The Plastics Revolution

How the Netherlands Became a Global Player in Plastics

Harry Lintsen, Marijn Hollestelle and Rick Hölsgens

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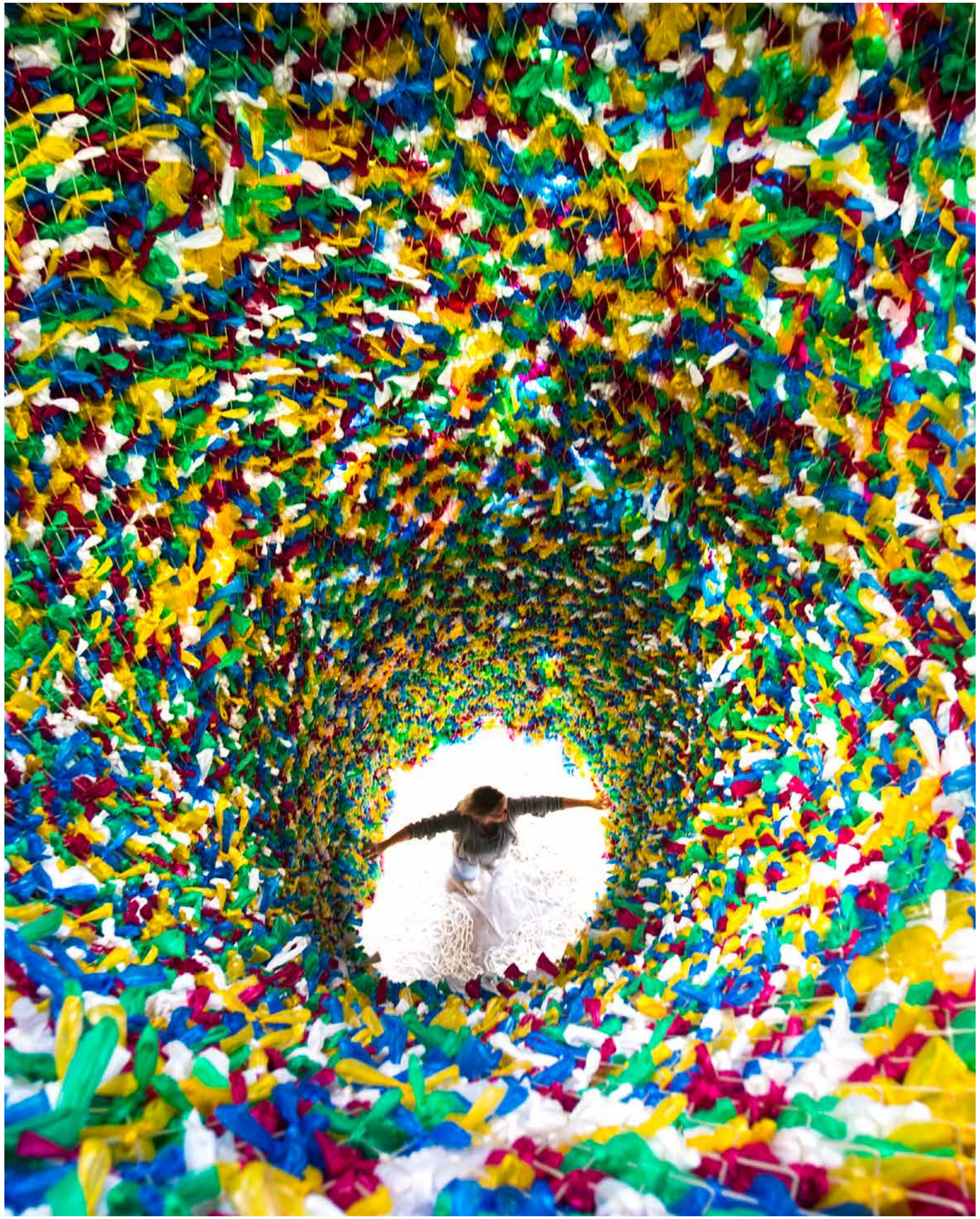


Foreword

Revolutions come in all shapes and sizes and they impact life in different ways. *The Plastics Revolution: How the Netherlands Became a Global Player in Plastics* is about the profound change brought about in our lives by the emergence of a new category of materials – plastics, or polymeric materials as they are also known. The book looks back at the invention and development of plastics between the two world wars, their 'revolutionary' growth after the Second World War and their widespread adoption in the subsequent decades. The book also reviews the current debate on the long-term sustainability of plastics and some of the prevailing ideas about future developments.

Although the book's focus is on the Netherlands, the authors place the history firmly in the context of developments in the wider world. They discuss the role the Netherlands played in the rapid growth of polymer science and technology and the expansion of the plastics industry. Having lagged behind in the first half of the twentieth century, the Netherlands soon succeeded in securing a place among the world's leaders. Not only in terms of production output and per capita consumption of plastics, but also as a strong force in polymer research and innovation. By the 1970s, the Netherlands was being hailed by some as 'the new plastics centre of Europe'.

In and around the Second World War, the emergence of plastics was experienced as a boon, enabling the replacement of scarce conventional materials such as metals and wood. Advances in technology led to their mass production, making them cheaper, more widely accessible and capable of fulfilling the needs of a burgeoning consumer society. During the rapid industrialisation of the post World War II era, plastics quickly became fully entrenched in our way of life and our economic infrastructure. Over the past decades, the use of plastic materials has spread to every single sphere of human life: household articles, building & construction, packaging, electrical and electronic devices, transport, as well as healthcare and medicine.

As the book shows, universities initially played only a marginal role in the development of the polymer sector in the Netherlands. New developments came mainly from the laboratories of big industrial companies with large research budgets. Alongside major foreign companies such as DuPont, Dow Chemical, ICI, IG Farben and BASF, the research and innovation efforts of Dutch companies such as Shell, DSM and Akzo not only gave the world many new life-enhancing products but also helped to build a strong knowledge base in polymer science and technology. It is interesting to see that these companies often explored the same strategic routes, such as diversification and forward integration, in pursuit of expansion and growth: Shell went into PVC piping, for example, and DSM into plastics processing and building & construction. The companies were often faced

For the Global Imaginations exhibition held in 2015 at De Meelfabriek complex in Leiden (Netherlands), volunteers help with the construction of the artwork "Plastic Bags" by Pascale Marthine Tayou.

with the same challenges: how to find the right balance between fundamental and applied research, how to secure the supply of raw materials, whether to develop new production processes in-house or licence them from others and how to build a balanced, profitable and innovative product portfolio in an increasingly competitive market.

In the years immediately following the Second World War, polymer research in the Netherlands was still largely limited to the industrial sector. Polymer science was not a prominent feature of the academic landscape. The plastics industry had the advantage of knowledge exchange through a thriving plastics platform, an open network consisting mainly of chemicals and plastics production companies. The scientific expertise at the heart of the plastics platform came primarily from these companies, which included foreign players, and from TNO.

From the 1960s onwards, polymer science gradually began to gain a foothold at the universities, thanks partly to incentives provided by industry as well as the government. The ministries of Economic Affairs and Education & Science increasingly recognised the importance of materials and materials science. Their initiatives helped to boost research and innovation. For example, the *Innovatieve Onderzoeksprogramma's* (IOPs, innovative research programmes) set up by the Ministry of Economic Affairs in the 1970s stimulated structural collaboration in R&D between industry and public-funded knowledge institutions. Also in the early 1970s, KRITNO (TNO's Plastics and Rubber Institute) began offering multi-client contract research programmes for industry.

Later still, in the 1980s and 1990s, several new impulses followed that gave a boost to polymer research. One was the creation of the *Adviesgroep Materialen* (AGM, advisory group on materials) at the joint initiative of the two ministries mentioned above plus NWO (the Netherlands Organisation for Scientific Research). In a crucial report issued in 1991, AGM recommended a doubling of the country's polymer research effort. This led, among other things, to a major public research programme for polymer science – the Priority Programme for Materials (PPM) – which was co-funded by NWO. A logical next step of PPM was the establishment, in 1997, of Leading Technology Institutes such as DPI, which had a crucial impact on the growth of research in polymer science, a strong increase in collaboration between industry and academia, and the building of a solid research infrastructure.

In reviewing the current situation and future prospects, *The Plastics Revolution* looks at the ambivalent public opinion and widespread concerns about plastics in the larger context of sustainability and the impact on human health and the natural environment. One of the issues highlighted in the book is that of plastic trash in the oceans – the so-called "plastic soup" – a problem that has ramifications extending beyond the pollution of the oceans and forming a threat to marine life as well as to human beings. The "miracle" materials of yesterday have today become a source of worldwide concern. While they have become indispensable to human life, their production, use and disposal are beset with a multitude of problems. The "Epilogue" section of the book brings the various strands of the debate together, discusses the main issues and reviews current thinking on the way forward.

