Staverman claimed that science and technology had gone hand in hand during the first few years after the war. 'Not only were the description of kinetics and the mechanism of polymerisation reactions of immediate interest to both technologists and academic researchers. The same applied to the interpretation of measurements of viscosity, light dispersion and osmotic pressure ... A great deal has changed since then...'[107]

Polymer chemistry and plastics technology began to acquire dynamics of their own. At the same time, it became increasingly difficult to keep track of developments in the two fields. 'First, you now need to plough through a much bigger pile of literature in order to identify the most pressing problems. Second, the as yet unsolved problems are much more detailed and much more specific than they were 25 years ago...' To illustrate his point, Staverman quoted the example of a big international conference in Amsterdam attended by 200 delegates in 1949, at which a total of 27 papers had addressed the physics and physical chemistry of macromolecules. An international conference in Leiden in 1971 on the physics and physical chemistry of polymers attracted 800 delegates and a total of 282 papers.

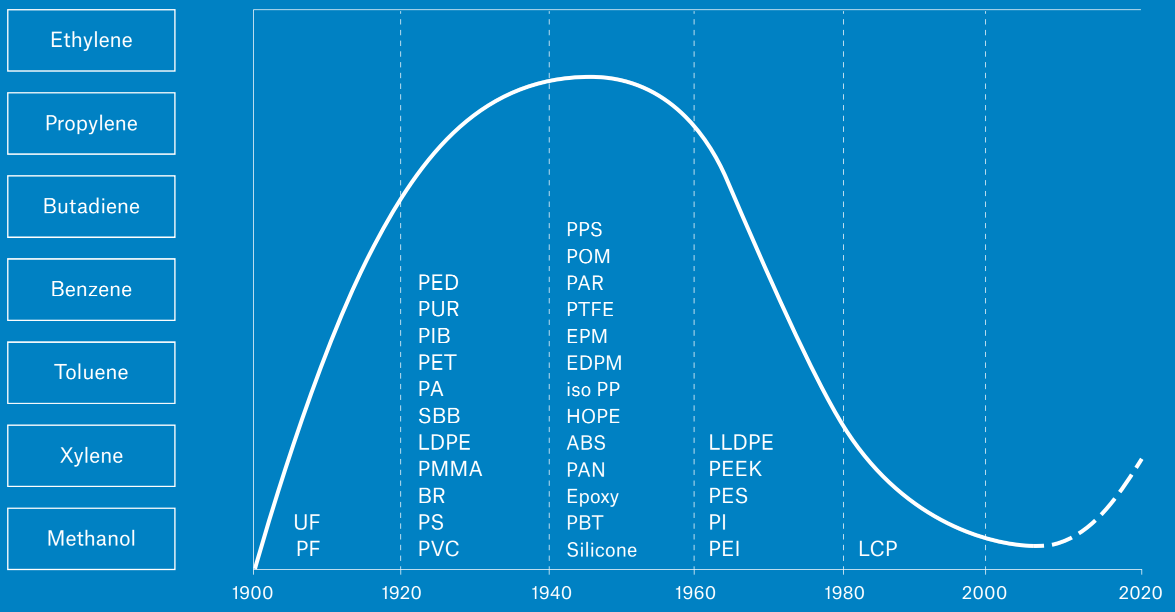
He looked back wistfully on the first few years. 'The atmosphere surrounding polymers and plastics in the years immediately after the war was full of hope for the future. There was a sense of glamour. Everything was new – not just from a scientific perspective, in terms of chemistry and physics, but also from a technological and commercial viewpoint. There was every reason for looking forward to great things in the future. And indeed, great things did happen. But now, in many respects, we have reached saturation point. Both commercially and technically, plastics are well-established, familiar products. The science of macromolecules has become one of the stock chapters in any history of chemistry and physics...' While research did continue – on an even bigger scale in fact – Staverman no longer expected it to generate any spectacular developments as in the past.

Developments in the field may indeed have been less spectacular after 1970 than before, but the saturation point had most definitely not been reached. What did happen was that the field changed beyond all recognition during the course of the next 40 years. We will illustrate the process by focusing on a number of distinctive trends.

The search for new polymers

When two researchers at the Royal Shell Plastics Laboratory published a list of plastics in 1974, they

GRAPH 10.1 The discovery of base polymers, 1900-2000



SOURCE: McKinsey, BASF, DSM

broke them down into the same basic categories as had been in vogue for the past 25 years, i.e. thermosetting plastics, thermoplastics and elastomers (rubbers), with various sub-categories falling under these.[108] Base polymers such as polypropylene, polyethylene and PVC figured prominently. However, polymer research had moved off in a different direction in the meantime: no longer was it all about identifying new base polymers (see Figure 10.1). Rather, the search was on for high-performance polymers.

As the search began to produce a growing diversity of plastics,[109] so the conventional classification now proved far from adequate. A base polymer such as polyethylene became a collective name for all sorts of materials, each specially developed for a specific processing technique and product.[110] Research also resulted in new plastics – such as polyether ether ketone (PEEK), polyphenylene sulfide (PPS) and polyethylenimine (PEI), with better properties in terms of rigidity, strength or temperature resistance. Experimenting with polymer composites – mainly plastics reinforced with glass, carbon or aramid fibres – was fashionable for a long time. Researchers also discovered the possibility of mixing two or more plastics. These 'blends' had better properties or came with a better price-performance ratio.

Engineering plastics

Consequently, the 1980s and 1990s saw the emergence of new categories of plastics – engineering plastics, functional polymers and biopolymers, for example. Engineering plastics differed from other types of plastics in that they had a high degree of rigidity and a high temperature-resistance. Their main purpose was to act as a metal substitute in structural sections and load-bearing structures, for example in cars. Their main advantage lay in their relatively low weight and cost, and the possibility of manufacturing a complex component in a single operation. Engineering plastics soon became commonplace, particularly in the automotive industry.[111]

Functional polymers

Functional polymers served a variety of special purposes. Liquid-crystal polymers (LCPs), for example, were readily used in watches, flat screens and other forms of consumer electronics. Piezoelectric polymers were suited for use in prosthetic hands, while photocopiers and plastic solar cells beckoned as potential future applications for electrically conductive polymers.[112] Some of these types of polymer are still very much in an embryonic stage. This is the case, for example, with plastic solar cells, which are being studied by an outstanding team of Dutch researchers.[113]

Biopolymers

Biopolymers formed another distinct category.[114] They found themselves in the spotlight in the wake of a public debate on the environmental and sustainability aspects of plastics (more on this in the following section). The idea behind

Plastics use in road construction work on the Bodegraven-Leiden railway line in the Netherlands in 2010. The photo shows the use of EPS geofoam blocks to support the grade-separated crossing being built to connect the N11 and N207 roads.

biodegradable polymers was that the polymer would break down after use into a number of natural substances. Biobased polymers were polymers that were produced from biomass rather than from fossil sources. Research into such polymers sparked a new trend: 'learning from nature'.

Researchers have pointed to the brute force that is often needed to produce conventional polymers: these require both high temperatures and high pressure. Nature has found a smarter way of doing it, however. Polymers occur naturally in all sorts of places. They are found, for example, in the starch in potatoes, in the cellulose in wood, in animal proteins, in human DNA, and so on. Nature produces natural polymers in 'natural' conditions, i.e. body temperature, ambient temperature, atmospheric pressure, etc. A variety of enzymes play a key role in this process. The question is: does this process lend itself to replication?

Biocatalysis is the name of the discipline that seeks to understand and control this process. The science of biocatalysis investigates the unique catalytic properties of enzymes that enable polymerisation processes to take place in mild conditions and with a low environmental impact.

Supramolecular polymers

Supramolecular polymers form a new category of polymers that were discovered only relatively recently.[115] Conventional polymers are made up of monomers held together by covalent (strong) bonds. Supramolecular polymers, in contrast, are made up of polymer chains held together by reversible, non-covalent (i.e. weak) bonds. This means that the mechanical properties of supramolecular polymers depend largely on non-covalent bonds. This has a number of major advantages, the main one being that the melt viscosity (which determines the material's flow behaviour) depends greatly on the temperature. A slight rise in temperature to above the melting point results in a sharp decline in viscosity, i.e. the flow resistance. This makes supramolecular polymers easier to process than conventional polymers with similar properties.

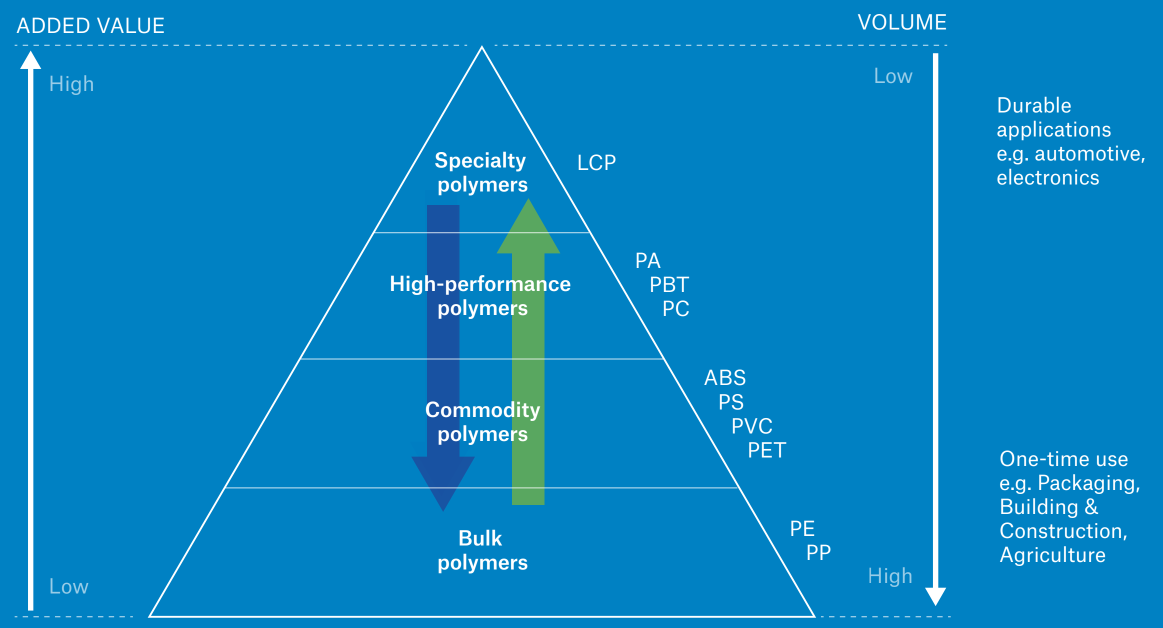
An array called UPy (or 2-ureido-4[1H]-pyrimidinone, to give its full name) plays a crucial role in this. A UPy is part of a monomer and contains four hydrogen bonds that link the monomers to each other by means of non-covalent bonding. UPy units can be used to produce monomers in such a way that supramolecular polymers are then self-assembled. Researchers are now also trying to find self-healing polymers that would enable a damaged plastic product or synthetic coating to repair itself, as well as self-organising polymers that would be capable of replicating complex, natural processes such as the dynamic behaviour of proteins.

This is a field of research that holds tremendous promise for the future. Researchers are studying potential applications in all sorts of different areas: medicine, electronics, inks, coatings, fibres, cosmetics and many more. One potential application is the targeted delivery of drugs for the treatment of tumours.[116] The idea would be to encapsulate the drug in a supramolecular polymer that reacts to a low pH value, a measure of acidity. The polymer would only disintegrate when it reaches the tumour, as tumours have a low pH value compared with other parts of the human body.

Value pyramid for polymers

The trends in the development of polymers may also be illustrated by classifying polymers on the basis of the two key features of price and functionality (see Figure 10.1).[117] The figure shows the value pyramid for polymers. The base consists of bulk polymers which, produced as they are in large volumes and at low cost, have only a low added value on the market. They are used in disposable plastic products, packaging materials, and film and sheeting for use in agriculture and horticulture. In short, they are suited for non-reusable (or 'one-time use') products.

FIGURE 10.1 The value pyramid for polymers



SOURCE: P. Nossin, *Biopolymeren in breder perspectief. Nut en noodzaak* (n.p. 2012), 19

Sitting at the peak of the pyramid are the specialty polymers. Produced in small volumes and at high cost, these have a high added value. They are either durable or have other, special properties. This category includes ultra-high-performance composites that are used mainly in the aviation industry, as well as the supramolecular polymer used for drug delivery purposes.

The area between the base and the peak of the pyramid is filled with commodity polymers such as PET (as in PET bottles) and high-performance polymers, including various types of polyamides and engineering plastics, and with a progressively rising added value and progressively declining production volumes.
The trend after 1970 has been a dual one. First, the plastics in the lower parts of the pyramid have been upgraded. Secondly, the plastics in the upper parts of the pyramid have been upscaled. Upgrading means that a polymer competes with a higher category, whereas upscaling leads to competition with a lower category in the pyramid.

