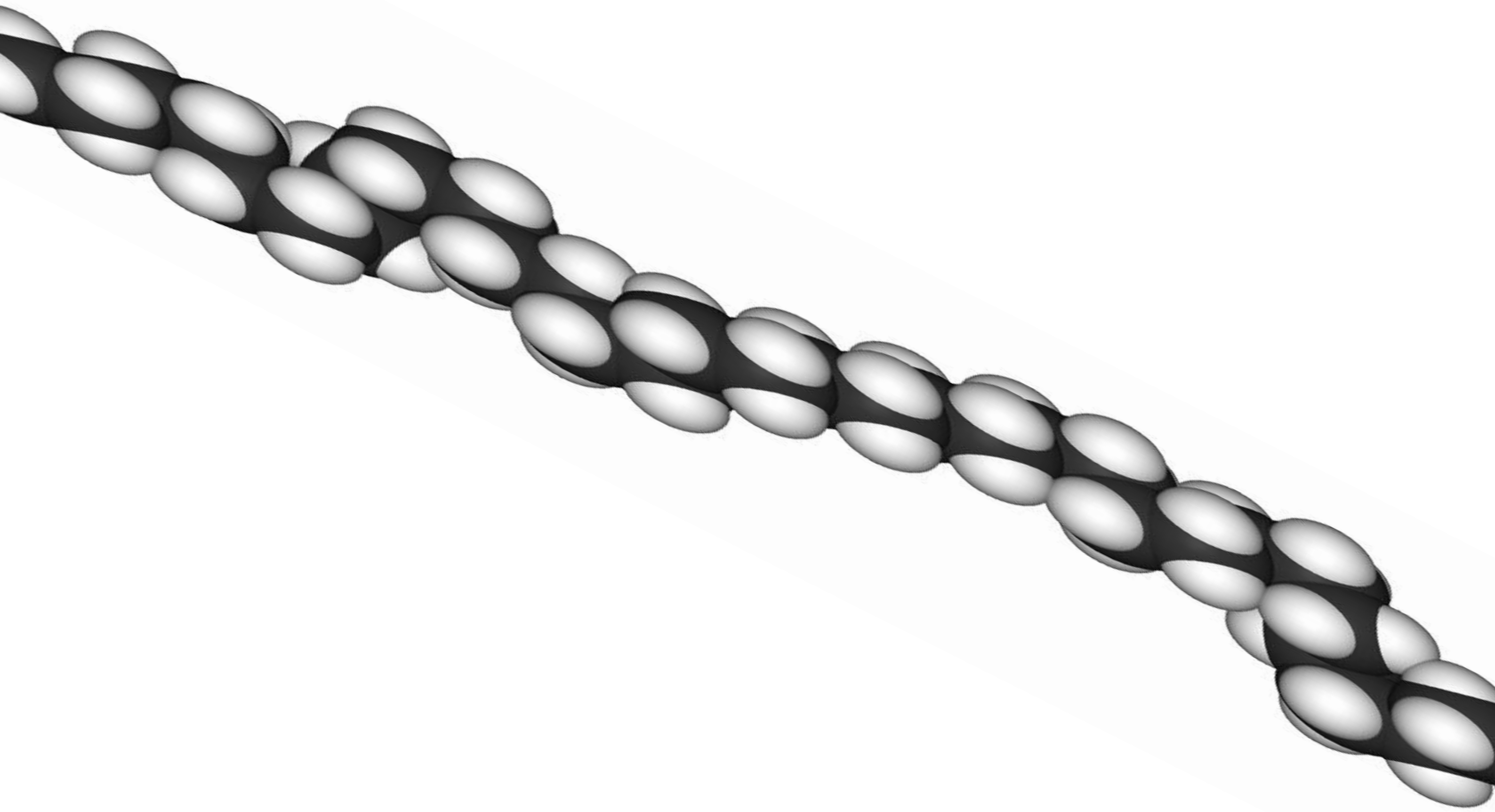
Experience Curves in the World Polymer Industry

Quantifying Reductions in Production Cost



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Picture on cover: Representation of a polyethylene molecule (adapted from: http://fogie.us/blog)

“The only source of knowledge is experience”

Albert Einstein

Acknowledgements

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Special thanks goes to my girlfriend, Vicky, for providing me with a warm cup of tea at times when I needed it most. Thank you all.