It is clear, for example, that the future of plastics – indeed the future of industry and society – lies in a shift from the current linear and open-ended economy to a circular, closed-loop economy that is "restorative and regenerative by design, and aims to keep products, components, and materials at their highest utility and value at all times"[1]. This implies a transition towards product and process development based on considerations such as the cradle-to-cradle principle, the use of renewable and – where appropriate – biobased feedstocks, a new approach to energy production and utilisation, and an eco- and cost-efficient waste management system. Although steps to initiate the transition towards a circular economy are already being taken, there is as yet no broad-based, coordinated effort either at the national or at the international level. What is needed is a holistic approach in which the plastics predicament is seen in conjunction with other scientific, economic and societal challenges.

Besides new economic models, we undoubtedly need new ideas, new scientific concepts. Perhaps even a paradigm shift. But these cannot be made to order. Nor can we simply wait for them to happen one day. There is so much more that we can already do if we share a sense of urgency. New ideas and concepts need to find their way into society and be translated into practicable solutions. Although industry will play an important role in this process, we must realise that by its very nature an industrial company – within the framework of the prevailing business models – is limited in terms of time, scope and money to address general societal problems. That is why coordination and collaboration between the private and public sectors is important for securing sustainability. Many of us will remember the definition of sustainable development formulated over three decades ago: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs…".[2] Today, this still calls for a sense of ownership and a commitment to work on both short-term and long-term goals. This is a challenge that will hopefully be taken up by a new generation of companies with a novel business and sustainability model.

How can we achieve the turnaround needed to ensure a sustainable future, a future in which there is a place for the plastic materials that we cannot really live without? As *The Plastics Revolution* indicates, a second plastics revolution – towards a circular economy – is both necessary and imminent. Indeed, the Dutch chemicals sector believes that the next few decades will witness such a revolution, one in which the Netherlands might once again be a major driving force. This seems a credible scenario. But we must bear in mind that given the globalised nature of both scientific and economic activities and the global dimensions of many of the problems associated with plastics, the revolution will need to have an international reach and impact.

The ambition expressed by the Dutch chemicals sector is not unrealistic, but a major transition on such a vast scale will demand concerted and parallel efforts on the part of several stakeholders. The ideal scenario would include sufficient monetary and other incentives designed to de-risk investments by individual stakeholders and creating room for responding to short-term needs as well as pursuing long-term goals.

Jacques Joosten
Managing Director, DPI

1 http://www.ellenmacarthurfoundation.org/circular-economy/overview/concept

2 http://www.iisd.org/topic/sustainable-development

19th century

1839 Charles Goodyear, vulcanisation of natural rubber

1856 Alexander Parkes, Parkesine, nitrocelluloid (semi-synthetic plastic based on nitrocellulose or gun cotton) → buttons, medallions, letter-openers, etc

1870 John Wesley Hyatt, nitrocelluloid-camphor → billiard balls, trinkets, children's toys

1888 John Dunlop, rubber tyre

1892 Charles Cross, Edward Bevan and Clayton Beadle, viscose based on cellulose fibre → artificial silk stockings and garments

Late 19th century Plastic as a substitute for conventional materials such as wood, glass, stone, ivory and metal

Late 19th century New market for imitation products, plastic jewellery, ashtrays, buttons, etc

1900-1940

1907 Leo Baekeland, Bakelite → switches, wall sockets, mounting plates, later: objects such as door knobs, telephone receivers, Formica and light fittings

1912 *Eerste Nederlandsche Kunstzijdefabriek* ('First Dutch Artificial Silk Factory') opened in Arnhem

1912 Friedrich Klatte, PVC. Production of PVC commenced in the 1930s.

1920 *Internationale Kunsthoorn Industrie* ('International Artificial Horn Industry') founded in Amsterdam, manufacturing artificial horn from casein

1920 Herman Staudinger, publication of article on polymerisation ('Über Polymerisation', *Ber. Chem. Ges.* 53 (1920) 1073)

1923 Philips of Eindhoven, production of Bakelite components for radios and electrical equipment → 1929 Philite plant

1929 Gebr. Van Niftrik, production of Bakelite components for electrical equipment

1930 Paul Frankl (designer) predicts the advent of 'a veritable plastics century'

1931 Julius Nieuwland in partnership with DuPont, synthetic rubber

1933 Eric Fawcett and Reginald Gibson at ICI, polyethylene

1935 Wallace Carothers at DuPont, nylon

1936 Herman Mark and C. Wulff at IG Farben, commercial production of polystyrene

1938 Earl Tupperware, Tupperware Home Parties (1951)

1939 DuPont's nylon stocking

1920s and 1930s Plastic discovered by designers and the middle classes as a material for contemporary design

Plastics markets Consumer products (such as trinkets, garments and toys), electrical equipment and electronics

1940-1945

1941 Rex Whinfield and James Dickson at Calico Printers Association, polyester (PET)
The war acts as a catalyst for the further development and production of plastics: nylon for parachutes, aircraft radar domes, etc

1945-1970

Development of mass market for plastic consumer products

New markets for plastics: building & construction industry, packaging and automotive industry

1945 Establishment of industry association of synthetic powder resin-processing companies, the forerunner of the Dutch Federation of the Rubber and Plastics Industry (NRK)

1946 Establishment of TNO Plastics Institute, later renamed the TNO Plastics and Rubber Institute

1946 *Journal of Polymer Science*, first scientific journal for the discipline of polymer science

1948 *Plastica*, later renamed as *Kunststof en Rubber* ('Plastic and Rubber'), the first Dutch trade journal for the plastics industry

1946 *Libelle*: article in Dutch women's magazine under the heading: 'Plastic. The wonder-product'

1950 Plastics consumption in the Netherlands stands at 1.7 kg per capita

1950 Shell, production of PVC. Start of plastics production

1951 Plastics processing industry consists of 46 companies employing a workforce of around 2,700

1952 DSM, production of caprolactam (base material for plastic); start of production of plastics and raw materials for the production of plastics

1953 Paul Flory, publication of *Principles of Polymer Chemistry,* a milestone in polymer science

1953-55 Karl Ziegler and Giulio Natta, catalytic process for production of polyethylene and polypropylene

1960 Plastics consumption in the Netherlands stands at 9.1 kg per capita

1964 *Plastica*: '…astounded to see that the hike in output from 79,500 tonnes in 1960 to 134,500 tonnes in 1963 [ed.: in the Netherlands] is likely to be followed by a doubling in output over the next three years…'

1970-2015

1970 Chairman of the Dutch Society for Industry and Trade: '… One of the most important problems of our time is the role played by plastics as an environmental pollutant.'

1970 Plastics consumption in the Netherlands stands at 35 kg per capita

1972 Akzo, superstrong Twaron fibre

1973 Article in *Der Spiegel* on 'Dangerous Plastic'

1973 James Guillet, biodegradable plastic

1974 Hideki Shirakawa, Alan McDiarmid and Alan Heeger, electrically conductive plastics

1979 Paul Smith and Piet Lemstra, ultra-high-molecular-weight polyethylene (UHMWPE), superstrong Dyneema fibre

1980s and 1990s Akzo/AkzoNobel withdraws from synthetic fibres to focus on coatings, paints and adhesives

1981 ACT, Industrial Moulding and MAGO, the first fully plastic garden chair

1990s Shell withdraws more or less entirely from the plastics market

1990 Richard Friend and Andrew Holmes, plastic light-emitting diodes (LEDs)

1997 Establishment of Dutch Polymer Institute (DPI)

1997 Charles Moore reveals the existence of a 'plastic soup'

2001 Spinoza Prize awarded to Bert Meijer, founder of macro-organic chemistry (of which polymer chemistry forms part)

2002 DSM sells bulk plastic production activities to the Saudi company SABIC; decides to focus on high-performance plastics

2011 Teijin Aramid, production of superstrong Endumax tape in Emmen

2011 Plastics processing industry comprises approx. 1,300 companies employing a workforce of around 30,000

2012 Plastics consumption in the Netherlands stands at between 110 and 120 kg per capita (estimate)

2013 Boyan Slat, founder of The Ocean Cleanup campaign

2015 Spinoza Prize awarded to René Janssen for research into plastic solar cells

Future

Scenario Biopolymers and the bio-based economy

Scenario Solar fuels, building blocks for plastics

Scenario The closed plastic loop and the circular economy

SOURCE: H. Meijer, U. Suter, N. Stingelin and P. Smith, 'A brief history of polymers', presentation given on 24 October 2006. See also this book (*The Plastics Revolution*).

Poster of the exhibition 'PLASTIC. Promises of a Home-made Future' held at Het Nieuwe Instituut in Rotterdam, 16 January – 6 April 2015.

Prologue

1. 'We're on the threshold of a plastics revolution'

In the spring of 2015, the New Institute in Rotterdam organised an exhibition on the future of plastic.[1] The central message the exhibition sought to convey was that a bright, new future beckoned for plastic. It's a material that is omnipresent in the world around us: it's in clothing, furniture, paintings, household appliances, coatings and building structures, to give just a few examples. It's used in packaging, bags, cups, shoes and all sorts of other products. In short, plastic is a common, everyday material. Unfortunately, though, its use comes with a downside.