Design and processing

Another trend has to do with the design of plastics. The rise in the design opportunities has been nothing short of spectacular.[118] The main reason for this has been the advent of computers, together with software packages for devising and designing plastic products and performing calculations on them. In 1982, for example, designers were able to use a software package called the 'mold flow system' to determine the ideal wall thickness of products, calculate their rigidity and strength, and analyse the effects of using different sprue points and cooling line diameters.

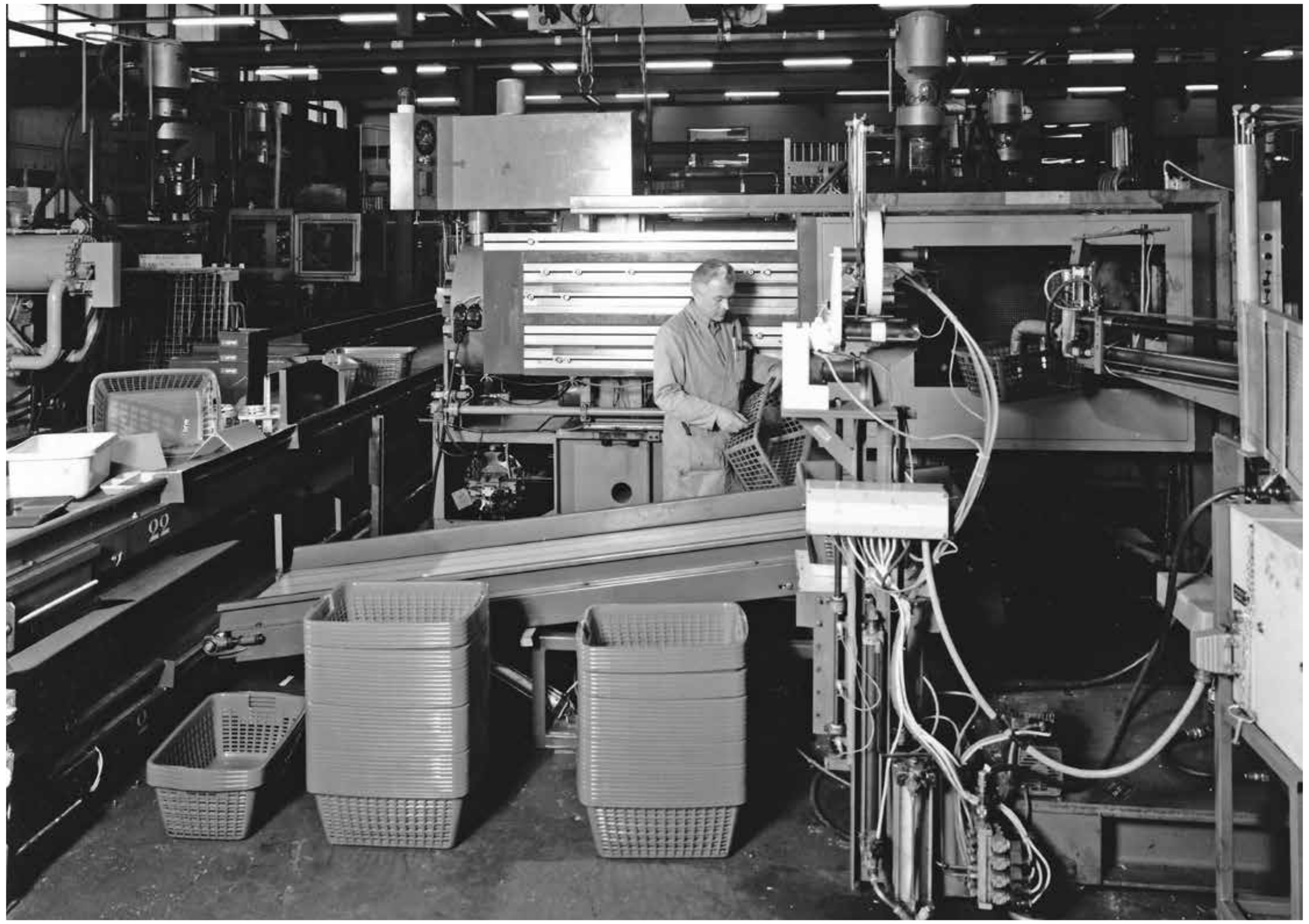
The introduction of the finite-elements method (FEM) was another, highly promising development. This enabled designers to optimise the design of their products, so that they were more reliable, more attractive and lighter in weight. It soon became easier to design and produce complex products consisting of a number of components as a single design. Designers began to appreciate the value of simulations.

In parallel with these developments, a new generation of machines launched in the 1980s offered designers all sorts of new opportunities. Computer-controlled injection moulding machines could be set to extremely narrow tolerances, thus allowing products to be made with curved parting lines and more closely aligned mould parts. Computer-aided design became the new buzz word in plastics technology and was used to prevent previously common errors such as the absence of draft angles, inconsistent wall-thicknesses and the absence of rounding.

A more recent development is the possibility of designing a product from start to end of the product life cycle. In other words, the designer plans the entire process, beginning with the raw material and ending with the disposal of waste and the recycling of the plastic – together with all the intermediate stages. The aim is to keep the product loop as closed as possible, and to produce a fully sustainable product (see the next chapter).

To a certain extent, the trends in the processing of plastics were foreseeable. Each new generation of machines consumed less energy and was more productive than its forerunner, i.e. it could produce more plastic per hour and per employee. Mechanical engineers played a vital role in this process, for example by improving hydraulic systems.[119]

AkzoNobel CEO Hans Weijers demonstrates the new product Expancel. Mixing the gas-filled plastic with hot water results in a 40-fold increase in the volume of the material without any increase in weight. The plastic is used in the production of lightweight shoes and tennis balls. (2011)



Plastic baskets roll off the injection moulding production line at Curver in Brunssum (Netherlands), 1982

Electronics

However, there was another major contributor. This took the shape of a new dimension in the processing of plastics: the use of electronic controls and computers. In the 1970s, machine manufacturers introduced the use of microprocessors. Stork Plastics Machinery was the first to come up with a new type of injection moulding machine equipped with a microprocessor-based control system including a computer screen.[120] Manufacturers started using hydraulics and mechanical transmissions. The use of automation and robotics soon became widespread, with injection moulding systems one of the main beneficiaries.[121]

Injection moulding machines produced products of a consistent quality, with short lead times and very little need for human supervision. It became easier to accurately control variables such as the melt temperature, the mould temperature, the injection speed and the product cavity pressure. Products could be adapted more quickly and more accurately to new conditions or new raw materials. Cycle times grew shorter and cost prices fell. The same trends were seen in relation to processing techniques such as blow moulding, thermoforming and coating.[122]

New processing techniques

New processing techniques were also needed to combine different materials in the end product.

Production of plastic buckets at Curver in Brunssum in the 1980s

Machine manufacturers started producing machines for two-component injection moulding, co-extrusion, tri-extrusion and the lamination of film, sheeting, tubes and bottles. A number of highly specific innovations also appeared on the market, such as plastic welding, gas injection moulding, gas counterpressure, decoration techniques and recycling. Special, high-speed injection moulding machines and special moulds were used in order to produce thin-walled articles for the packaging industry. A tie-rod-free injection moulding machine was one of the key inventions of the 1990s, paving the way for the use of bigger moulds, the production of bigger components and a more efficient use of robots. Energy consumption fell as fully-electric injection moulding machines arrived on the scene.

A more recent development is 3D printing, a technique in which a plastic product is built up layer by layer with the aid of special software. Apart from enabling prototypes to be produced quickly and cheaply, 3D printing also makes it easy to adjust the product.

New peripherals and accessories

There were also plenty of new developments in relation to peripherals and accessories. The innovations came in the form of pre-dryers, i.e. dry-air dryers; colouring equipment, i.e. the use of dyes or coloured pastes; mould-heating equipment designed to allow moulds to be heated up or cooled down in a controlled process; manipulators, which allowed the product to be removed from the mould with the aid of ‘pick and place’ machines, robots and so forth; and rapid-exchange systems for quickly replacing moulds and raw materials.[123]

The production of moulds was a story in itself. The quality of the end product depended greatly on the use of a good mould. New tools and processing equipment – such as electrical discharge machines (EDM) or spark erosion machines and numerically controlled machine tools – made complex products easier to make. Computer-aided design techniques reduced the risk of errors and the computing power of computer-aided engineering led to far more accurate designs.[124]

A final trend worth mentioning was the tendency for plastics processing operations to evolve into assembly plants. This was often associated with very strict specifications in terms of shape and dimensions, along with stringent quality controls and the imposition of new demands on both operational management and staff training.

Polymer processing: a new discipline[125]

While polymer research evolved into a scientific discipline after the Second World War, the processing of plastics long remained a ‘craft’, based largely on practical knowledge and experience. After 1970, this field also developed into an academic discipline, with its own journals, conferences, professorships and networks.

Today, polymer processing is a multidisciplinary field encompassing fluid dynamics, heat transmission, flow properties (rheology) and mechanical engineering. The links with polymer chemistry and polymer physics have helped to broaden the scope of the field. The complexity of processing techniques has made a form of ‘smart’ simplification essential. Subject-specific knowledge is acquired with the aid of simplified calculations and models, together with measurements using carefully selected modelling systems, encompassing both the processing machine and the polymer itself. The use of the finite-elements method has enabled researchers to obtain excellent results from complex strength and flow calculations. The aim in all cases is to objectivise and universalise knowledge. In other words, it must be possible to extrapolate the results achieved with a particular modelling system to other machines and polymers. The findings must also help researchers to work out the exact nature of the demands that machines and polymers need to meet. While the use of models helps to understand the practical aspects of plastics processing, they will not generate any innovations in the short term.

The bio-based economy

Whereas the circular economy is all about the efficient reuse of raw materials, limiting the amount of waste and reducing the production and use of new raw materials, the bio-based economy revolves around the use of renewable biological materials. Their main advantage is that they are inexhaustible. Biological materials offer exciting new opportunities for plastic materials and products based on biopolymers.

There are three different methods of using biological materials in the production of biopolymers. The first involves extracting bio-based building blocks, i.e. monomers, from biomass. These monomers form the base material from which polymers are produced. Certain building blocks, such as ethylene, are similar to their petrochemical counterparts, which means that they are easy to slot into existing production techniques. For others, such as lactic acid, a degree of special expertise is needed to process them into polymers and plastic products.

The second method involves extracting natural polymers such as starch, cellulose, lignin and proteins from vegetable matter. The advantage offered by these polymers is that they no longer need to be built up step by step. All that is required in most cases is for them to be ‘modified’ to a certain degree: this means adding properties such as heat resistance, flexibility and water resistance.

Algae and micro-organisms form the basis of the third way of producing biopolymers. The advantage of algae and micro-organisms is that they take up relatively little space (unlike plants, algae can also be grown in vertical cylinders and cylinder stacks). As a further bonus, genetic modification can be used to grow algae and micro-organisms so that they produce certain polymers that have a specific value for human beings.

In addition to working on biopolymers, researchers are also trying to develop bio-based additives such as plasticisers and stabilisers. One of the leading research centres in the Netherlands is the Food & Bio-based Research Department at Wageningen University & Research.

Biopolymers are used in car components, domestic appliances and floor coverings. Coffee cups can be made from polylactic acid, while packaging materials can be produced from tomato stalks. Biopolymers can serve as base materials for products such as paints, coatings and adhesives.

However promising the bio-based economy may seem, it does not come without certain drawbacks. And it is due to these problems that the future of the bio-based economy is clouded in uncertainty. The first generation of biofuels was (and still is) derived from sugar (sugarcane and cane sugar), starch (wheat and corn) and vegetable oils (sunflower, rapeseed, soya, palm, etc.). Given that sugar, starch and oils are also used as foodstuffs, biofuels have attracted fierce criticism for competing with food production for agricultural land.

One way of resolving this problem is by applying the principle of cascading. This means that the most valuable parts are extracted first from the raw material (see also the description of the second method above) and used for the highest value purposes. This allows the inedible components of food crops to be used (as ‘second-generation biofuels’). High-value applications are often relatively small-scale. The least valuable parts are then used as fuel, thus minimising the degree of competition with food production.
A potential problem is that the separation of high-value polymers from other polymer may prove costly.

Fuels based on algae form a third generation of biofuels. These do not compete with food production and only require sunlight in order to grow. As we have already seen, this generation of biofuels can be used for producing specific polymers.