Tristan Simon, December 2009

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Abbreviations

ABS	poly(Acryl-butadiene-styrene)
EB	Ethyl-Benzene
EDC	Ethylene-dichloride
EPS	Extruded Polystyrene
FCC	Fluid Catalytic Cracker
GER	Gross Energy Requirement
HDPE	High Density Polyethylene
LDPE	Low Density Polyethylene
LLDPE	Linear Low Density Polyethylene
kt / a	kilo tonne per annuam
Mt	Mega tonne
PE	Polyethylene, polythene, poly(methylene)
PP	Polypropylene
PS	Polystyrene, Polystyrol
PVC	Polyvinylchloride
SEC	Specific Energy Consumption
VCM	Vinyl-chloride monomer

Executive summary

Introduction

Compared to traditional bulk materials like paper and steel which have been produced for centuries, plastics are relative new comers. Mass production of plastics just started in the 1950s. However, with 260 Million tonnes of plastics produced in 2007 the plastics industry is one of the biggest in the world in terms of volume. And the industry is growing at rates that exceed world GDP growth. Plastics have become increasingly more important in our lives. Some applications would not even be possible without plastics (e.g. airbags). Currently plastics are mainly used in the packaging and construction sector in which they have replaced more traditional materials. In Western Europe in 2007 100 kg plastics were used per capita and this figure is even expected to increase to 140 kg per capita for 2015.

The drivers for this growth are manifold. Economic growth and the increasing wealth in newly industrialized and in developing countries play an important role. The share of plastics has been increasing at the expense of the other bulk materials. This is partly a result of new needs, which can best be fulfilled by plastics (e.g., safety devices such as airbags, mulch films for agriculture and certain medical devices and implants). Another important driver is material substitution, e.g. the replacement of glass by polymers in consumer goods such as computer screens and inroads made by plastics into the traditional applications of paper/board in packaging and metals (e.g. in consumer goods and buildings). Here, the costs for production and processing of the competing materials play an important role.

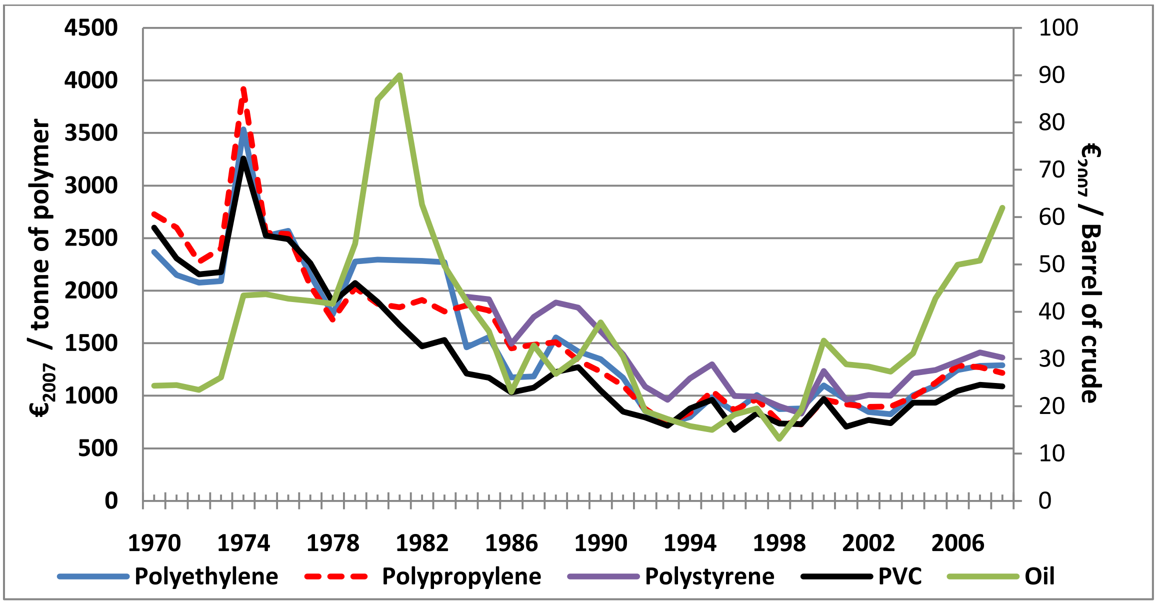
The experience curve approach is a way to quantify technological developments in aggregated form for a sector or an industry. In the method cost reductions are related to experience and experience in turn is related to the cumulative production. In other words, the more plastics are produced the more experience is gained, the cheaper the plastics become. The change in production cost at doubling of cumulative production is expressed in the progress ratio.