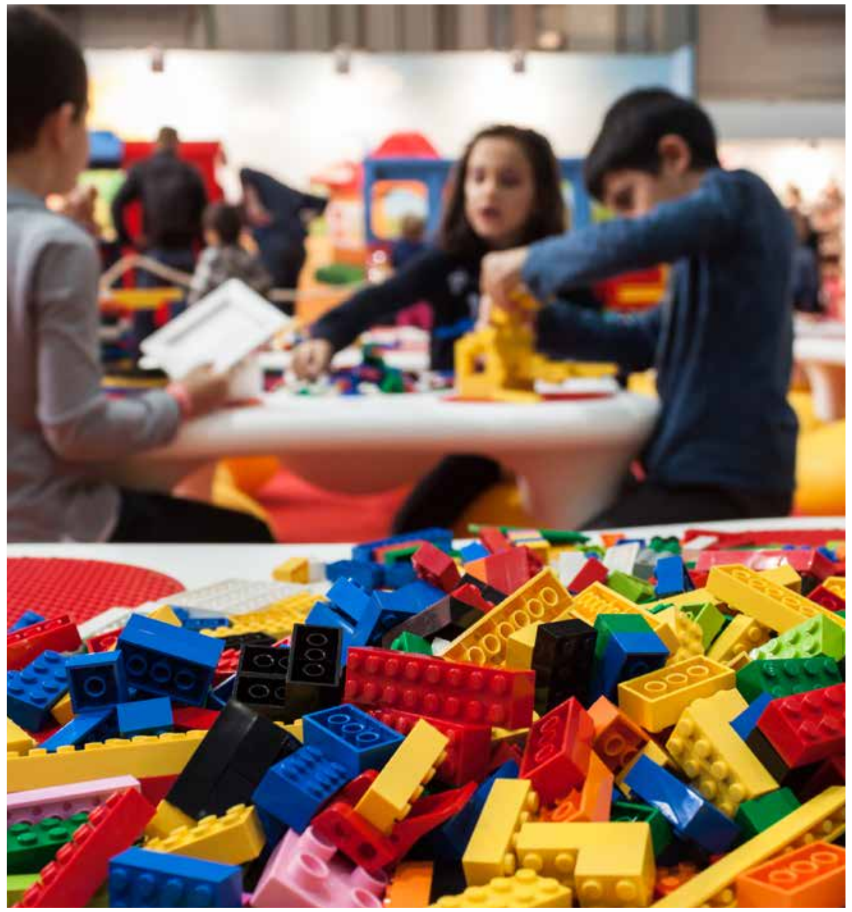
'We use plastic all the time, without ever actually stopping to think about it,' the exhibition designers made clear.[2] Plastic is produced at low cost, in huge volumes and all over the world. At the same time, it's a disposable material that places a tremendous burden on the environment. This situation has got to change. Fortunately, the route to change lies open. New plastics are now being developed that are either biodegradable or are made from organic raw materials. Plastic waste can be turned into new products. And new technologies are making it possible not only to produce plastic products closer to the markets where they are needed, but also to design them in such a way that they meet very specific requirements.

In other words, 'blind consumerism' is now giving way to 'responsible consumerism'. At the core of the new trend are consumers who can actually produce their own plastic products from plastic waste. Sounds great. There must be a hitch. And there is: if one thing is made clear by history textbooks, it is that future plans do not always work out as intended. Any attempt to seek out pastures new invariably involves a clash between new and existing interests, between new and existing patterns of consumption, and between the heart, the mind – and the purse. The aim of this book is to describe how these clashes have affected the history of plastics in the past and how they are likely to affect their future development.

The chemical industry in the Netherlands has also claimed that we will undergo a 'plastics revolution' by the year 2050. By the middle of the century, so chemical manufacturers reckon, the Netherlands will have gained a reputation for itself as the heartland of a new, 'green' chemical industry.[3] In this vision,

> '... raw materials sourced from biomass have become the principal ingredients in the production of foodstuffs, energy and plastics. The chemical industry has designed clean, sustainable production processes that are capable of converting biomass into a wide range of new and existing products...'

The aim is also to ensure that, by 2050, the Netherlands ranks as one of the world's top three leading producers of 'smart' materials:



Lego building bricks at the G! Come Giocare trade fair in Milan in November 2013. The fair targets children and their families and highlights new toys and games.

'… Dutch-based companies are making creative, innovative products with high added value. They include materials for storing energy, catalytic converters made from easily accessible materials that are in plentiful supply (rather than from rare metals that are in short supply, for example). Plastics are lightweight, self-healing, self-cleaning and fully recyclable.'

Plastics play a pivotal role in the joint position paper (entitled "Innovation Contract 2012") issued in the Netherlands by the government, the chemical industry and knowledge institutes. Plastics (and the polymers that form their building blocks)[4] are among the most important materials of the 21st century, and deserve close examination for this reason. They form the core of the Dutch government's 'Smart Polymeric Materials' programme.[5]

Three research strands for the future

The hope is that researchers will eventually come up with 'biobased materials' such as biobased plastics made from for example lactic acid, biobased catalysts to replace fossil catalysts and biobased alternatives to toxic additives such as bromine (used as a flame retardant) and calcium-zinc (used as a heat stabiliser).

Research also needs to be performed into ways and means of closing the plastics cycle. A closed plastics cycle does not require the input of any new materials except for its own growth. The processes of extraction, separation and recovery are designed in such a way as to generate a base material that is of high enough quality to enable new materials with equivalent characteristics to be produced.

Finally, research also needs to be performed into superior materials, i.e. materials that are not just sustainable, but also smart (for example, self-cleaning materials and shape-memory materials), more effective (meaning that they can meet the same performance requirements with less material use or that they can meet higher performance requirements with the same material use) and healthier or safer (by reducing the emanation of toxic substances such as styrene, for example).

Why the Netherlands?

But why should all this take place in the Netherlands? Why should the Netherlands take the lead in producing a new generation of plastics? For a start, the Innovation Contract reckons that the Netherlands is in an excellent starting position. It claims that the chemical industry is varied – in terms of companies, commercial activities and forms of international cooperation – and that it holds a strong position on the world market, including as it does a number of global players. The country's universities and research institutes are a source of valuable expertise. The small and medium sized firms (SMEs) operating in the sector (and not just the chemical industry in general, but the plastics industry in particular) have a reputation for innovation.[6]

TABLE 1.1 World output of various materials, 1938-1970 (in millions of tonnes)

	1938	1950	1960	1970
Plastics:	0.31	2.12	8.25	36.0
- Synthetic rubbers	*0.01*	*0.5*	*1.9*	*4.5*
- Synthetic fibres	*-*	*0.12*	*0.65*	*4.5*
- Other synthetic materials	*0.3*	*1.5*	*5.7*	*27.0*
Crude iron	88	153	241	448
Aluminium	0.5	1.3	3.6	8.1
Copper	1.8	2.3	3.7	6.1
Zinc	1.4	1.8	2.4	4.0
Cotton	5.2	6.0	7.1	9.1
Wool	1.6	1.7	2.1	2.2
Natural rubber	0.92	1.9	2.0	2.9

SOURCE: *UN Yearbook of Statistics* (New York 1961); *UN Monthly Bulletin of Statistics*; C. Freeman and L. Soete, *The economics of industrial innovation* (Third Edition, London 1997), 107, table 5.1

Do these claims hold water? Is the Netherlands indeed potentially capable of playing a leading role in the development of plastics technology and becoming one of the three leading countries in the world, as the Innovation Contract would like to see? This is one of the questions addressed in Part I of this monograph.

A look at the past

Is such a role for the Netherlands warranted by past achievements? An examination of past events suggests that this ambition is indeed justified. As we shall see, the Netherlands was a European centre of plastics at the beginning of the 1970s. This is striking enough in itself: during the period immediately after the Second World War, the Netherlands was a pretty insignificant plastics producer. The US and Great Britain were the front runners then. Although the war had deprived Germany of its former lead, it would soon join in the fray once again. And yet, despite all the powerful foreign competition, the Netherlands managed to take the lead. How did it achieve this? This, too, is a question we shall be trying to answer.

The development of plastics after the Second World War has been nothing less than a revolution. Playing merely a marginal role just before the war, plastic had become one of the most important materials in the world just 30 years later. By 1970, the volume of plastics produced around the world had risen to 36 million tonnes, more than one hundred times as much as the comparable figure in 1938 (see Table 1.1). The only material to be produced in a greater volume was crude iron. The output of other materials such as aluminium, copper, zinc, cotton and wool was much lower. Plastics had surpassed them all – and in just a short space of time.

In the space of a few decades, plastics consumption per capita in the Western world rose to startling heights: whereas the US (the leading consumers of plastics) had been consuming around 0.7 kg per capita in 1938, this figure had risen to 6.4 kg in 1950, before shooting up to around 42 kg in 1971.[7] By this time, the US

For Europe in the early post WWII years, America was the beacon towards a brave new world of plastics. This photo shows a housewife surrounded by a variety of products made from PVC.

had been overtaken by West Germany, which consumed 62 kg per capita in 1971. For their part, the Dutch consumed 35 kg per capita in the same year.