In spite of all this progress, there is little likelihood of a switch to a bio-based economy in the near future. The algae-based technology is still in an embryonic stage and there are all sorts of problems involved in scaling-up the process to an industrial scale. It remains the case that many of the bioplastics produced with the aid of the two other methods are unable to compete with conventional plastics in economic terms. Even though university research into bio-based chemistry and polymer technology continues to thrive, the interest shown by industrial companies is on the decline. And while a large number of chemical and petrochemical companies embraced bio-based chemistry as a highly promising field several years ago, many of them have now discontinued their research programmes. Particularly for bulk chemical giants such as Shell, bio-based chemistry does not appear to offer attractive prospects at present. The situation is different for speciality chemical companies such as DSM.

SOURCES:
P. Harmsen and M. Hackmann, *Groene bouwstenen voor bio-based plastics. Bio-based routes en marktontwikkeling* (Wageningen 2012)
R. Hölsgens, *A petrochemical industry beyond petroleum? An exercise in applying the multi-level perspective to a still to come transition* (Unpublished RMA thesis, Maastricht University 2011)
Website of Wageningen UR Food & Bio-based Research, retrieved June 2015

11. The debate on plastics and sustainability

The Big Plastic Globe (called Wereld Nest in Dutch, 'world nest') in the Dutch city of Dordrecht, 2013. It was created in order to draw public attention to the problem of plastic litter in the oceans.

TNO's Plastics and Rubber Institute celebrated its 40th anniversary in 1986. It was decided to mark the occasion by publishing a book on the past, present and future of the plastics industry. Some 70 experts working in the plastics sector were invited to contribute articles. The end result was a book of almost 350 pages in length presenting a wide-ranging review of plastics, their properties, production and processing techniques, and applications. The tone was optimistic.

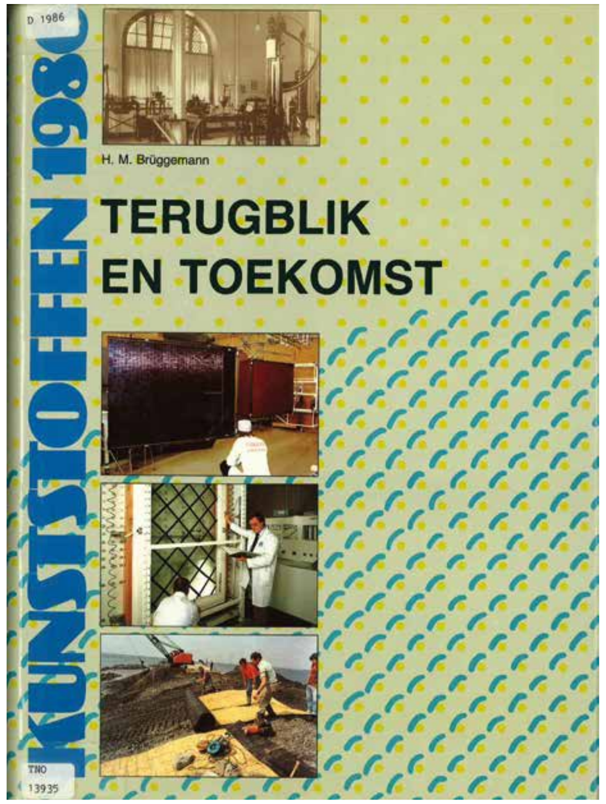
Interestingly though, barely a word was mentioned about the controversies surrounding plastics. There was the odd oblique reference to '...the actual or alleged risks and the environmental effects...'[126] The subject of plastic waste was given a little over two pages, with discussion primarily focussing on the relative merits of landfill and incineration.[127] Here and there, there was talk of the potential drawbacks of plastics, but these were either downplayed or parried with counterarguments. This, in sum, was all that the select band of representatives from TNO, the universities and the industrial companies had to say about the public debate on the environmental and sustainability aspects of plastics.

They should have known better. Plastic had already acquired an ambivalent image back in the 1950s and 1960s. Whilst conjuring up an impression of progress and modernity, it was also associated with junk, litter and waste. These negative connotations were very much still in evidence. Not only that, but the rise of the environmentalist movement had thrown up all sorts of other issues, too. The upheaval culminated in a fierce assault on PVC in the 1980s.

During the same period, a debate arose about the health and environmental risks associated with the use of additives in plastics. The publication of the Brundtland Report in 1987 extended the debate to the issue of sustainability: the key elements here were the energy supply and the limited stocks of fossil fuels.

The attitude taken by the plastics experts typifies the approach adopted by the chemical industry in general – and the plastics industry in particular – during this period. Although the latter was reactive and prepared to adapt, it did so with a certain degree of reluctance. It complied with industry regulations on an ad-hoc basis and opposed any changes it regarded as being too far-reaching.

In the Netherlands, the industry gradually started to change in the 1990s. Companies adopted an idea the seeds of which had been sown abroad and which boiled down to what is now called 'corporate social responsibility' or 'responsible corporate citizenship'. Environmental, health and sustainability issues were accepted as part and parcel of a company's responsibility and



To mark its 40th anniversary, TNO published the book Kunststoffen 1986, Terugblik en Toekomst *(Plastics 1986, Looking Back and Looking Ahead).*

thus demanding an active and preventive policy response.

Today, this line of thinking is propagated by the Dutch Federation of the Rubber and Plastics Industry. It is supported in this respect by PlasticsEurope, an association of leading European plastics producers, and the Association of the Dutch Chemical Industry (VNCI). All three organisations perform research into plastics and sustainability, support sustainability campaigns mounted by companies, work together with the government and try to publicise their work. The image they seek to project is one of an industry that accepts its responsibility as a partner '... to policy-makers and other pressure groups, in trying to find solutions to the critical problems of climate change, energy conservation, the efficient use of natural resources, consumer protection and waste management...'[128] Plastics have a major – and indeed positive – role to play in relation to these issues. Plastics can help solve these problems.

The question is: can the plastics industry deliver on these claims?

PVC, additives and health

A new and important topic of debate in the 1970s and 1980s was the risk posed by plastics to public health. The debate centred on PVC. Before then, there had been no controversy whatsoever surrounding the use of PVC. With PVC production on the rise around the world, PVC production volumes in the Netherlands shot up, too. Then, in the 1960s, the first stories began to surface of diseases affecting workers who had been involved in the production of the vinyl chloride monomer, i.e. VCM, the monomer used in the production of PVC.[129] An investigation performed in the early 1970s (in part at the request of foreign plastics producers) established a link between VCM and various forms of cancer, notably liver cancer.

In West Germany, an article in *Der Spiegel* in December 1973 about *'Gefährlicher Kunststoff'* ('Dangerous plastic') led to reports of illnesses among staff working on the production of PVC. In the following year, a Dutch newspaper called *De Waarheid* ('The Truth') reported 12 fatalities around the world. A Dutch daily, *Nederlands Dagblad*, claimed (together with various other newspapers) that there had in fact been 25 PVC-related deaths.[130] A Dutch journalist later wrote in a book on occupational disease that '...the doctors and university researchers who were involved in the 'discovery' [of the carcinogenic properties of VCM] were kindly requested not to cause any industrial unrest by publicising their findings.'[131] There were no reports of any fatalities in the Netherlands.[132] In 1976, an interim report published by the then Minister of Social Affairs claimed that a study of over 700 workers employed by companies producing VCM and PVC had failed to identify any symptoms of disease. The report did note, however, that a number of the people examined had reported minor complaints, but said that 'it was impossible to say whether these were the result of their exposure to PVC'.[133]

In the Dutch town of Broek in Waterland, PVC water pipes were replaced by copper pipes after toxic substances had been found in the drinking water (January 1981).

Health risks affecting PVC production

In 1974, the Dutch government decided to reduce the maximum concentration of vinyl chloride to which workers were permitted to be exposed, initially from 200 ppm to 50 ppm. But when 13 cases were identified in West Germany in which workers' auto-immune system had been affected, it was decided to lower the upper limit even further, to 10 ppm.[134] In response, DSM informed the staff of its PVC production plant that exposure levels were already under the new limit of 10 ppm, but that extra precautions (such as the use of gas masks) would be taken to protect any workers who might potentially be exposed to a level of more than 10 ppm. In the end, the government lowered the limit even further, to 1 ppm. The leading PVC producers, such as AKZO-Zout Chemie, Shell and DSM, protested, claiming that the new limit was both unrealistic and financially unaffordable.[135] Despite their objections, the exposure limit was lowered and companies were forced to adjust their working practices. Although this action remedied the initial problems surrounding PVC, the material's image nonetheless suffered considerable damage.

Health risks affecting PVC use

The debate then shifted from the production of PVC to the use of PVC.[136] Although the plastics industry had insisted since the early 1970s that PVC did not pose any health risks and that there was no unpolymerized VCM in PVC, a fierce debate was sparked about the safety of foods wrapped in PVC. The US, Sweden and Denmark took the lead in this respect. Keen to arm themselves against a looming national debate, Dutch PVC manufacturers set up their own pro-PVC lobby group.[137]

At the end of the 1980s, environmental activists launched an all-out assault on PVC, both as a material in general and more specifically as a form of packaging. This was despite the absence of any irrefutable scientific evidence to suggest that PVC constituted an immediate threat to food safety.[138] The packaging industry defended itself by pointing out that the levels of residual VCM were so low as to be totally incapable of causing any damage. In 1989, three pressure groups, the Dutch branch of Friends of the Earth, the Dutch Society for Nature and the Environment and the Dutch Consumers' Association, joined forces with other consumers and environmental organisations in mounting a campaign against the use of PVC packaging.

The campaign was a success.[139] One of the big nationwide supermarket chains was one of the first to decide to stop using PVC packaging – not so much because they were convinced it was dangerous, but rather because they wanted to preclude any arguments and problems with their customers.[140] For its part, the government kept a fairly low profile in the debate. The end result, however, was that the packaging industry felt compelled to reduce the use of PVC packaging by 90% within a two-year period.[141]

Today, PVC is seldom used as a packaging material. Thanks to its durability, it is however used in large volumes in a wide range of products, such as plastic window frames, sewage pipes, water pipes, cars and also – albeit in smaller volumes – in articles such as toys.

Dioxins

Another issue involving PVC also arose around the same time as the health concerns described above. In 1989, higher than usual concentrations of dioxin were found in milk originating from a cheese farm in the province of South Holland. It was decided that two incinerators in the near vicinity, one operated by a local waste processing company and the other by Akzo, were the likely sources of the contamination. Despite the fact that not much was known about the relationship between PVC and dioxin, commentators identified materials such as PVC, which were present in the incinerators, as being the main culprits. The waste processing company was forced to install filters on its two gigantic chimneys. A study performed by Marike Leijs in 2010 showed that the emission of dioxins (stemming in part, but not exclusively, from PVC) during the incineration of waste did indeed create health risks for local residents. She identified a number of effects on the health of children who had been brought up in the vicinity of the waste incinerators. However, even in the early 1990s, people were so anxious about the effects of dioxins that measures were immediately taken.[142] These days, the flue gases from incineration are treated to prevent any dioxins from being emitted.[143]

Curiously, the debate about PVC has not been replicated in relation to any other plastic. There has not been any opposition to the production, use and processing of plastics such as polyethylene or polypropylene. Where there has been debate, it has been about plastics in general, with secondary debates on issues such as additives cropping up at regular intervals. Additives are used to give plastics special properties, such as a particular degree of hardness, a colour, resistance to a particular temperature, a certain degree of light-sensitivity, etc.