The plastics industry is dominated by four bulk polymers Polypropylene (PP), Polyvinylchloride (PVC), Polyethylene (PE) and Polystyrene (PS). Analyzing developments for the bulk-polymer industry can be of great interest to polymer producers to aid in decisions regarding strategic marketing. From a theoretical point of view it is interesting to see how the experience curve method copes with energy demanding products, like polymers, as the development in production cost for such products is to some extent related to drivers which are not related to technological learning.

Previous studies regarding experience curves in the polymer industry show progress ratios between 64% and 87% but always focused on regional markets. To our best knowledge no study is available assessing experience curves in the world polymer industry as whole. This study tries to fill that gap by identifying the rate at which the polymer industry builds up experience by deriving experience curves using world polymer demand data. Because cost data is not readily available European prices were used as a proxy for costs.

Methodology

The main objective was to identify experience curves for the world polymer industry**.** One of the issues when deriving experience curves is the effect of drivers which are not related to technological learning. The oil feedstock for the bulk polymers is to a large extent correlated (up to 82%) in price to the polymer prices showing the importance of the oil feedstock. Because oil prices are too a large extent determined by other factors than technological learning (e.g. geopolitical conditions, scarcity and economic conditions) one needs to correct for the feedstock price fluctuations. In the following graph the relation between the oil price and the polymer price can be seen.



Four methods were used to account for the oil feedstock. One regular regression in which the oil price was taken into account and three adaptations of the experience curve expression in which either relative prices and / or a dummy variable was used. The dummy variable accounted for oil prices which were 18% above average for three years in a row.

Besides deriving experience curves, the curves where also explained by identifying drivers that actually led to the observed developments. Identifying drivers was done based on the available literature. Also the results were compared to other studies regarding the polymer industry. Based on extrapolations of the experience curves a growth potential in demand for bulk polymers in 2020 was identified.