Within just a few years of the end of the Second World War, there were already around one thousand brand names in circulation in the plastics industry. A Dutch reference work published in 1949 needed over 20 pages to list them all.[8] With plastics growing in public popularity, they were spread over a huge range of applications. Never before had a new material become so widely accepted so quickly.

The period from 1945 to 1970 could be regarded as constituting the first plastics revolution. Which would mean that the present time heralds the start of the second revolution. If this is true, it is the context in which we should view the Chemicals Innovation Contract. And there is every reason for doing so. Plastics are under fire at the moment. There is a broad groundswell of unease about plastics, a feeling that gathers into fierce resistance from time to time. An issue that has been the focus of considerable debate recently is that of 'plastic soup': floating 'rubbish dumps' of plastic waste in oceans covering millions of square kilometres. The 'soup' is a plastics cemetery, fed by flows of waste from all over the world.[9]

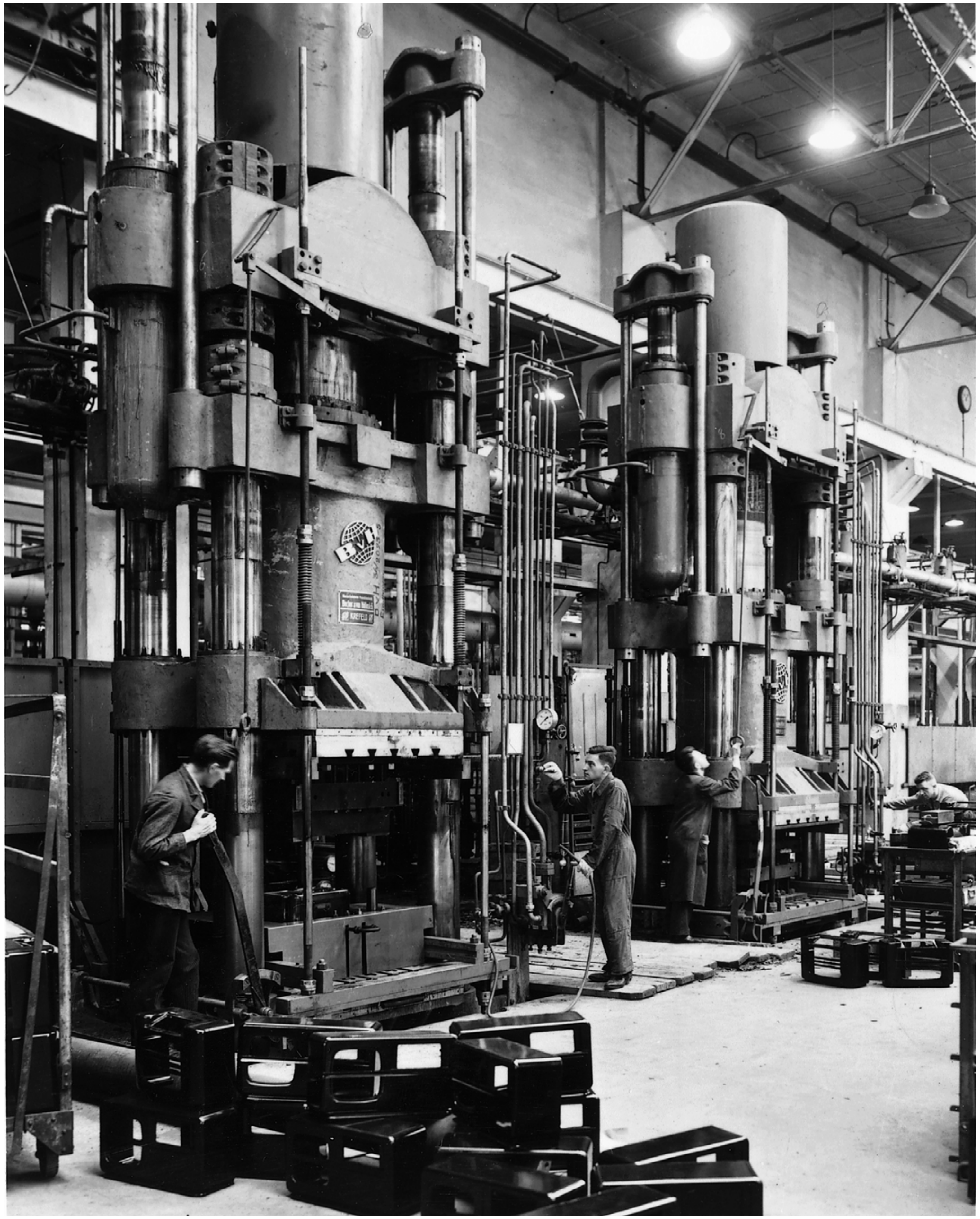
Simply doing away with plastics is not an option, though. Plastics have drilled far too deep into society and permeated far too widely for them to be scrapped. The applications range from coatings in the paints industry, fibres in textiles, films in packaging, laminates in buildings, organic solar cells in the energy sector, plastic machine parts, countless car components, hundreds of consumer products and applications in medicine, IT and transport. The list is endless. A new generation of plastics is needed to meet the demands of sustainability. The question is: what exactly are sustainable plastics? With plastics now used in so many different forms and ways, it's not an easy question to answer. However, we're going to try and formulate an answer in this monograph.

From bulk to specialty

Sustainability is not the only aspect of the second plastics revolution. The chemical industry in the Netherlands has embarked on a new course, shifting from bulk chemicals to specialty chemicals. This also applies to Dutch plastics producers, DSM, AkzoNobel and Shell in particular. As mass producers of plastics such as PVC, polyethylene, polystyrene and nylon, the three companies used to have to contend with the cyclical nature of the market, with its high peaks and deep troughs. It is worth bearing in mind, though, that bulk plastics are still produced in the Netherlands – by foreign producers such as SABIC.

Today, however, the emphasis lies on the production of specialty plastics tailored to offer specific characteristics and functionalities for specific applications. These high-tech products are produced in smaller quantities and are less susceptible to the swings of the trading cycle. Dutch manufacturers believe that they are now in a better position to compete on the world stage than they would be as bulk producers. If high production costs in the Netherlands are the problem, then specialisation with high added value is the answer.

The second plastics revolution is about the combination of sustainability and high tech. We will be tracking down the historical roots of this combination in Part II of this monograph. After all, we cannot place the revolution in its context without painting a clear picture of the historical developments leading up to it.



2. The events leading up to the plastics revolution

Any explanation of the first plastics revolution generally starts with the innovations that took place shortly before the outbreak of the Second World War. Research in the 1920s and 1930s had led to the discovery of new plastics that were capable of being mass produced and many of which combined outstanding characteristics with a relatively low price. It's the classic explanation for the emergence of a new key technology, in which the supply side (i.e. research, production and enterprise) plays the dominant role.

Having said this, it's also possible to come up with an explanation based on demandside factors such as the market situation, consumption and users. It's the demand side that we're going to take as the starting point for our own analysis.

The market

The main market for the small number of plastics produced before the war – products such as celluloid, Bakelite and rayon – was that for household articles and appliances and products in day-to-day use. They were used in the production of utensils such as beakers, tableware, jugs and buttons; luxury items and baubles such as statuettes, medallions, trinkets and chains; and toys like dolls and beads. Although these products were traditionally made of wood, leather, glass, clay, metal or ivory, there was no reason why they shouldn't be made of plastic. The same applied to consumer durables such as cupboards, tables and chairs: they could also be made of plastic or coated with synthetic coatings. Dresses, shirts, stockings and other knitwear garments were also capable of being produced with synthetic fibres. These were all products to be found in the homes of many a middle- and upper-class family. In other words, there was a huge latent market.

In the period before the Second World War, the burgeoning demand from the growing middle classes, particularly in the US, showed how much potential the plastics market offered. It was they that bought the plastic imitations of marble ashtrays, wooden figurines and ornate wooden cupboards. These imitations were cheaper – and frequently a lot cheaper – than the originals made from natural materials, which were difficult and time-consuming to produce. Indeed, at the outset, imitation formed the core of plastics applications.

A paradise beyond the reach of the working classes?

The pre-war market was relatively small-scale, compared with the huge potential presented by the future purchasing power of the working classes. In the Netherlands, the town houses of the middle and upper classes were like castles compared with the cramped terraced houses occupied by working people. Working-class houses were generally only

Production of radio casings at Philips' Philite plant in the 1940s spartanly furnished; their contents consisted only of essentials – there were no luxuries. Working-class mothers cooked on a stove, using a single pan from which the whole family would eat. There would have been a few plates and mugs, but no tea set or 30-piece dinner service. The house would contain a few items of furniture and perhaps some prints, knick-knacks and simple toys, but nothing else. For a long time, working-class people regarded the world of the rich as a paradise that was beyond their reach.