Additives

In the 1980s for example, Heineken was attacked by consumer organisations and environmental activists for its use of cadmium.[144] Cadmium is a heavy metal that the brewing company used so as to ensure that its beer crates retained their bright yellow colour. Once it came under pressure, Heineken tried to find a suitable alternative – which it ultimately succeeded in doing in 1989, in collaboration with its supplier.[145]

The production hall of VDL Nedcar in Born (Netherlands) was converted and re-equipped for the production of the new MINI under contract to BMW. (2014)

To give another example: the Dutch Consumers' Association first reported in 1974, based on a publication by its German sister organisation, that certain toys (such as monsters and mice made of soft plastic) could be dangerous when used by children. If a child swallowed a toy and if the toy then spent a number of days in the child's stomach and bowels, this might debase the plasticiser (generally di-2-ethylhexyl phthalate or DEHP) in the toy to such an extent that the plastic could then become 'as hard as glass' and might also get sharp edges. The German Consumers' Association had reported that a West German child had died in 1962 from a perforated bowel caused by swallowing one of these toys.[146] Although the Dutch authorities were aware of the risks, a study by the Consumer Products Inspection Department did not indicate there was any need to 'ban these creepy animal toys as being unlawful'. However, the Department said that this did not necessarily mean that the plasticiser used in the toys was harmless.[147]

The debate on plasticisers in toys still flares up from time to time.[148] In 2004, for example, a controversy arose over the use of phthalate plasticisers in 'Scoubidou' strings, i.e. PVC threads and tubes that children knot together to form different objects. Once again, there were reports from West Germany that the strings contained too much plasticiser, i.e. over 30% by weight. The Dutch Food and Consumer Product Safety Authority published the findings of a study of its own, which concluded that the proportion of phthalates in the products was between 5% and 28% by weight and that the rate of emission of phthalates varied between 0.1 and 3.2 µg/min/10cm²: 'The National Institute for Public Health and Environmental Protection has concluded that plasticiser emissions do not constitute a threat to children's public health'.[149] However, Michael Braungart, one of the originators of the cradle-to-cradle concept, has claimed that phthalates disrupt hormonal regulation and cause infertility and that, on these grounds, they should be banned outright.[150]

The use of lead in PVC is a final example. Rigid PVC may contain lead as a stabiliser. It is unclear whether the lead is dangerous: the PVC industry claims it is not, because the lead is bonded to the plastic and cannot therefore be released. The European Union has decided to play safe on account of lead's toxicity and has demanded that PVC should be fully lead-free in the future. Dutch manufacturers of plastic piping decided a few years ago to stop using harmful heavy metals such as lead and zinc.[151] European PVC manufacturers have promised to replace all lead stabilisers with safe alternatives, such as calcium salt, by 2015.[152]

The effects of the use of additives are clouded in doubts and disagreements. Michael Braungart[153] believes there is a 'pernicious alliance between governments, the scientific community and industry ...As long as studies are performed, researchers get paid, no one needs to take action to implement solutions and companies do not need to take responsibility...'[154]

At the same time, the plastics industry is doing its best to project an image of credibility. For example, manufacturers of plastic piping asked the Dutch Institute for Building Biology and Ecology (NIBE) and the Belgian research agency VITO (which plays a role similar to that played in the Netherlands by NWO) to assess the sustainability and environmental aspects of its piping systems.[155] However, both users and the public at large find it hard to know exactly how much is true of all the claims and allegations made about plastics.

Energy and the environment

'Most plastic products need less energy to be produced than other materials, especially in application areas such as transport, building and construction, packaging and electronic devices. If plastics had to disappear and be replaced by alternatives, the life-cycle energy consumption for these alternatives would be increased by around 57% and the GHG emissions would be 61% higher,' so the PlasticsEurope industry association claims.[156] But is this true?

Back in the 1970s, shortly after the oil crises, Professor Anne Klaas Van der Vegt of Delft University of Technology asserted '... that the amount of energy required to produce a plastic product is virtually always smaller – and in some cases much smaller – than the amount needed to produce a similar article from another material, such as glass, metal or ceramics'.[157] He did not provide any statistical evidence to back up this assertion, as did Pilz, Schweighofer and Kletze, on the other hand, in 2005, when they published the findings of an extensive survey, casting in doubt a number of Van der Vegt's claims.[158]

Energy savings in production?

They concluded for a start that 19% of the plastic materials included in their study were not replaceable by other materials. Where alternatives were available, an examination of the energy consumption during the production process generated a wide range of results. For example, the production of thin, plastic piping required between 70 and 140 mega joules less energy per kg than comparable pipes made of alternative materials.[159] In other cases, the production of a plastic product was more energy-intensive than the alternatives. The production of insulation for refrigerators, for example, required 68 mega joules more per kg of plastic than if other materials were to be used. The authors of the study did not provide any data on the aggregate energy savings. A study performed five years later, in 2010, suggested that the aggregate level of energy savings in the production process could be potentially around 25%.[160]

However, plastics are capable of delivering major energy savings not just in the production process, but also during their actual use. Indeed, this is one of the main benefits of plastics in terms of their contribution to a sustainable future.[161] Many plastics are extremely durable and relatively low in maintenance – plastic window frames being a good example.

Plastics are also much lighter than other materials. Cars can reduce their fuel consumption if certain components are made of plastic instead of metal. Plastic bottles consume more energy during production than glass bottles, but they are less energy-intensive in transport and use. The same applies to the refrigerator insulation to which we have already referred. However, the validity of these conclusions depends enormously on the way in which the products in question are used and reused, which makes them hard to quantify. Moreover, it is clear from practical experience that the purported degree of energy-saving during usage is often nullified by extra consumption and functionality. For example, even though cars are becoming more fuel-efficient, they are now used more intensively and are more likely to be fitted with air-conditioning than was the case in the past.

Finally, energy is also generated from plastic when plastic waste is incinerated. In the Netherlands, almost 60% of plastic waste is reused, and just over 30% is more or less fully incinerated (generally in the form of household waste) in incinerator plants fitted with heat recovery systems.[162] Obviously, CO_2 is released during the incineration of plastic. On the other hand, filters are used to remove the vast majority of contaminants, which means that incineration these days is a fairly clean method of waste disposal.[163]

The proponents of the incineration of plastic waste regard plastics as forming an intermediate stage between oil and gas as crude raw materials and the final phase in which they are used as a source of energy: the carbon atoms have been put to use in the form of plastic, but retain 90% of their calorific value as they have not been immediately incinerated. Many commentators regard reuse as the ideal method of waste management. Although it requires energy, it is still the most energy-efficient alternative.

Life-cycle assessment

While there is some evidence to support the plastic industry's claim that the life cycle of plastic products is more energy-efficient than that of comparable products made of 'conventional' materials, it is probably not quite as watertight as the industry would like to make out. The range of products is simply too great and the matter too complex to allow simple conclusions to be drawn that apply across the board. Moreover, energy and the use of fossil fuels are not the only important factors in relation to product life cycles. A comprehensive analysis also requires that an assessment be made of environmental aspects such as land use, water contamination and the contribution to climate change. In other words, the status of plastics is even more complex than appears at first sight. A tool known as a life-cycle assessment (LCA) can help to clarify things.

However, even an LCA of something ostensibly so simple as a carrier bag can be a source of confusion. A press release issued by the Dutch Federation of the Rubber and Plastics Industry reports that 'plastic carrier bags have the lowest environmental impact', noting that this finding is in sharp contrast with their poor reputation. A closer examination reveals that the LCA in question was performed by an organisation called the 'Netherlands Institute for Sustainable Packaging',[164] which examined bags made of a range of different materials. Admittedly, the production of certain plastic bags has a low environmental impact. 'I realise that this is something they are keen to stress,' the institute's director commented, 'but they failed to take account of the fact that bags may end up as litter. Where this happens, plastic bags actually score badly, because they do not easily degrade – if at all.'[165] The findings of the LCA show that two particular types of bag perform better than the rest: medium-sized bags made of recycled paper, and 'big shopper' bags made of jute. These are more easily degradable if they end up as litter in the natural environment.[166]

Biodegradable plastics, bio-based polymers and recycling[167]

Litter is an old problem that has been around since the beginning of the previous century (see Part I). Paper packaging was initially the main culprit, but it was superseded by plastics after 1970. This was one of the reasons behind the quest to find biodegradable plastics. One of the pioneers in this connection was a Canadian professor called James Guillet, who managed to find a solution to the dichotomy facing him: on the one hand, plastic packaging needed to protect its contents by resisting attacks from micro-organisms, while at the same time it had to be capable of being degraded by the very same organisms if it ended up in the environment.[168]

Most plastics are resistant to micro-organisms. Neither the long carbon chains nor the crystalline structure of polymers provides organisms with a useful starting point for converting carbon atoms into CO_2 and water. Although these footholds are to be found at the ends of the chains, they do not result in any meaningful degradation of the plastic, whether during or after use.[169]

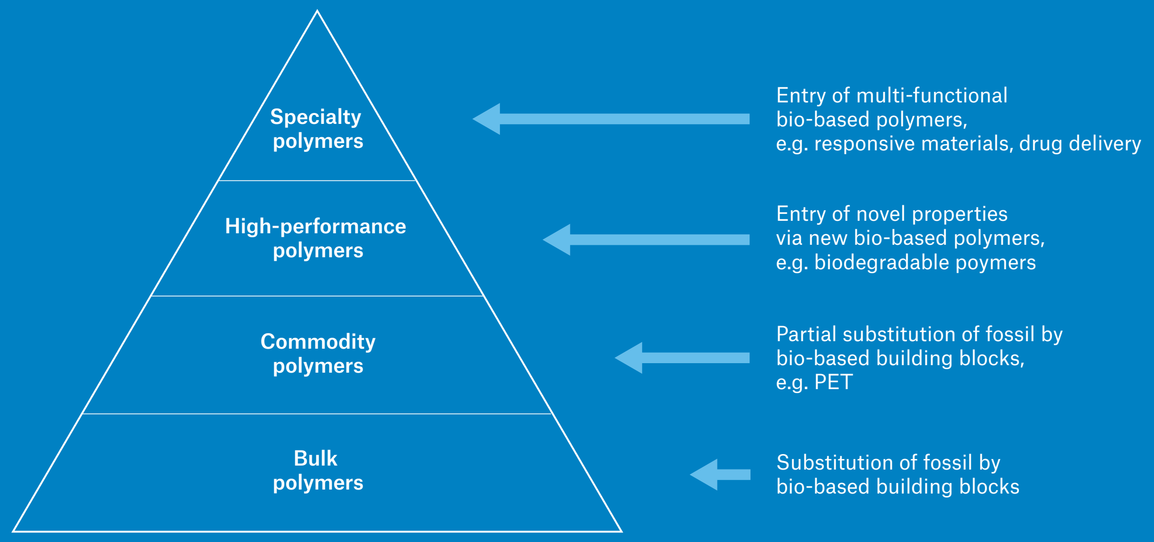
In other words, in order to make plastics fit for degrading, they first need to be divided up into smaller pieces. Professor Guillet found the answer in the form of sunlight – and more specifically, in the ultraviolet light emitted by the sun. By adding to the polymer certain additives that were sensitive to sunlight, he was able to break down both the molecular chain and the crystalline structure, so that micro-organisms could do their work better. The technology was patented by Guillet's employer, the University of Toronto. A joint venture set up by a Toronto-based company called Eco-Plastics Limited and a Dutch firm called Royal Packaging Industries Van Leer took on the task of commercialising this degradable plastic, which was given the trade name of Ecolyte.[170]

Unfortunately, the results were disappointing. The plastic was only degradable in the presence of sunlight. It did not degrade if it was covered with earth or buried in a landfill site. Another problem was that the plastic did not actually degrade so much as crumble into tiny pieces. And it took micro-organisms a long time to degrade these tiny pieces – many years in some cases.

Today, aliphatic polyesters account for the majority of biodegradable plastics. These are synthetic polymers that can be digested by micro-organisms thanks to their resemblance to certain natural polymers. However, digestion can take place only in ideal conditions that are seldom found in the natural environment. Moreover, they are relatively costly to produce, making them too expensive to replace bulk polymers in packaging materials, agricultural film and disposable articles.

The situation today is that a biodegradable polymer has an added value only in certain niche markets such as packaging for organic foods. In short, it does not form a viable means of reducing the volume of litter. As an added problem, its often poor material properties make it unsuitable for higher-performance applications. Biodegradable polymers have failed to live up to their expectations. After 40 years of research and development, the global volume of production is approximately 300 kilotonnes per annum, representing 0.13% of world output.

FIGURE 11.1 Entry of bio-based polymers in the polymer pyramid



SOURCE: P. Nossin, *Biopolymeren in breder perspectief. Nut en noodzaak* (n.p. 2012), 21

Bio-based polymers

A similar fate lies in store for bio-based polymers (see also Box 11: 'The bio-based economy'). These include natural polymers such as cellulose, starch, proteins and gelatine, either obtained from crops or produced by micro-organisms or algae, as well as polymers based on bio-based building blocks obtained from renewable sources, such as sugar (from sugarcane or cane sugar), starch (from corn and wheat) and vegetable oil (from coleseed and rapeseed). The idea is that bio-based polymers should help both to replace fossil fuels with renewable energy sources and to solve the climate-change problem by reducing greenhouse-gas emissions.

Peter Nossin, a Programme Area Coordinator at the Dutch Polymer Institute, believes that the technical potential of bio-based polymers is huge.[171] In theory, around 90% of the plastics currently in use could be replaced by bio-based polymers. In practice, however, the results achieved to date have been discouraging. One of the main problems has been how bio-based polymers can gain entry to the polymer value pyramid (see Figures 10.1 and 11.1).

Bio-based polymers inevitably need to compete with a rival in each segment. Among the bulk polymers, for example, bio-polyethylene has to compete with polyethylene, primarily in terms of its cost price. Bio-polyethylene loses just about every one of these battles.

The cost price is also the determinant factor among commodity polymers, although there are certain opportunities for bio-based building blocks for plastics, so that there is some degree of partial substitution. This applies, for example, to the use of polyethylene terephthalate (PET) in PET bottles.