During the course of the 20th century, however, that same paradise gradually began to beckon in the distance. In many countries, pressure from socialist and left-wing movements had resulted in the enactment of new legislation laying down minimum requirements for working-class housing. Wages began to rise and the working classes gradually found themselves spending less and less of their pay packets on food, drink, clothes and housing. More income was now available for spending on luxury items. Although the rise in prosperity did not necessarily mean that workers were ready to move into stately homes, they could start looking forward to buying small-scale imitations. Plastics manufacturers made plans for catering for this new market – which did not fully materialise until after the Second World War, with the US leading the way and Western Europe following suit. It was this mass market which, alongside the demand for imitation products, formed the second essential aspect of the growth of the plastics market.

The consumer society

At the same time, a new trend was also overtaking a section of the middle classes. During the period between the two world wars, civil servants, teachers, engineers and other white-collar workers began to experiment with new technologies that had emerged around the turn of the century.[10] They became acquainted with new services such as telephony and with consumer durables such as radios. They spent their disposable income on visits to the cinema, holidays, photography and other 'modern' activities. New ideas about comfort, hygiene, beauty, adventure, personal development and quality of life altered the nature of their day-to-day lives. It was they who paved the way for the advent of the consumer society.

The new middle classes embraced new art forms, new building styles and new designs.[11] *Art Deco*, the *Bauhaus* and *Stijl* movements, and the architecture of Le Corbusier were all expressions of the pervasive sense of progress and modernity. The new trends were underpinned by new industrial materials such as reinforced concrete, aluminium and stainless steel. Designers sought to create modern shapes using modern materials.

The same applied to the plastics that were on the market at the time, with European designer émigrés to the US taking the lead. For example, in around 1930, the Vienna-born architect and furniture designer Paul T. Frankl predicted the advent of 'a veritable plastics century', with its own, new idiom, all made possible by malleable materials that were remarkable for their 'detail, durability and stability'. He proclaimed himself opposed to the principle of cautious imitation, claiming that imagination was needed in order to 'visualise and realise the potential of new materials and to treat them on their own terms – in other words, to acknowledge the autonomy of the new media.'[12]

Modern design

The arrival of the radio signalled the entry into the private home of modern design with plastic. In the 1930s, radio casings made of shiny, black laminate became the streamlined symbols of the start of the electronic age for the living room. In designers' eyes, plastics formed an invitation to paint elegant wooden furniture black, to design

tables with a glossy top and a chrome steel frame, and to combine polished Bakelite with brushed metal in furniture. Phenolic laminate (or Formica, as it was more commonly known) became a popular material in cafeterias, railway carriages and other public spaces which needed to project a modern image. Instead of being assembled from a number of component parts, items could now be made from a single piece of plastic. The cast or moulded casings of radios, telephones, clocks and scales became the black boxes of modern technology. Designed in flowing, sculpted lines, they concealed the electronic and moving parts within them. Plastic acquired a new image alongside that of imitation and mass production: it now stood for modernity, creativity and functional convenience.

Up to the Second World War, the consumer market was the main market for plastics, with electronics forming an important segment. With their outstanding insulating properties, plastics such as Bakelite were highly suited for use in switches, wall sockets, mounting plates and as components in electrical lighting, telephony and radio communication. A wide range of industrial markets also beckoned.

The properties of plastics varied according to the type, with some types being more water and abrasion resistant, pliant and strong than others. Manufacturers designed products for applications in the building & construction industry, textiles, packaging and the automotive industry. However, it was ultimately from a totally different direction that the development of plastics received a huge boost: war, and the military market. Polyethylene, for example, was needed for the production of aircraft radomes, i.e. protective housing for radar antennae, as it was transparent to radio waves. Nylon was immediately snapped up for use in parachutes, after Japan had placed an embargo on exports of silk, the material traditionally used for the production of parachutes. In short, new products were needed in order to meet these various needs.

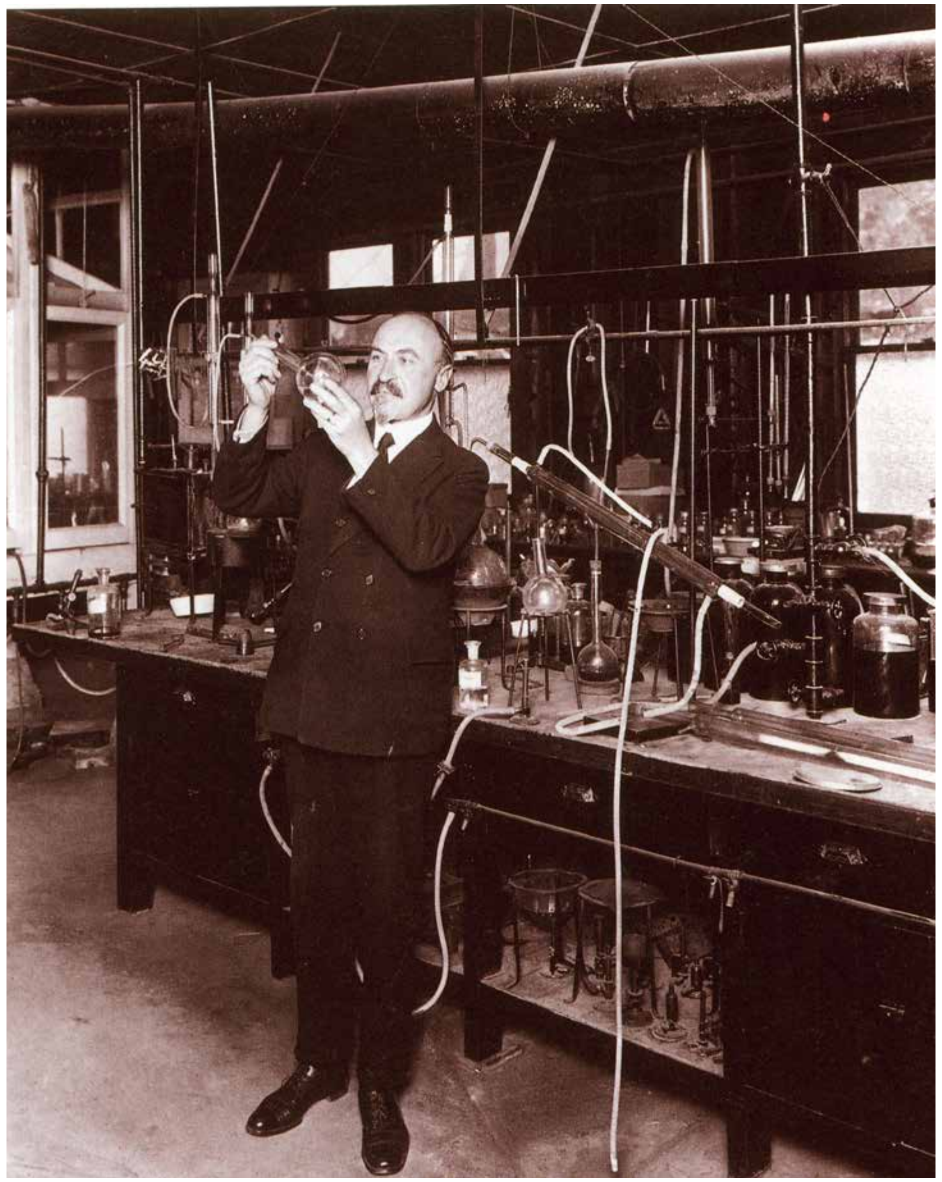
The supply side of the market

Which brings us nicely to the supply side of the plastics market. The first question to ask is: what exactly is a plastic? It's difficult to come up with a generally accepted definition (see also the text boxes entitled 'What is a polymer? What is polymerisation?' and 'Plastics and polymers'). Most definitions from the early years of plastics consist of three elements:[13]

- their macromolecular character (plastics consist of very long chains of mainly carbon atoms which, as molecules, are between 1,000 and 100,000 times bigger than water or sugar molecules, for example);
- the term 'synthetic' is generally used to indicate that plastics do not occur naturally;
- their plasticity, from which plastics derive their function as a material. In other words, there is a stage of the production process at which plastics are either malleable or liquid, after which they then take on a more or less solid state.

Parkesine

Malleable, or mouldable, materials were the subject of a great deal of experimentation in the mid-19th century. Materials such as papier-mâché (made from paper and paste) and vulcanised natural rubber (made from natural rubber and sulphur) were not generally categorised as plastics – as indeed they still are not. Parkesine, which was named after its inventor, Alexander Parkes (1813-1890), was the first material to be designated as a plastic, albeit with certain qualifications.[14] It was referred to in some circles as a semi-synthetic plastic, as it was derived from cotton.[15] The cotton was treated with nitric acid and sulphuric acid before being mixed with vegetable oil and organic solvents. The result was a mouldable dough-like substance that could be used to mould, shape, cut and paint a wide range of products such as medallions, billiard balls, buttons and letter-openers. Unfortunately,



Leo Baekeland in his laboratory

the material was also brittle, fragile and combustible. The addition of camphor proved a great improvement, as this made it both strong and pliant. It was an American inventor called John Wesley Hyatt (1837-1920) who succeeded in producing the new material (commonly referred to as 'celluloid') and its derivatives on an industrial scale at the end of the 19th century.[16]

Bakelite

Bakelite was the first 'fully synthetic plastic' to appear on the market. Again, it was named after its inventor, the Belgian-American chemist Leo Baekeland (1863-1944), who emigrated to the US in 1891. Bakelite was formed from a reaction of phenol (from coal tar) with formaldehyde (made from a combination of coal and water). The phenol resin resulting from the reaction was then mixed with different fillers such as wood flour, asbestos fibre, cotton fabrics and pieces of paper, all of which produced forms of Bakelite with different properties.

Bakelite was initially used mainly for the production of electrical insulators, but the General Bakelite Company (founded in 1910) soon turned its attention to products for the mass market, including door knobs, light fittings and telephone receivers. The company's carefully planned marketing campaign in the 1930s was

the first attempt to give plastic a modern image. Designers were invited to design new Bakelite products and their designs then formed the subjects of fresh publicity campaigns.

Until then, most of the research into plastics and ways and means of commercialising them had been undertaken by inventors, either in conjunction with a commercial firm or after setting up a business of their own (as in the case of Hyatt and Baekeland). They spent many years working in small laboratories and workshops, experimenting with small teams of helpers with the aid of capital from friends and relatives. Once they had patented their inventions, they could then cautiously start producing their plastic and processing it into end products. The laboratories, workshops and production plants all formed part of one and the same workflow. In some cases, the laboratory took up part of a factory, in others it was located in a separate room close to the production hall. However, this form of innovation was to become less and less common during the later development of new plastics.

Chemical giants

Just about all the main plastics introduced after the First World War were produced by big chemical companies boasting extensive research and development facilities. Most of these chemical giants were founded in the US and Germany at the end of the 19th century. Their growth was given a huge boost by the emergence of new technologies in the fields of electricity and chemistry, the development of which required massive investments in research. Due to the high cost of development, certain products were profitable only if they were produced on a large scale. This also meant that big markets needed to be found for them, which in turn meant investing in distribution, marketing and management. These were things that only large companies were able to do: they were the first organisations to build large research laboratories.

The mass markets now coming into view for plastics justified the massive investments by big chemical companies in this branch of technology. The Second World War was another important factor: the countries at war were at risk of being cut off from their supplies of natural resources (or indeed had already been cut off) and were keen to find suitable alternatives. This was the case with rubber in Germany, for example. The three plastics that were later to dominate the market during the post-war period were developed by large chemical conglomerates: polystyrene was developed by two chemical companies, Dow Chemical from the US and IG Farben from Germany; polyvinyl chloride (PVC) by IG Farben; and polyethylene by ICI, a UK-based company. The most important of the synthetic fibres, nylon, was invented by DuPont, a US chemical company. Let's take a closer look at these four plastics.

Polystyrene

Polystyrene is made from styrene, a derivative of benzene (at the time based on coal tar). Under the combined influence of heat and a catalyst (to speed up the reaction), the styrene molecules combine to form a polymer chain, thus gradually transforming from a liquid into a glassy solid. The process had already been discovered in the 19th century.[17] A medium-sized US chemical company first started commercial production in 1925, but this was not successful. Then, in the 1930s, both Dow Chemical and IG Farben, working entirely independently of each other, attempted to master the technology. They found that polystyrene was easy to process and work with, very clear and a good electrical insulator, and that it had good mechanical properties. Production went into overdrive after the war.

PVC

IG Farben was also successful in another branch of plastics technology: the development of PVC.

Prior to the outbreak of the Second World War, the company was known as the biggest chemical producer in the world.[18] It was formed in 1925 following the merger of a number of German firms. One of the reasons for joining forces and forming a trust was the need to bring together and fund research activities in plastics technology. In certain years, the amount spent by the company on research was more than the amount it distributed to its shareholders in the form of dividend. IG Farben was a big patent-holder, possessing 20% of all the industrial patents filed around the world between 1931 and 1945. However, even IG Farben was unable to develop PVC on its own – although its groundwork was to prove of immense value.[19]

Both vinyl chloride and polyvinyl chloride had already been produced in academic research labs in the 19th century, without this leading to any industrial applications. Vinyl chloride could be produced from acetylene (extracted from coal tar) in a reaction with hydrochloric acid. In 1912 and 1913, a German chemist called Fritz Klatte, who worked for Hoechst (which became part of IG Farben in 1925), was granted a series of patents that had a bearing on the production and use of PVC. Unfortunately, though, it proved to be a challenging material:[20] it tended to break when exposed to light, was extremely difficult to process and produced chlorine gas when heated. All these problems needed to be solved by a combination of additives and careful process control. In the end, IG Farben was only able to do this with the help of expertise from Bayer (which also became a member of the IG Farben group in 1925) and various British and US companies, and with the close cooperation of the academic world. Various types of PVC were soon used for electrical cable jacketing, piping, fibres (clothing), shoes and so on.

Polyethylene

Polyethylene, which grew to become the main bulk plastic after the Second World War, was discovered by accident by Imperial Chemical Industries (ICI), a company that was formed in 1926 as a conglomerate of four British firms.[21] At the time, ICI was working on a long-running research programme into high-pressure chemical reactions. Its research chemists discovered polyethylene during one of their experiments in 1933, in an attempt to get ethylene to react with benzaldehyde at an extremely high pressure (1900 bar) and a temperature of 170°C. They reported finding a 'waxy solid in the reaction chamber', which was attributed to a defect in the equipment. The material's good insulating properties were soon recognised. However, it took many years – and huge investments – before the company was able to develop safe, high-pressure equipment.

Interestingly, the Dutch physicist and researcher Professor Teun Michels (1889-1969) played an important role in the development of polyethylene.[22] Apart from helping to construct a high-pressure lab and train laboratory staff, he designed special-purpose research tools and assisted in the design of a compressor, which was a crucial component of the pilot plant where production was launched in 1938.

Nylon

Nylon is the common name for a polymer made up of a chain of amides, a so-called polyamide. It is normally produced using dicarboxylic acids and diamines. Amino carbonic acids (in their cyclic form known as lactams) are also used as raw materials. Nylons are most widely used in the form of synthetic fibres. Another application is the use of nylon as a base material for plastics.

Nylon was first produced in DuPont's laboratories.[23] Its spiritual father was the brilliant researcher, Wallace Carothers, who joined DuPont in 1928 and devoted himself to researching polyamides. It took him five years to test the chemical reactions before a nylon-like

DuPont advertisement
1949

synthetic fibre was discovered on a laboratory scale. It then took a further five years before the discovery was commercialised. During this second period, DuPont invested large sums of money in the development of the production process and the necessary production equipment, formed alliances with textile manufacturers and undertook painstaking market research.

In the event, nylon proved to be one of the biggest commercial successes in DuPont's history. After the first nylon stockings appeared on the market in 1939, a staggering 64 million pairs were sold within the space of one year. The success of nylon was a huge boost to future industrial research into plastics.

The story of these four plastics is ample illustration of just how much time, money and energy (expended by big research teams) went into their development. Even in those cases in which a plastic was invented outside a large chemical lab, a big chemical company was still needed to bring its development to fruition. The route to profitable production and a commercial market was so labour- and capital-intensive as to be out of the reach of small and medium-sized companies.

Processing techniques

The development and production of new plastics is just part of the story of the supply side of the market. Plastics needed processing, for which special equipment was required. The principles underlying the majority of the processing techniques used after the Second World War dated from before the war. These included compression moulding, injection moulding, extrusion and casting. Shaping malleable materials was a centuries-old technique that had a number of advantages. Basically, it required much less labour to produce a series of simple products compared with the traditional methods (such as planing, drilling and milling) used for working natural materials such as wood and iron. The techniques used for injection moulding, extruding and moulding plastics were early-20th-century inventions.

Compression moulding involved forcing the plastic in powder form into a mould (which in certain cases was preheated) at high pressure. In the case of injection moulding, the plastic was first melted in a moulding machine before being injected horizontally into a mould at high pressure. Extrusion involved first turning the plastic into viscous form, before using a worm wheel to press it through the aperture of a mould. Casting was used to produce complex shapes or sheets and films. Plastic film could be made with the aid of calendering, which involved passing a viscous plastic through two or more rollers. Sheeting could be made by planing or by cutting off a sheet of plastic from a larger piece. Lamination was another familiar technique: layers of paper, fabric, glass fibre or other material were soaked in synthetic glue or resin and then pressed together. Nylon fibres were produced with the aid of a spinneret, a technique previously used for the production of artificial silk or rayon.

The revolution in plastic production after the Second World War was not merely the result of the important inventions that took place in the US, Britain and Germany in the 1930s. The history of plastics goes back a lot further in time. Experience had already been gained with plastic and plastic products in the 19th century, albeit on a small scale. However, even then, people realised that plastic was potentially capable of satisfying a mass market demand for day-to-day products.

The consumer society took on concrete shape before the Second World War, particularly in the US, where vital production and processing machinery had already been developed. The foundations for the post-war plastics revolution had in fact been laid over the course of the preceding century – in technical, economic and cultural terms. It was simply a question of waiting for the right conditions in which to bring the technology to full maturity. This is what happened in the years between 1945 and 1970.