In Vinkeveen (Netherlands), refuse collectors from the waste management company SUEZ Environment pick up 'plastic heroes' bags. Plastic Heroes is an initiative of packaging manufacturers in the Netherlands, who have set up a waste collection system for used PET bottles and other plastic packagings. (2009)

The cost price is less important in the segment of high-performance polymers. Here, functional properties such as a high temperature resistance and resistance to wear are the critical factors. Once again, the bio-based polymers tend to lose out to the competition, with one or two exceptions, such as polyethylene furanoate (PEF), which would appear to have better properties than PET.

The uppermost segment, i.e. the speciality polymers, is the segment with the best opportunities for bio-based polymers. Here, bio-based polymers with certain specific characteristics are capable of meeting a market need that is not currently being catered to. A polymer that is used for making heart valves using cells from the patient's body is a good example of a specialty polymer. The cells in question are grown on a plastic scaffold in a biogenerator, and the scaffold gradually degrades as the cells take on the shape of a heart valve.

As bio-based polymers tend to have a poor price-quality ratio, they are seldom a viable substitute for synthetic polymers. The situation in the European Union is that biopolymers, i.e. both biodegradable and bio-based polymers, account for between 0.1% and 0.2% of the aggregate polymer output. Out of this relatively small amount (i.e. between 55 and 110 kilotonnes), 65% is used in packaging (including padding), 21% in rubbish bags, 8% in fibres and 6% in miscellaneous products.

The Dutch Polymer Institute believes that the role of biopolymers is unlikely to become much more important during the coming decades. Synthetic polymers have the backing of mature technologies, a wide range of fossil fuels (including shale gas and coal) and well-established production chains offering plenty of scope for innovation. The technology of bio-based polymers, on the other hand, is in an embryonic stage; full production chains going all the way from the farm to production and use are yet to be put in place. Most production facilities are still in the pilot stage.

The centre for bio-based polymer research in the Netherlands, Food & Bio-based Research in Wageningen, is much more optimistic about the future. The centre believes that levels of interest in biopolymers are running high, and that the government and consumers alike are keen to invest in sustainability. The chemical industry is looking to replace more and more petroleum-based raw materials – which are growing scarce – with biomass.[172]

In economic terms, the best opportunities for bio-based polymers are to be found in countries such as Brazil, with its emerging economy and surfeit of renewable energy sources. From a technical viewpoint, a promising future for bio-based polymers beckons in biotechnology. Research into enzymes (proteins that act as catalysts for chemical reactions) for polymerising and functionalising biopolymers presents a big challenge for the future. Even so, the Dutch Polymer Institute has decided to discontinue its research programme for bio-based polymers. According to the institute, one of the reasons for taking this decision is that there is a completely different and more promising route for improving the sustainability of synthetic plastics: recycling.

Recycling

The Dutch government's 'national waste management plan' describes the way in which waste is to be processed.[173] The plan states that

An above-ground container for the collection of plastic waste, 2010

John Vernooij, director of Omrin, a Dutch company specialised in the collection and processing of plastic waste, shows one of the products – a marble game tile – made by his company from recycled plastic waste. (2016)

as much plastic waste as possible should be recycled and that, where this is not possible, such waste should be incinerated. Landfilling in the Netherlands has virtually ceased.

However, the recycling of plastic waste is complicated by the difficulty of separating and sorting the wide variety of plastics in use. One of the main reasons for this is the way in which plastic products are designed. Manufacturers and designers design products to be 'fit for purpose', and not to be 'fit for recycling'. As a result, the cost of use is out of kilter with the environmental impact during the product's life cycle; it is society at large that pays the environmental cost. Sustainable use requires a different approach to design, taking account of the costs and benefits of plastic products throughout their entire life cycle. Laws and institutions are needed to support this process. Slowly but surely, this is now the direction in which society is moving.

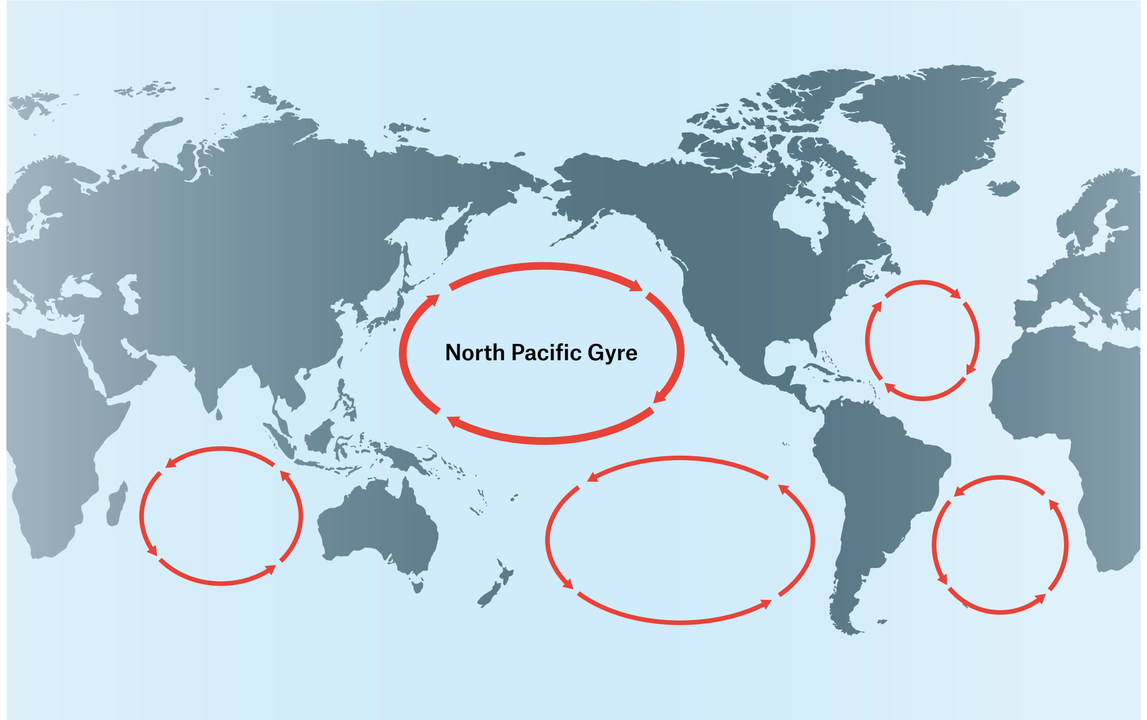
As a further point, recycling cannot succeed without constant research into new technologies. Virtually all large flows of plastic waste produced during the course of industrial processing are now recycled. While this is the ideal method of disposing of plastic waste, it is restricted to flows of pure plastic waste, i.e. plastic waste that is not mixed with other types of waste. Mixed waste flows, as in the case of household waste, are generally incinerated instead of being separated.[174] Consumers often find it difficult to separate plastic waste from other forms of household waste as they are not sure as to how it should be classified.[175] Where mixed waste flows are recycled, this is generally confined to low-value applications such as boards for use in scaffolding, drainpipes, playground equipment and park benches. Research is currently being performed into ways of simplifying the separation of plastic waste, but the solutions under investigation are expensive and still in an experimental stage.[176]

Plastic soup

Plastic waste in the sea is likely to become one of the main sustainability issues involving plastics in the coming decades. This is due to the unimaginable quantities of plastic that end up in the oceans every year: the effects of this problem are virtually incalculable and we are still a very long way from finding a solution to it. A recent article in *Science* reported on a study in which researchers had worked out that a total of 192 littoral states produced some 275 million tonnes of plastic waste in 2010. Of this amount, it was estimated that between 4.8 and 12.7 million tonnes ended up in the sea, a much larger amount than had previously been assumed.[177]

A large part of this waste collects in five different places in the oceans. Known as gyres, these are spots where a number of ocean currents flow together in a spiral movement. The most famous of these gyres is the 'Great Pacific Garbage Patch', which was discovered by Capt. Charles Moore in 1997.[178] The area of plastic rubbish is estimated to be between 1 and 15 million square kilometres, larger than the area of the United States. The issue hit the headlines in the Netherlands when Jesse Goossens published a book entitled *Plastic Soep* ('Plastic Soup') in 2009.

There are four aspects to the problem of plastic soup – or rather, plastic litter in the sea, to use a term with a broader scope. First, there is the visual problem: plastic littering the sea and the coastlines is an eyesore. Second, birds and other animals mistake plastic waste for food, so that it ends up in their stomachs. A small number of animals succumb straightaway, while others gradually weaken. An examination of dead fulmars found along the Dutch coast in 2009-2013 showed that 94% of the birds had bits of plastic in their stomachs, the number averaging 28 per bird.[179] The researchers found that, in 52%



The North Pacific Gyre, where the Great Pacific Garbage Patch is said to be located.

Boyan Slat, the founder of The Ocean Cleanup, speaking to the press, with in the background the North Sea prototype of the floating system he has devised for cleaning up plastic waste from the oceans. (2016)

of the birds, the volume of plastic constituted a breach of 'environmental safety limits'.[180]

The two aspects described above involve relatively large pieces of plastic. However, the third aspect of the problem is the fact that, as it drifts in the sea, plastic is broken down into countless minuscule particles. These particles then provide a growth environment for organic matter, which is then consumed by fish. It is as yet unclear whether this has an adverse impact on fish stocks.

Finally, the presence of plastic particles in the sea may attract toxins such as dioxin. A certain proportion of these toxins then builds up in the polar ice or settles in the seabed. Again, very little is known at present about the effects of this. Another fraction of these toxins is ingested by fish and thus ends up in the food chain. Here too, we know very little about the effects this has on the natural environment and human health.

Various obstacles stand in the way of a lasting solution. One of the main hindrances is the status of the ocean as a 'global commons': accessible to everyone, its availability declines as more use is made of it. Or, as one headline writer put it, 'The sea belongs to everyone, so no one cleans it up'.[181] Apart from environmental groups, both political organisations and organisations from the plastics industry such as PlasticsEurope, the Dutch Polymer Institute and the Dutch Federation of the Rubber and Plastics Industry are aware of the issue. However, the problem has no 'owner', which means there is no powerful party that is capable of instigating international action. Accordingly, most of the action taken to date has been in the form of national campaigns. In the Netherlands, for example, attempts have been made to stem the flow of litter into the sea. The main polluters, however, are China, Indonesia, the Philippines and Vietnam,[182] all countries in which the resolution of environmental problems does not figure prominently on their government's list of priorities.

There is also a big technical barrier hindering a solution. While it would be technically feasible to 'fish' the big pieces of plastic out of the sea (and one of the biggest clean-up campaigns in history, 'The Ocean Cleanup', was launched by Boyan Slat, a student from the Delft University of Technology),[183] how on earth would it be possible to get rid of all the minuscule particles? This remains an intractable problem. The main strategy proposed thus far is one of prevention, the idea being that recycling and other measures should help to prevent plastic waste from ending up in the natural environment in the first place.

Plastic soup is likely to remain a problem for a long time to come. Drifting in the oceans is a massive legacy from the past to which present and future generations will only add even larger expanses of plastic. The debate will be clouded in all sorts of uncertainties and confusion: the scale of the problem remains unclear and studies are not always representative and do not always result in clear conclusions. What the world needs is a technical breakthrough and an adequate international context. There is a genuine risk that the problem of plastic soup will ultimately assume the same proportions as that of climate change.

Notes

1 W. Bongers. 'De Nederlandse kunststofindustrie in 1975', *Plastica* 29(1976), 239.

2 Ibid., 239.

3 'Nieuwjaarstoespraken DSM', *Plastica* 28(1975), 26.

4 For example, around 1985 the payback period for a brand new polypropylene (PP) plant was less than two years and in some cases even as short as six months. H. Meijer, former researcher at DSM, interviewed by H. Lintsen, 27 April 2015.

5 K. Sluyterman, *Concurreren in turbulente markten, 1973-2007, Geschiedenis van Koninklijke Shell, deel 3* (Amsterdam 2007), 96-98. See also: M. Davids, H. Lintsen and A. van Rooij, *Innovatie en kennisinfrastructuur. Vele wegen naar vernieuwing* (Amsterdam 2013), 174.

6 For Shell, see: K. Sluyterman, *Concurreren in turbulente markten*, 125-155.

7 For DSM, see: A. van Rooij, *The Company That Changed Itself. R&D and the Transformations of DSM* (Amsterdam 2007), chapter 4 and H. Lintsen (ed.), *Research tussen vetkool en zoetstof. Zestig jaar DSM Research 1940-2000* (Zutphen, 2000), 84-87.

8 For Akzo, see: K.F. Mulder, *Choosing the corporate future. Technology networks and choice concerning the creation of high performance fiber technology* (PhD dissertation, Groningen 1992).

9 K. Sluyterman, *Concurreren in turbulente markten,* 125-155.

10 This paragraph is based on: E. Homburg, 'Part 3: The era of diversification and globalization (1950-2012)', in: K.Bertrams, N. Coupain, E. Homburg, *Solvay. History of a multinational family firm* (Cambridge 2015) in particular 20.2, 22.2 and 23.