Products made from Philite, the 'Bakelite' material that Dutch manufacturer Philips introduced in the years before WWII

Was the Netherlands ready?

But was the Netherlands ready for a plastics revolution? The Netherlands already harboured a modest plastics producing and processing industry.[24] When Philips began producing and processing Bakelite in 1923, it was probably the first Dutch company to do so. Bakelite was used to make loudspeakers, radio housings and insulation panels for X-ray equipment, as well as light fittings, plugs and switches and later on even non-core products such as pen trays and fruit bowls. The 'Philite' plant (as it was called) built in 1928 was one of the biggest and most modern in the world. Apart from Philips, a number of Bakelite moulding plants, including Gebr. van Niftrik in the province of Brabant, made products for electrical equipment used by the Dutch post, telegraph and telephone service and the Dutch railways.

With a little licence, one could also regard the artificial horn and artificial silk industries as forming part of the plastics industry. In reality, these were semi-synthetic plastics (to use the term that was in vogue at the time), given that artificial horn was made from casein, a by-product of the dairy industry, and artificial silk was made from cellulose obtained from wood and cotton. A company called *Internationale Kunsthoorn Industrie* ('International Artificial Horn Industry', or IKI), for example, was a member of the plastics industry. ENKA (*nv Eerste Nederlandsche Kunstzijdefabriek*, or 'First Dutch Artificial Silk Factory', to give it its full name), which was founded in Arnhem in 1912, was the first Dutch manufacturer of artificial silk. Other new plants soon followed. ENKA acquired one of these, the *Hollandsche Kunstzijde Industrie*, in 1928, before merging in 1929 with *Vereinigte Glanzstoff Fabriken AG* to form a new company called *Algemene Kunstzijde Unie NV* (or AKU).

Research

The Netherlands also had a modest research infrastructure.[25] Philips already had its own research labs: a Chemical Laboratory (founded in 1910) and a Physics Laboratory (1914). AKU set up a research lab of its own in Arnhem in 1925. This was accorded the status of a public limited company in 1933 and became the focal point for all Dutch research activities. It was styled NV Onderzoeksinstituut 'Research'. In 1941, AKU founded the Institute for Cellulose Research in Utrecht, where researchers enjoyed a greater degree of freedom than their counterparts in Arnhem. As far as we are aware, none of these entities was actually on a quest to discover new plastics before the Second World War.

After the war, however, the Dutch chemical industry became keenly aware of the gathering revolution. A reference work published in 1949 opened with the following passage: 'Apart from atomic physics and radar, no single field has probably appealed as much to the public imagination in recent years as plastics has. All over the world, new materials have been adopted and new applications found, resulting in either the emergence of new industries or the unparalleled growth of existing industries. The process has been largely concentrated in the US, Britain and Germany. The Netherlands has shared the fate of most European countries, where the war has been a powerful brake on developments.'[26]

The intriguing question is, therefore: how did the Netherlands manage to join the pioneers of plastics technology so soon after the Second World War?

AKU laboratory in the Netherlands in the 1950s

What is a polymer? What is polymerisation?

In 1920, the German chemist Hermann Staudinger (1881-1965) caused incredulity among his colleagues by postulating the existence of very long molecules. None of them had the slightest inkling that he would later be awarded the Nobel Prize for Chemistry for this very idea. Macromolecules, as he called them, could be made by stringing together a large number (upwards of 10,000) of short molecules to form a sort of chain. He claimed that rubber, starch, cellulose and proteins all consisted of this type of extremely long molecules. Most of his colleagues were sceptical, believing this to be impossible.

The 1930s brought proof for Staudinger's theory. Wallace Carothers, a chemist working for the American company DuPont was bent on testing Staudinger's hypothesis. He discovered various types of macromolecules during the course of his study, including nylon. This new synthetic material was to become a huge commercial success for DuPont. The result was a breakthrough in a fascinating branch of science and technology that continues to produce new discoveries and Nobel prizes even today.

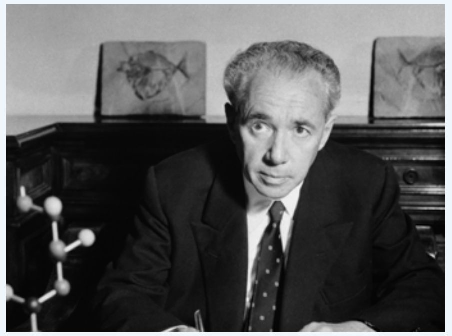
The Austrian chemist Hermann Mark (1895-1992), who had emigrated to the US, described the very long molecules as 'high polymeric', because they consisted of a large number of molecular elements known as 'monomers'. The shortened form, 'polymer', was adopted as the standard international term around 1950 and was reserved explicitly for very long molecules. Staudinger did not like the term and retained a preference (right up to his death in 1965) for the term 'macromolecule', the scope of which is broader than that of 'polymer' and which in theory encompasses all large molecules. In Germany and the Netherlands, the terms 'macromolecule' and 'polymer' are used interchangeably.

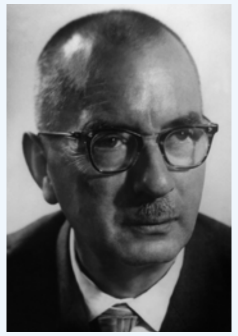
Polymerisation is a reaction in which a large number of small molecules or monomers form one very long molecule called a polymer. Such reactions constantly occur all around us in the natural environment. That's how trees and plants produce cellulose and the human body makes proteins and DNA. Around 1900, natural polymers such as lactoprotein (milk protein) and cellulose were very popular raw materials for the production of buttons and artificial silk. The first person to make a fully synthetic plastic with the aid of polymerisation was the Belgian-born chemist Leo Baekeland, when he produced Bakelite in around 1907. Other synthetic polymers – such as PVC, nylon and polyethylene – were invented and commercialised in the 1920s and 1930s. Ethylene is the monomer in the latter case, providing the basis for the formation of a polymer, i.e. polyethylene, by means of polymerisation.

Other types of polymerisation needed to be developed for new polymer applications. For example, the inclusion of two or more types of monomer (instead of one) in the polymer chain – in a process known as 'copolymerisation' – results in the formation of polymers with specific characteristics (in terms of elasticity, melting point and chemical resistance) and hence with other applications.

Conventional polymerisations use monomers obtained from coal or petroleum. Now that sustainability has become a standard goal, a new field of research is opening up: polymerisation with the aid of biomass.

Nobel Prize winners in polymer science





1953
Hermann Staudinger

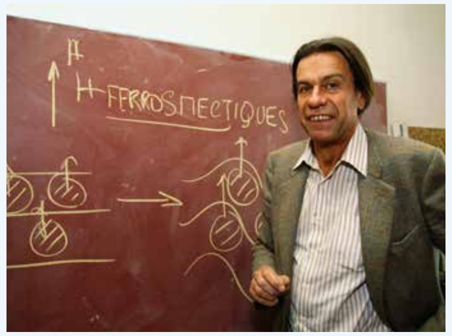
for 'his discoveries in the field of macromolecular chemistry'

1963
Giulio Natta – Karl Ziegler

for 'their discoveries in the field of the chemistry and technology of high polymers'

1974
Paul J. Flory

for 'his fundamental achievements, both theoretical and experimental, in the physical chemistry of the macromolecules'



1991
Pierre-Gilles de Gennes

for 'the discovery that methods developed for studying order phenomena in simple systems can be generalized to more complex forms of matter, in particular to liquid crystals and polymers'

2000
Hideki Shirakawa
Alan G. MacDiarmid
Alan J. Heeger

for 'the discovery and development of conductive polymers'

Plastics and polymers

When the famous scientist Hermann Mark visited the Netherlands in the late 1940s, he made a lasting impression on an audience of rather startled students in a packed university lecture theatre by laying out a collection of colourful plastic objects on a table in front of him. Hardly anyone had ever seen these types of plastics. The best known plastic was Bakelite, which was commonly used to produce dark radio casings. But thanks to the fact that (unlike Bakelite) the new plastics could be softened and coloured after production, they could be made into all sorts of different shapes and colours.

These days, the number of plastics in circulation runs into many thousands. Most of them are made up of a given type of polymer that is blended with additives in order to obtain certain specific product characteristics – such as a particular colour, impact resistance, elasticity, electrical insulation, fire resistance, and so on. The additives, including pigments, fillers, plasticisers, anti-oxidants and stabilisers, constitute a global market of their own.

Plastics can be classified in a number of different ways. A commonly used classification is based on a division into three categories: *thermosetting plastics*, *thermoplastics* and *elastomers*. Bakelite is an example of a thermosetting plastic.

Thermosetting plastics

In the case of thermosetting plastics, molecules (monomers) bond together to form long chains (polymers) that are strongly bonded together by means of crosslinking. The presence of this ‘mesh’ (or network) of polymers means that a thermosetting plastic will not tend to melt or liquefy when heated. Thermosetting plastics such as Bakelite are moulded into their definitive shape during the production process.

Thermoplastics

When a thermoplastic is formed from monomers, the bonds connecting the long chains of polymers are relatively weak. This type of plastic can be softened fairly easily by heating and moulded into a wide range of objects. There was a sharp rise in the popularity of thermoplastics after the Second World War.

In terms of its behaviour, rubber lies halfway between thermoplastics and thermosetting plastics. This type of plastic is known as an elastomer – and with good reason. The polymer molecules acquire elastic properties because of the special way in which they are linked to one another. Thanks to the Dutch rubber plantations in Indonesia, particularly during the period prior to 1950, the Dutch used to have a thriving latex (natural rubber) industry. During and shortly after the war, Dutch companies gained their first experiences with synthetic rubbers such as isoprene, meshed polyurethane (PUR) and styrene butadiene rubber (SBR).

Five big families

Plastics may also be divided into the five families of bulk polymers that dominate today’s world market: polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC) and polyethylene terephthalate (PET). Each family comes with its own applications and market.

Polyethylene (PE) is used for making products such as plastic bags, plastic cups, plastic bottles, shrink-wrapping film, toys and flexible tubes. PE is the largest family among the plastics. The most widely used plastic in the world, it subdivides into high-density polyethylene (HDPE), low-density

polyethylene (LDPE) and linear low-density polyethylene (LLDPE).

Polypropylene (PP) has a higher melting point and is stronger than polyethylene, making it suitable for certain niche packaging markets, such as barrels and containers. Cars are full of polypropylene: it’s in the upholstery, housings, dashboards and bumpers, to name just a few applications.

As an outstanding heat insulator, polystyrene (PS) is eminently suited for use in disposable cups, for example. As it can also take the shape of a strong, hard plastic, it can be used in cartridges, disposable cutlery, clothes hangers and test tubes.

Polyvinyl chloride (PVC) is a highly versatile material that comes in all manner of different shapes and can readily be mixed with additives. Among the objects made of PVC are walls and ceilings, as well as pipes, flexible medical aids and jackets for electrical and steel cables. The most common application of polyethylene terephthalate (PET) is in the familiar PET bottles. It is also used for industrial fibres, textile fibres (such as fleece) and cooking utensils.

Alongside these five big families, there are other, smaller plastic families, such as the phenolic resins (which include Bakelite) and the polyamides (one of which is nylon). There are some 20 families in total that researchers use to develop new plastics and which serve as a basis for manufacturers to produce the many thousands of plastic varieties.

SOURCES
A. E. Schouten and A.K. van der Vegt, *Plastics. Hoofdlijnen van de huidige kennis en toepassing van de synthetische macromoleculaire materialen* (Utrecht 1966, 5th edition 1974)
S. Freinkel, *Plastic. A Toxic Love Story* (Boston 2011), 61-62; 236-239

Notes

1 'Plastic, Promises of a Home-made Future'. Exhibtion at Het Nieuwe Instituut, Rotterdam, 16 January 2015 - 6 April 2015.

2 This and the following quotes are from the written and spoken texts at the exhibition. An exhibition catalogue does not exist.

3 The quotes are from *Innovatiecontract 2012-2016. Topsector Chemie* (n.p. 2011) [first page of the summary].

4 To put it more precisely: plastics are made up of a specific type of polymer combined with additives, such as plasticisers, UV stabilisers and fillers (e.g. calcium and sawdust) and sometimes mixed or blended with other types of polymers or reinforcing materials.

5 The programme comes under one of the Top Consortia for Knowledge and Innovation (TKI) set up in the Netherlands. Each of these consortia is a collaboration platform for companies, universities and public research institutions, which brings together activities extending across the entire chain from research all the way to the market introduction of new or improved products and processes. The social relevance of the TKI Smart Polemeric Materials is defined as follows: TKI Polymeren is meant to accelerate the transition from plastics based on fossil materials to plastics based on renewable resources. It should lead to plastics which are sustainable and reusable and which can be produced and processed in a sustainable way. The aim is to develop plastics that will replace materials that are becoming scarce. Eventually, the Netherlands should be able to generate income from 'smart' and 'superior' materials. *Innovatiecontract 2012-2016. Topsector Chemie* (n.p. 2011).

6 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)

7 A. E. Schouten and A.K. van der Vegt, *Plastics. Hoofdlijnen van de huidige kennis en toepassing van de synthetische macromoleculaire materialen* (Utrecht 1966, Fifth edition 1974), 278, table 11.4.

8 R. van de Kasteele, *Het kunststoffengebied. Chemie, grondstoffen en toepassingen* (Amsterdam 1949), 159-181.

9 J. Goossens, *Plastic Soep* (Rotterdam 2009), 15-17.

10 H. Lintsen, *Made in Holland. Een techniekgeschiedenis van Nederland [1800-2000]* (Zutphen 2005), 255-266, 346-349.

11 The following is based on: J.L. Meikle, 'Materia Nova: Plastics and Design in the U.S., 1925-1935', in: S. Mossman and T. Morris (eds.), *The development of plastics* (Cambridge 1994), 38-45.

12 Quote from Meikle, 'Materia Nova', 41.

13 For other countries, see: C. Williamson, 'Victorian plastics. Foundation of an industry', in: S. Mossman and T. Morris (eds.), *The development of plastics* (Cambridge 1994), 2-3.
For the Netherlands, see e.g.: Van de Kasteele, *Het kunststoffengebied*, 13-18
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Schouten and Van der Vegt, *Plastics. Hoofdlijnen van de huidige kennis*, 13-14.

14 S. Mossman, 'Parkesine and Celluloid', in: S. Mossman and T. Morris (eds.), *The development of plastics* (Cambridge 1994), 10-25.

15 The difference between semi-synthetic and synthetic is that semi-synthetic products contain macromolecules from biomass, whereas synthetic products contain polymers whose building blocks are monomers derived from fossil raw materials.

16 Hyatt and his brother together set up the 'Alany Dental Plate Company'.

17 B. Berendsen, 'Polystyreen: voorbeeld van geleidelijke evolutie', in: H. Brüggeman, *Kunststoffen 1986. Terugblik en toekomst* (Delft 1986), 34-39.

18 C. Freeman and L. Soete, *The economics of industrial innovation* (Third Edition, London 1997), 111-121.

19 Ibid. 121-123; C. Blanjean, 'Polyvinylchloride', in: H. Brüggeman, *Kunststoffen 1986. Terugblik en toekomst* (Delft 1986), 40-46.

20 Initially, PVC served as a solution to another problem: it was a simple way of binding the toxic chlorine gas resulting from the production of lye (caustic soda) from sodium chloride (common salt) to ethylene to form a solid that could easily be stored or landfilled. The problem with the processing of PVC is that it is not completely amorphous in character. Due to the presence of a limited crystallinity, PVC only melts at high temperatures. Given the material's limited thermal stability, which can result in the emission of hydrochloric acid, it could only be processed at low temperatures and consequently it did not melt completely. Because of this, the material was highly viscous and generated a lot of frictional heat during processing, which in turn entailed the degradation of the PVC and – again – the emission of hydrochloric acid. This made it necessary to apply all sorts of lubricants and stabilisers, both externally and internally, to minimise mechanical shearing and thermal loading of the material during processing. Also, special (counter-rotating) twin-screw extruders were developed. Once the processing problems had been solved, PVC proved to be an excellent and, above all, cheap material that was also very versatile. For example, with the help of plasticisers it could be transformed into imitation leather and flexible, transparent packaging material or material for sheathing cables. The plasticisers used for this purpose included DOP, dioctyl phthalate. Later on, PVC became a suspect material because of the hydrochloric acid resulting from its incineration and because of the (carcinogenic) lead stabilisers used. Also a subject of debate was the health hazard that the plasticisers in PVC posed when the material was used in pacifiers, bottles and toys for babies. See Part II of this book.

21 Freeman and Soete, *The economics of industrial innovation*, 123-126; P. Pols, 'De drie polyethenen', in: H. Brüggeman, *Kunststoffen 1986. Terugblik en toekomst* (Delft 1986), 22-28.

22 P.J. Knegtmans, 'Michels, Antonius Mathias Johannes Friedrich (1889-1969)', in *Biografisch Woordenboek van Nederland*. URL:http://resources.huygens.knaw.nl/dagboekenaalberse/BWN/lemmata/bwn5/michels [12-11-2013].

23 D. Hounschell and J. Smith, Jr., *Science and corporate strategy. DuPont R&D, 1902-1980* (Cambridge 1988), 236-248, 257-274.

24 F. van der Most, E. Homburg, P. Hooghoff and A. van Selm, 'Nieuwe synthetische producten: plastics en wasmiddelen na de Tweede Wereldoorlog', in: J.W. Schot, H.W. Lintsen, A. Rip and A.A. Albert de la Bruhèze (eds.), *Techniek in Nederland in de Twintigste Eeuw* (Zutphen 2000) Part II, 361.

25 For more information, see: E. Homburg, *Speuren op de tast. Een historische kijk op industriële en universitaire research* (Inaugural Lecture, Maastricht 2003).

26 Van de Kasteele, *Het kunststoffengebied*, 13.