11 In the 1990s, Shell US also developed an improved route for polytrimethylene terephthalate (PTT), which was used in clothing and especially in carpet tiles (as a substitute for nylon). Shell eventually discontinued the production. Information provided by Alexander van der Made of Shell.

12 Carilon was intended for use in products such as fuel tanks in cars, but Shell had underestimated how time-consuming it was to convince car manufacturers. Information provided by Alexander van der Made of Shell.

13 The financial losses that Shell suffered in the Carilon project in fact spelt the end of the company's development of new bulk plastics worldwide. If Shell couldn't turn its enormous efforts into success, who could...? In the event, polyketon (Carilon) was given a new lease of life. In 2014, the Korean company Hyosung took up production of polyketon based on the patents acquired from Shell.

14 'Japans Shin-Etsu koopt fabrieken in Botlek en Pernis', *Trouw* 9 October 1998 (see also: http://www.trouw.nl/tr/nl/5009/Archief/article/detail/2731006/1998/10/09/Japans-Shin-Etsu-koopt-fabrieken-in-Botlek-en-Pernis.dhtml (consulted on 15 January 2016) and 'Shell verkoopt vinylfabrieken aan Shin-Etsu', *NRC Handelsblad* 9 October 1998.

15 M. Abrahamse, 'Basell voorziet nieuwe fusiegolf chemie', *Financieel Dagblad* 10 April 2002.

16 'Rendement een op tien Shell-dochters onder de maat', *Financieel Dagblad* 17 December 2001.

17 'Shell en Basf verkopen joint-venture Basell', *Financieel Dagblad* 29 April 2005.

18 Including epoxy resins and KRATON rubbers.

19 Information provided by Alexander van der Made of Shell.

20 See Shell's website: http://www.shell.com/business-customers/chemicals/manufacturing-locations.html#EU (consulted on 14 January 2016). Among others at the site of CNooC & Shell (Shell Nanhai BV 50%, CNOOC Petrochemicals Investment Limited 50%) in Nanhai (China).

21 On the sale to SABIC, see for example: 'Saudi mogen van Brussel DSM petrochemie kopen', *Financieel Dagblad* 20 June 2002.
On the sale to Lanxess, see for example: 'DSM heeft 'belangrijke overnames' in het vizier', *Financieel Dagblad* 14 December 2010.

22 See for example: http://fd.nl/ondernemen/1096777/aandeel-dsm-hoger-na-verkoop-caprolactam (consulted on 14 January 2016).

23 According to Emmo Meijer, who was in charge of technology and innovation at DSM for several years, DSM became less innovative in bulk polymers in the 1990s; it lost its strong technology position in this field and became too dependent on licences owned by other companies. This, together with the other factors mentioned in this chapter, contributed to DSM's decision to withdraw from the bulk polymer business. E. Meijer, interviewed by H. Lintsen, 24 May 2016.

24 G. ten Bosch, 'Met schaar terug naar de kern', *De Telegraaf* 11 October 2014, T38-39 and 'Nederlandse kandidaten', *De Telegraaf* 11 October 2014, T39.

25 'Akzo Nobel verkoopt zijn vezeldochter', *NRC Handelsblad* 1 November 1999.

26 Ten Bosch, 'Nederlandse kandidaten', *De Telegraaf* 11 October 2014, T39.

27 See the Shin-Etsu website at: http://www.shinetsu.nl/ (consulted on 15 January 2016).

28 'Basell versterkt positie in mondiale petrochemiesector', *Financieel Dagblad* 17 July 2007.

29 *ICIS Chemical Business*, 7-13 September 2015, 30. Ranking for 2014.

30 G. Coerts and H. Engelenburg, 'Sabic Europe hoopt oud-moederbedrijf DSM snel in omzet voorbij te streven', *Financieel Dagblad* 17 October 2007. L. Berentsen, 'Strategie concurrentiepositie – Europese chemie houdt stand', *Financieel Dagblad* 20 September 2007.

31 M. Abrahamse, 'Teijin Twaron voert aramidecapaciteit verder op', *Financieel Dagblad* 9 July 2003.

32 W. van Reijendam, 'Drentse chemie zegt bulk vaarwel en zoekt heil in groen plastic', *Financieel Dagblad* 17 November 2011.

33 Boy Litjens, Chairman of the Board of Management of SABIC Europe, in *Financieel Dagblad*. 'Sabic Europe hoopt oud-moederbedrijf DSM snel in omzet voorbij te streven', *Financieel Dagblad* 17 October 2007. The company also opts for production facilities in Europe, close to its European customers, rather than in Saudi Arabia.

34 M. Abrahamse,'Chemie moet kunnen blijven groeien', *Financieel Dagblad* 7 August 2004.

35 See for example: H. Engelenburg 'Ovenamecircus chemie draait volop', *Financieel Dagblad* 28 April 2008 and J. Kool, 'Shell zou zelfs Pernis ooit kunnen sluiten', *Financieel Dagblad* 10 April 2014.

36 E. Homburg, interviewed by H. Lintsen, 20 January 2016.

37 M. Abrahamse,'Chemie moet kunnen blijven groeien', *Financieel Dagblad* 7 August 2004.

38 G. Coerts, 'Sabic stelt investering grote naftakraker uit'. *Financieel Dagblad* 9 June 2006.

39 Some comparative figures: number of companies in 2014 = 432; number of people employed in 2011 = 30,000; aggregate turnover in 2013 = €7.8 billion. For the figures for 1977, see: 'Momentopname van de kunststofverwerkende industrie in Nederland', *Plastica* 34 (1981) no. 4, 97-100. For 1968, see: 'Eerste productiestatistiek van het CBS over de Nederlandse kunststofverwerkend industrie', *Plastica* 23(1970), no. 10, 528-529. For 2014: CBS, bedrijven; grootte en rechtsvorm, 22 Rubber- en kunststofproductindustrie (SBI 2008), 2007-2014, *StatLine* (The Hague/Heerlen, 13 November 2014).

40 'Momentopname van de kunststofverwerkende industrie in Nederland', *Plastica* 34 (1981) no. 4, 97.

41 'Tussenbalans branche-onderzoek Nederlandse kunststofverwerkende industrie. Interview met drs. C.M.F. van Lotringen en drs. J.G. Burgers (NEHEM)', *Plastica* 34 (1981) no. 9, 246-249.

42 See for example: Rick van den Bosch, Polyester Processing: www.rickvandenbosch.nl (consulted in December 2014).

43 See for example: MR-Design: www.mr-design.nl (consulted in December 2014).

44 See for example: Deventer Dichtingsprofielen: www.deventer-profielen.nl (consulted in December 2014).

45 One of the top companies, Inalfa Roof Systems Group, is headquartered in Venlo: www.inalfa-roofsystems.com (consulted in December 2014).

46 See for example: NP Plastics: www.np-plastics.nl (consulted in December 2014).

47 For the company's history, see: P.M.A.V. Hooghoff, *70 Jaar Plastics Van Niftrik te Putte. Van persplastiek tot spuitgietwerk. Van 1929 tot 1999* (Putte 1999).

48 *Sectorplan Nederlandse Rubber- en kunststofindustrie* (The Hague, 28 May 2014), 7. Both direct and indirect export are involved. In the case of indirect export, the customer converts the semi-finished product into the end-product, which is then exported.

49 See for example Alligator Plastics: www.alligator-plastics.nl (consulted in December 2014).

50 J.L. Heij, 'Wildgroei kunststofonderwijs', *Kunststof & Rubber* (1988), no. 10, 3.

51 Adviesgroep Materialen (Materials Advisory Group), *Materiaal om mee te werken*, (Zoetermeer, 1991), 25.

52 *Sectorplan Nederlandse Rubber- en kunststofindustrie* (The Hague, 28 May 2014), 4.

53 The quotes are, respectively, from: http://www.metron.nl/over-ons/; http://www.ankro.nl/; http://www.jbventures.nl/; http://www.batelaan.nl/ (consulted in December 2014).

54 'Klein profiel. Groot effect', *Raam en Deur* (2014) no. 6, 40-41.

55 The government made subsidies available. Although initially the idea was to target the entire sector, eventually two sectors were chosen for reasons of diversity: injection moulding contractors and companies specialising in glassfibre-reinforced polyester. J.L. Heij, 'De kunststoffenindustrie in Nederland 1947-1987', *Plastica* (1987), no. 12, 68-71. 'Momentopname van de kunststofverwerkende industrie in Nederland', *Plastica* 34(1981) no. 4, 97-100.

56 *Materiaal om mee te werken*, Final Recommendation by the Materials Advisory Group (Zoetermeer, 1991), 11.

57 J.P.J. de Jong and A.P. Muizer, *De meest innovatieve sector van Nederland. Ranglijst van 58 sectoren* (Report by EIM Onderzoek voor Bedrijf en Beleid, Zoetermeer 2005).

58 This paragraph is based on: E. Homburg, *Speuren op de tast. Een historische kijk op industriële en universitaire research* (Inaugural Lecture Maastricht 2003), 47-51.

59 A. van Rooij, *The Company That Changed Itself. R&D and the Transformations of DSM* (Amsterdam 2007), 281-282 and H. Lintsen (ed.), *Research tussen vetkool en zoetstof. Zestig jaar DSM Research 1940-2000* (Zutphen 2000), 27, 91-94.

60 Homburg, *Speuren op de tast*, 44.

61 H. Lintsen et al., *Made in Holland. Een techniekgeschiedenis van Nederland [1800-2000]* (Zutphen, 2005) 310 ff.

62 Davids, Lintsen and Van Rooij, *Innovatie en kennisinfrastructuur*, 172.

63 The following section on DSM is based on: Van Rooij, *The Company That Changed Itself* and Lintsen, *Research tussen vetkool en zoetstof.*

64 There was also a fourth category: that of service research and support for the divisions. This included quality control, troubleshooting and advice on safety, environmental and energy matters. The orders for this work were placed by the divisional management directly with the relevant departments of the Centtral Laboratory. In the mid-1970s, this service and support research accounted for approximately 10% of the budget of the Central Laboratory.

65 Lintsen, *Research tussen vetkool en zoetstof*, 94-95.

66 Lintsen, *Research tussen vetkool en zoetstof*, 107.

67 The innovation strategy was expanded to include pre-corporate development projects, in which pioneering research took centre stage. The Central Laboratory's brief was to pay special attention to ideas whose commercial value had not yet been demonstrated but which clearly had commercial potential and were in line with the corporate strategy. (Lintsen, *Research tussen vetkool en zoetstof*, 110-111).

68 These are the words of former Research Director L.J. Revaillier (Lintsen, *Research tussen vetkool en zoetstof*, 100).

69 The following section is based on and partially borrowed from H. Lintsen (ed.), *Tachtig Jaar TNO (1932-2012)* (n.p. 2012), 62-64.

70 The quote is to be found in Lintsen, *Tachtig Jaar TNO*, 64, based on an interview with Prof. G. Challa by M. Hollestelle, 16 September 2011.

71 The quote is to be found in Lintsen, *Tachtig Jaar TNO*, 64, based on an interview with Prof. P. Lemstra, 12 October 2011.

72 Lintsen, *Tachtig Jaar TNO*, 64, based on a personal communication from Prof. L. Struik, 6 September 2011.

73 M. Hollestelle, 'De academische polymeerwetenschap in Nederland, 1945-2011. Visies op haar nut bij universiteit en industrie', in: L.J. Dorsman and P.J. Knegtmans (eds.), *Universiteit, publiek en politiek. Het aanzien van de Nederlandse universiteiten, 1800-2010* (Hilversum 2012) 83-110, in particular 102.

74 The quote is to be found in, *Tachtig Jaar TNO*, 64, based on an interview with Prof. L. Struik by M. Hollestelle, 5 September 2011.

75 E. Homburg and L. Palm (eds.). *De geschiedenis van de scheikunde in Nederland* (Delft 2004), 241.

76 L.C.E. Struik, *Polymeerfysika, terugblik op 22 jaar Twente*, Valedictory lecture (n.p. 2007) 4-5.

77 Hollestelle, 'De academische polymeerwetenschap in Nederland, 1945-2011. Visies op haar nut bij universiteit en industrie', information derived from interview with Prof. G. Challa by M. Hollestelle, 16 September 2011.

78 Struik, *Polymeerfysika*, 5.

79 Adviesgroep Materialen (Materials Advisory Group), *Materiaal om mee te werken* (Zoetermeer, 1991), 42.

80 In 1988 SON and FOM defined a Prioriteitsprogramma Materialenonderzoek (Priority Programme for Materials Research), which was launched in 1990 with the support of NWO. In 1995 FOM, NWO Chemische Wetenschappen and STW, armed with a budget of EUR 31 million, started the NWO-Prioriteitsprogramma Materiaalonderzoek; one of the aims was to promote interaction between academia and industry. The programme was also intended to strengthen materials research in selected key areas, promote an interdisciplinary approach and to train researchers. The programme generated 80 projects, 110 PhD positions and 65 postdoc appointments. See: *NWO-Prioriteitsprogramma Materiaalonderzoek (PPM). Eindverslag* (Utrecht 2005).

81 H. Schaffers et al., *De technologische Kennisinfrastructuur van Nederland* (TNO Report, Apeldoorn 1996), I-12 – I-14.

82 Struik, *Polymeerfysika*, 5-6.

83 This section is based on: M. Hollestelle, *Onderzoekscoördinatie bij het Dutch Polymer Institute. Een rapport in opdracht van het Rathenau Instituut* (Stichting Historie der Techniek, Eindhoven 2012).

84 DPI was to translate industry needs into a multiyear research programme with a multidisciplinary character and focusing on topics centred around the relationship between the nature of a polymer and the required material properties of the end-product (the entire knowledge chain). See: L. Struik, P. Lemstra et al., *Business Plan Leading Technological Institute Polymers & Polymer Processing* (n.p., n.d.).

85 Two additional clusters – Corporate Research and Emerging Technologies – provided scope for research that was not of immediate or topical relevance to the companies or research in promising areas that did not fit in the Technology Areas. For example, Corporate Research could address topics of societal relevance, such as Plastic Soup, the problem of plastic waste in the oceans.

86 The Bridge Business Innovators, *Findings from the interviews with DPI participants* (presentation, 5 October 2008). Quoted in: Hollestelle, *Onderzoekscoördinatie.*

87 Cor Koning, who was at the time professor of Polymer Chemistry at Eindhoven University of Technology, had the following to say on this subject: 'People who are capable of addressing a problem at the molecular level but who at the same time understand and speak the language of all the specialists in the chain of knowledge will always be needed in industry.' Quote to be found in DPI Annual Report 2007, 21.

88 Interview with J. Roos, 18 April 2012. Quoted in: Hollestelle, *Onderzoekscoördinatie*, 22.

89 Ibid.

90 Ibid.

91 Prof. Paul Blom, quote to be found in *DPI Annual Report 2007*, 32.

92 As Piet Lemstra put it, industrial researchers who were actively involved were increasingly difficult to find. Interview with Piet Lemstra, 12 October 2011. Quoted in: Hollestelle, *Onderzoekscoördinatie*, 30.

93 Interview with J. Joosten, 20 March 2012. Quoted in: Hollestelle, *Onderzoekscoördinatie*, 27.

94 Ibid.

95 It was also observed that suppliers were somewhat reluctant to make material samples available for DPI research. *DPI Annual Report 2007*, 32.

96 Based on interview with M. Cohen Stuart, Scientific Director of DPI, 5 April 2012. Quoted in: M. Hollestelle, *Onderzoekscoördinatie*, 27. Cohen Stuart also identified another problem: in the coordination of projects, it was necessary to bridge a communication gap – or a gap in knowledge, as it were. (Interview with M. Cohen Stuart, 5 April 2012. Quoted in: M. Hollestelle, *Onderzoekscoördinatie*, 31).

97 Especially the fact that biobased was becoming increasingly important for all companies made collaborative research in a pre-competitive framework very important. They all had to deal with the same challenges, while the research was still in an exploratory stage. This was exactly the context in which companies could gain by sharing with one another and build a knowledge base together. Interview with Jan Roos, 18 April 2012; Interview with M. Cohen Stuart, 5 April 2012.

98 Based on quote by Prof. Paul Blom, head of the Physics of Organic Semiconductors research group at Groningen University, in: *DPI Annual Report 2007*, 31.

99 According to Prof. Cohen Stuart, former Scientific Director of DPI, the *Scientific Chairman* and the *Programme Area Coordinator* played a key role in ensuring the success of the public-private collaboration. M. Hollestelle, *Onderzoekscoördinatie*, 30.

100 Besides securing continued interest on the part of the industrial partners, it was important for DPI to ensure that the knowledge institutes continued to find it challenging to work on certain areas of research. (Hollestelle, *Onderzoekscoördinatie,* 27.) The universities were keen to engage with new challenges in new fields, whereas industrial needs included research in areas for which universities were likely to lose their interest or had already lost it.

101 G. van Veen et al., *Evaluation Leading Technological Institutes. Final Report* (Technopolis, September 2005). The Dutch Minister of Economic Affairs quoted these findings in his covering letter when submitting the evalutation report together with the budget proposal for the institutes in 2006 and 2007. This was the conclusion and recommendation: valorisation 'apparently does not take place automatically; it requires a targeted effort on the part of the institutes. Letter by the Minister of Economic Affairs, 30 January 2006: House of Representatives, Dutch Parliament, parliamentary year 2005-2006, 30 300 XIII, no. 66.

102 *DPI Annual Report 2006*, 4.

103 *DPI Annual Report 2007*, 2.

104 In addition to working with companies and knowledge institutes, DPI also worked closely with various organisations in the Netherlands and in other countries. DPI was often asked to act as coordinator of consortiums under EU programmes. DPI also organised workshops and other events in cooperation with institutions in and outside the Netherlands. A good example is the workshop on Hybrid Materials that DPI and SusChem jointly organised in 2010.

105 Hollestelle, *Onderzoekscoördinatie*, 54
DPI Annual Reports 1998 to 2010; M.A.J. Michels, *Wanorde en structuren* (Eindhoven 2012) 21. The quality of DPI research was independently confirmed at the end of 2014 in a study carried out by Elsevier on behalf of the Netherlands Enterprise Agency, an operational unit of the Dutch Ministry of Economic Affairs. The study focused on scientific papers published by the Top Consortium for Knowledge and Innovation (TKI) for Smart Polymeric Materials, in which DPI was the principle participant. The results show that the Netherlands ranks high globally in terms of publication output, citation impact and patent citations. The Netherlands scores particularly very high for co-publications in two areas that form the cornerstones of the DPI research platform: international collaboration and public-private collaboration. *International Comparative Benchmark of Dutch Research Performance in TKI Themes: Smart Polymeric Materials. A report prepared by Elsevier for the Netherlands Enterprise Agency* (n.p. 2014).

106 Dominik Heinisch, Önder Nomaler, Guido Buenstorf, Koen Frenken, Harry Lintsen, 'Same Place, Same Knowledge – Same People? The Geography of Non-Patent Citations in Dutch Polymer Patents', (article submitted: Economics of Innovation and New Technology). Dominik Heinisch, *Citations to non-patent literature on Dutch Polymer Patents* (Universität Kassel master's thesis 2013).

107 A.J. Staverman, '25 jaar polymeerwetenschap en kunststoftechnologie', in: *Plastica* 25 (1972) 529-534, in particular 531.

108 D. Schouten and A. van der Vegt, *Plastic. Hoofdlijnen van de huidige kennis en toepassing van de synthetische macromoleculaire materialen* (Utrecht 1974, fifth edition).

109 T. Frieling, 'Voorgeschiedenis van de kunststoffen', in: H.M. Brüggemann (ed.), *Kunststoffen 1986. Terugblik en toekomst* (Delft 1986), 9-10.

110 H. Meijer, 'Polymeerverwerking', in: H.M. Brüggemann (ed.), *Kunststoffen 1986. Terugblik en toekomst* (Delft 1986), 134-135.

111 J.H. Geesink,'Kunststoffen in de jaren negentig. Van standaard kunststoffen tot zeer hoogwaardige technische polymeren', *Kunststof en Rubber* 44 (1990), no. 8, 15-20.

112 See, for example, 'Functionele polymeren', *Kunststof en Rubber* (1992), no. 3, 16.

113 The research group is part of Eindhoven University of Technology and is headed by Prof. René Janssen. Janssen was awarded the 2015 Spinoza Prize granted by the Netherlands Organisarion for Scientific Research (NWO). NWO lauded Janssen as 'world leader in the field of organic solar cells'. See also: E. Berkers, 'Plastic zonnecellen. Worstelen met een weerbarstige energiebron', in: H. Lintsen and H. Schippers, *Gedreven door nieuwsgierigheid. Een selectie uit 50 jaar TU/e-onderzoek* (Eindhoven 2006), 98-102.

114 Geesink,'Kunststoffen in de jaren negentig', *Kunststof en Rubber* 44(1990), no. 8, 15-20.

115 T. de Greef and E.W. Meijer, 'Supramolecular polymers', *Nature* Vol 453/8 May 2008, 171-173. The work being done by E.W. Meijer and his research group at Eindhoven University of Technology is internationally leading.

116 E. Berkers, 'Polymeren. Eindhoven, 'kunststof stad'', in: H. Lintsen and H. Schippers, *Gedreven door nieuwsgierigheid. Een selectie uit 50 jaar TU/e-onderzoek* (Eindhoven 2006), 65-71.

117 The rest of this section is based on: P. Nossin, *Biopolymeren in breder perspectief. Nut en noodzaak* (n.p. 2012), 18-20.

118 'De jaren 1978-1987. De introductie van de computer voor besturing, optimalisatie en materiaalkeuze', in: Themanummer *Kunststof en Rubber*: 'Kunststof en Rubber 50 jaar', *Kunststof en Rubber* 50 12 (1997) 55-63.

119 Meijer, 'Polymeerverwerking', 134-138.

120 S. Squires, 'Injection moulding – quo vadis? !', in: *Plastica* 34 (1981) 42-45.

121 W. van der Meulen, 'Spuitgieten', H.M. Brüggemann (ed.), *Kunststoffen 1986. Terugblik en toekomst* (Delft 1986), 142-148.

122 H.M. Brüggemann (ed.), *Kunststoffen 1986. Terugblik en toekomst* (Delft 1986). See the sections on blow moulding, thermoforming, rotational moulding, PVC coating and film winding onto rolls.

123 Van der Meulen, 'Spuitgieten', 145-147.

124 Ibid., 148.

125 This section is based on: Meijer, 'Polymeerverwerking', 136-138. See also: H. Meijer, *Van struktuur tot eigenschappen* (Inaugural Lecture Eindhoven University of Technology 1990). Over the past several decades, H. Meijer and his research group at Eindhoven University of Technology have developed their discipline into a fully-fledged field of research.

126 Brüggemann (ed.), *Kunststoffen 1986. Terugblik en toekomst*, 11.

127 Ibid., 217-219.

128 See the websites of these organisations: www.nrk.nl, www.vnci.nl and www.plasticseurope.org (consulted on 15 February 2015. The quote is taken from the PlasticsEurope website.)

129 Homburg, ‘Part 3: The era of diversification and globalization (1950-2012)’, 369-373. One of the examples mentioned was the occurrence of painful and deformed fingers among the workers in VCM production plants.

130 ‘Leverkanker gevolg van PVC-produktie’, *Nederlands Dagblad*, 21 October 1974, 3.

131 R. Kagie and G. Walraff, *Arbeid maakt ziek: de relatie werken-gezondheid* (Baarn 1977), 68.

132 ‘DSM zit onder nieuwe norm bij PVC-fabriek’ *Limburgs Dagblad*, 5 November 1974, 13; Kagie, *Arbeid maakt ziek*.

133 ‘Geen consequenties vinylchloride’, *Limburgs Dagblad*, 17 February 1976, 11. This mainly concerned connective tissue disorder. ‘Giftig gas veroorzaakt leverkanker: Sterfgevallen in PVC producerende industrie’, *Leeuwarder Courant*, 1 October 1974, 11.

134 Kagie en Walraff, *Arbeid maakt ziek,* 67. This was about liver cancer.

135 ‘DSM zit onder nieuwe norm bij PVC-fabriek’, *Limburgs Dagblad*, 5 November 1974. 13; Kagie, *Arbeid maakt ziek.*

136 In relation to PVC, see also Note 20 in the Prologue.

137 A. Tukker, *Frames in the toxicity controversy: Based on the Dutch chlorine debate and the Swedish PVC debate* (Veenendaal 1998). For Belgium, see: Homburg, ‘Part 3: The era of diversification and globalization (1950-2012)’, 501-505.

138 See also R. van Duin, *Milieu- en energieaspekten van kunststoffen* (Utrecht 1991).

139 Tukker, *Frames in the toxicity controversy*. A contributing factor was the Lickebaert case, which brought to light dioxin contamination resulting from PVC incineration (see also further in the main text).

140 Tukker, *Frames in the toxicity controversy,* 179.

141 Ibid., p. 178-179.

142 ‘Veehouders blij met sluiting vuiloven’, *Nieuwsblad van Het Noorden*, 17 July 1990, 3.

143 https://www.vwa.nl/onderwerpen/meest-bezocht-a-z/dossier/dioxine/regelgeving (consulted on 17 July 2015).

144 K. Sluyterman and B. Bouwens. *Brewery, brand, and family: 150 years of Heineken* (Amsterdam 2014), 397-398. See also various comments in for example the *Consumentengids*, including: ‘Krat met kleurtje’, *Consumentengids*, 1985, 253 and ‘Cadmium nog steeds in krat’, *Consumentengids*, 1987, 10–11.

145 The cadmium-containing crates were in use until 1999, when the company switched to green crates. (Under the terms of a covenant signed by Heineken, the manufacture of new cadmium-containing crates was to end as of 1 January 1990. Heineken had come to an agreement with the environmental movement regarding the disposal of used cadmium-containing crates: the crates were to be ground into granulate and stored until a responsible method had been found for their disposal. *Trouw*, 5 September 1999, 7.

In 2003, a solution seemed to have been found for the disposal of the granulate. Heineken teamed up with Sea Way Refinining, a company based in Vlissingen (Flushing), that had developed a method for separating the cadmium from the polyethylene. The process was not such a success at commercial scale, however, and following a big fire in 2005, Sea Way Refining was declared bankrupt in 2007. The mountain of cadmium-containing granulate remained as it was. Ironically, a European Commission Decision (2009/292/EG) announced in 2009 permitted the recycling of cadmium-containing granulate provided no cadmium was released during the process. However, in the Netherlands this solution was precluded by the fact that Heineken had signed a covenant with the government that prohibited the use of cadmium in crates. The Dutch Environment Minister at the time, Jacqueline Cramer, wrote to Parliament that she was working with the beer brewers to find a solution (including the possibility of a restart of Sea Way Refining). It is still unclear at the time of writing what the current situation is with regard to cadmium-containing granulate.

146 ‘Er is nog steeds gevaarlijk speelgoed’, *Leeuwarder Courant*, 18 November 1978, 23; ‘Speelgoed van PVC kan gevaarlijk zijn’, *Nieuwsblad van Het Noorden*, 29 March 1977, 14.

147 ‘Er is nog steeds gevaarlijk speelgoed’, *Leeuwarder Courant*, 18 November 1978, 23.

148 As an example: in November 1985, the regional newspaper *Limburgs Dagblad* reported about the introduction of a ‘toy telephone’, a complaints and information service for problems related to dangerous toys. In this connection, Ton Smits, the spokesperson of Stichting Consument en Veiligheid (the Consumer and Safety Foundation) was still speaking of the hazards related to the use of plasticisers in PVC toys. Free phone service for consumer complaints and consumer information: ‘Speelgoedtelefoon voorziet in behoefte’ (Toy phone fills a need), *Limburgs Dagblad*, 30 November 1985, 35.

149 K. Bouma, F. Dannen, A.J.J, van Peursem, L. Steendam, C.I.H.M Nieman, B.A. Douwes, B. A. and D.J. Schakel, *Chemische veiligheid van Scoubidou touwtjes* (Groningen 2004), 5. It is striking that Bouma et al. refer to earlier studies into the use of plasticisers in PVC toys (between 2000 and 2003) and note that the plasticiser content of the strings was lower than the level found in other studies. In so doing, they seem to suggest that the commotion around the Scoubidou strings was unjustified. They also noted that the *dibutyltin* content, while it was close to the permissible value, did not exceed it. *Dibutyltin* is added to PVC as a stabiliser and can affect metabolic functions and the immune system. Gumy, C., Chandsawangbhuwana, C., Dzyakanchuk, A. A., Kratschmar, D. V., Baker, M. E., and Odermatt, A. ‘Dibutyltin disrupts glucocorticoid receptor function and impairs glucocorticoid-induced suppression of cytokine production’, *PLoS ONE*, *3* (2008), no.10, 1–11.

150 M. Braungart and W. McDonough co-authored *Cradle to Cradle: Remaking the Way We Make Things* (San Francisco 2002). The basic idea they propound is that consumer articles can be fully recycled. See also: J. Goossens, *Plastic Soep* (Rotterdam 2009), 162.

151 *Kennis dossier. Duurzaam kunststof leidingsystemen* (Leidschendam, n.d. [downloaded on 16 February 2015]), 9.

152 Another issue is the recycling of large quantities of lead-containing PVC. A ban on the recycling of lead-containing PVC would constitute a setback for the reuse of materials. ‘PVC-recycling in gevaar’, *De Ingenieur*, 2014, 4

153 See note 150.

154 Goossens, *Plastic Soep*, 163.

155 *Kennis dossier. Duurzaam kunststof leidingsystemen* (Leidschendam, n.d. [downloaded on 16 February 2015]), 26-29.

156 See the PlasticsEurope website, consulted on 2 June 2015. Quoted verbatim from the English original.

157 A.K. van der Vegt, ‘De toekomst van plastics’, in M. Boot, A. Von Graevenitz, H. Overduin, and G. Staal (eds.), *De eerste plastic eeuw: Kunststoffen in het dagelijks leven* (The Hague 1981), 37-39.

158 H. Pilz, J. Schweighofer and E. Kletzer, *The contribution of plastic products to resource efficiency: Estimation of the savings of energy and greenhouse gas emissions achieved by the total market of plastic products in Western Europe by means of a projection based on a sufficient number of examples* (Vienna 2005). Retrieved from file:///X:/My Downloads/GUA_-_The_Contribution_of_Plastic_Products_to_Resource_Efficiency_(full_report)_-_January_2005 (1).pdf.

159 Comment: the discussion is about the energy costs per kilo of plastic pipe as compared with energy costs of, say, iron pipe with the same functional characteristics (length, thickness, strength, etc.). The discussion, therefore, is not about the energy costs per kilo of plastic pipe and iron pipe. The pipe made of an alternative material might be much heavier. What is important is that the functionality is the same.

160 H. Pilz, B. Brandt and R. Fehringer, *The impact of plastics on life cycle energy consumption and greenhouse gas emissions in Europe* (Vienna 2010). Here, too, no data is provided on the total savings during production. However, the graph (Figure 1) shows that the total savings amount to about 25%.

161 Pilz, Schweighofer and Kletzer, *The contribution of plastic products to resource efficiency.*

162 The European House-Ambrosetti, *The excellence of the plastics supply chain in relaunching manufacturing in Italy and Europe* (n.p. 2013), figure 17. Plastic waste recycling and energy recovery rate in the EU-27, 2011.

163 See, for example, http://www.avr.nl/energy-inside/.

164 E. Boukris et al., *DoorTAStend, LCA studie van draagtassen*, TNO Report (Utrecht 15 January 2015), in particular pages 68-69 and appendices C1-C3.

165 P.H. Smit, 'Als je ze niet weggooit, zijn plastic tassen best duurzaam', *De Volkskrant* 21 February 2015, 33.

166 In this connection, the European Union and the Dutch government are pursuing a policy whereby the use of lightweight plastic bags is severely restricted. The sector adheres to this policy.
Another topic that often gives rise to discussions is the question of what is better or worse for the environment: a single-use plastic coffee cup or a porcelain cup. In order to obtain a full picture, all instances of environmental impact, including those occurring during production and waste processing, need to be taken into account in a life cycle analysis (LCA). However, it appears that the assumptions about the use phase have a strong bearing on the total impact. If, for example, the single-use cup is used multiple times and/or the porcelain cup is cleaned with detergent after every use, the impact of the plastic cup will be smaller. If, on the other hand, a new single-use cup is used each time whereas the porcelain cup is used multiple times, the balance will tilt in favour of the latter. See T.N. Ligthart and A.M.M. Ansems, *Single use cups or reusable. Coffee drinking systems: An environmental comparison* (Apeldoorn 2007). Retrieved from http://www.tno.nl/downloads/Summary Research Drinking Systems.pdf. Ligthart and Ansems are therefore cautious in drawing conclusions, although they affirm that disposable, single-use cups (with a slight preference for paper rather than polystyrene) are less harmful.

167 This section is based on: P. Nossin, *Biopolymeren in breder perspectief. Nut en noodzaak* (n.p. 2012).

168 J.E. Guillet, 'Polymers with controlled lifetimes', in J. E. Guillet (ed.), *Polymer science and technology volume 3: Polymers and ecological problems* (New York 1973), 125. It should be noted, however, that Guillet is talking specifically about the problem of litter;
plastic waste should normally speaking be treated via the regular waste processing method, but if it spreads or is likely to spread to the natural environment it should be degradable. See also J.E. Guillet, 'Plastics and the environment', in G. Scott and D. Gilead (Eds.), *Degradable polymers: Principles & application* (London 1995), 216-246. Nevertheless, plastics were also a problem in the case of landfill sites, especially because they occupied so much space. An important aim of developing biodegradable plastics was to achieve compaction of the ever-increasing volume of the waste dumps. Incidentally, the first scientific research into degradable plastics was not prompted by environmental considerations, but had to do with medical applications: H. Stapert, P. Dijkstra & J. Feijen, 'Biodegradable polymers', in M. Smits (ed.), *Polymer products and waste management: A multidisciplinary approach* (Utrecht 1996), 71-105.

169 Guillet, 'Polymers with controlled lifetimes', 5. This is different in the case of natural polymers such as starch, proteins and DNA, which provide micro-organisms with sufficient footholds. In 1990 Huang, Shetty and Wang presented a very optimistic view of biodegradable plastics. Not only did they have high expectations of starch-based polymers or plastics made up of natural polymers such as polyhydroxybutyrate (PHB), they moreover expected that Nature would find a way of dealing with unnatural polymers: 'Microorganisms are highly adaptive to environment and secrete specific enzymes depending on the substrate on which they feed (...). These enzymes can attack and eventually destroy almost anything. Nature can devise, in due time, enzymes capable of attacking nylon 6 and poly(vinyl alcohol) (...). Most synthetic polymers have been added to landfills for a relatively short period of time. It is expected that in due time microbes will eventually be able to produce enzymes that can efficiently attack most polymers': J.-C Huang, A.S. Shetty & M.-S. Wang, 'Biodegradable plastics: A review' *Advances in Polymer Technology*, *10* (1990), no.1, 23–30, p. 25.

170 Guillet, 'Polymers with controlled lifetimes', 17.

171 Nossin, *Biopolymeren in breder perspectief*, 22. The following argumentation is also derived from this report.

172 P. Harmsen and M. Hackmann, *Groene bouwstenen voor bio-based plastics. Bio-based routes en marktontwikkeling* (Wageningen 2012), 59.

173 Landelijk afvalbeheerplan 2009-2021 (LAP; National Waste Management Plan). The plan was finalised on 11 November 2009 and became effective on 24 December 2009 (25 November 2009, Staatscourant 2009, no. 17866). The first revision was finalised on 16 February 2010 and became effective on 25 March 2010 (24 February 2010, Staatscourant 2010, no. 2730). The second revision was finalised on 3 December 2014 and became effective on 5 January 2015 (Staatscourant 8 December 2014, no. 31258). See: *Landelijk afvalbeheerplan 2009-2021. Naar een materiaalketenbeleid* (The Hague 3 December 2014).

174 Ibid.

175 E. Brenninkmeijer and E. Meijer, 'Afval scheiden, zo eenvoudig is dat nog niet', *De Consumentengids* May 2016, 57-63.

176 T. Können, 'Beter hergebruik. Kwaliteit van kunststoffen moet omhoog', *De Ingenieur* 128 (2016), no. 3, 14-21.

177 J.R. Jambeck et al., 'Plastic waste inputs from land into the ocean', *Science* 347 (2015), no. 6223, 768-771.

178 Goossens, *Plastic soep*, 14-17.

179 J.A. van Franeker et al., *Fulmar Litter EcoQO monitoring in the Netherlands - Update 2012 and 2013* (Wageningen 2014), Report number C122/14. The Wageningen University & Research website provides the following information: 'The Ecosystems department of Wageningen Marine Research (known as IMARES) is the founder of a permanent programme for monitoring the amount of plastics in the stomachs of Northern Fulmars in the North Sea. This method of environmental research has been integrated into the European Marine Strategy Directive (MSFD) as a basis for litter monitoring in other European seas. This includes monitoring the ingestion of plastics by other bird species as well as turtles, marine mammals and fish in European waters and elsewhere.' (consulted on 24 February 2015).

180 This refers to the EcoQO threshold level of 0.1g of plastic in the stomach of a Northern Fulmar. The governments of the countries bordering the North Sea aim for a situation in which less than 10% of these birds exceed this level.

181 E. König, 'De zee is van iedereen en dus ruimt niemand op', *NRC.NEXT* 9 June 2009, 4.

182 Jambeck et al., 'Plastic waste inputs from land into the ocean', 768-771.

183 Boyan Slat launched the Ocean Cleanup project in 2013 for collecting plastic debris floating in the oceans using floating inflatable barriers. The project is attracting a lot of enthusiastic response as well as financial support from across the world. Slat is working together with students, engineers, oceanographers and industrial experts. A feasibility study is underway. A first pilot project was started in 2016. See: www.theoceancleanup.com/. (Consulted on 8 March 2017).