Results

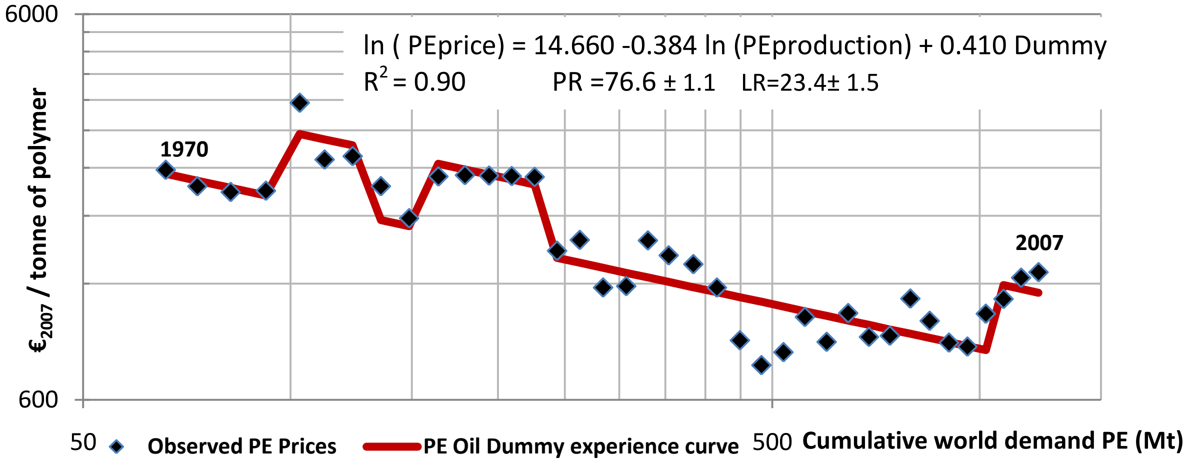
It was found that including a dummy variable, to account for the feedstock, in the experience curve expression provided the best fit with the data. The following table gives an overview of the progress ratios found in this study.

Standard Experience with Oil dummy	Progress ratio (%)	N**	R^2
Polyethylene	76.6 ± 1.5	4.21	**0.90**
Polypropylene	82.3 ± 1.1	6.21	**0.86**
PVC	69.6 ± 1.6	3.61	**0.89**
Polystyrene	63.2 ± 4.6	3.50	**0.65**
Generic Polymer1*	83.4± 1.0	7.40	**0.89**
Generic Polymer2*	82.4± 1.2	7.40	**0.88**

* Generic polymer1 is based on weighing polymer prices on their cumulative production. Generic Polymer 2 is based on weighing polymer prices on the annual polymer production.
** N, Number of cumulative production doublings in the dataset

Over time many drivers have driven down the experience curve. In the early 1970s the first oil crisis let the oil prices spike and with it the polymer prices. This raised awareness to produce polymer more energy efficiently. Already the effect of this awareness is seen when the second oil crisis starts.

During this period the oil price surges even further than with the first crisis, but the polymer prices did not surge more than during the first oil crisis.



In the 1970s most of the polymer production was located in the western world (70%). The share in production gradually shifted to Asian countries like china. For example Asia is expected to produce 50% of the world demand for PVC in 2012, while in 1992 only 27% came from Asia. A large part of the geographical shift can be explained with the increased economic growth in Asia. With increased wealth more plastic can be consumed making it interesting for producers to settle close to their market. The growth potential in Asia is still huge. In 2005 in Asia 20 kg plastics were consumed per capita and it is expected that this will grow to 36 kg per capita in 2015, which is only a quarter of the consumption in western Europe or the us.

Discussion

There is a relative large difference between the progress ratios of PE and PP (76.6% – 82.3%) versus the progress ratio's found for PVC and PS (63.2% – 69.6%). PS and PVC are found to have relatively low progress ratio, displaying a larger price decrease at cumulative production than PE and PP do.

One reason for this can be found in the similar production steps in relation to the production. Ethylene is a basis for PE, PVC and PS. Propylene. a side product when creating ethylene. is used as a basis for PP. As such experience gained in ethylene production will follows to some extent through into all four bulk polymers[1]. On top of that for all four polymers similar polymerization techniques are used. As such the experience gained in the PS sector is not solely represented by experience gained in the polystyrene sector, but also partly to experience from the polyethylene and polypropylene sector. Due to this linkage in experience polymers with a relative low market share show a high degree in learning as they can profit from the experience gained for other polymers.

Because of the possible link in experience a generic polymer was derived based on weighted average polymer prices. The generic polymer represents industry developments for all the polymers together. In contrast to what was expected, the generic polymer shows higher progress ratio (83.4± 1.0%) than the progress ratios for each polymer individually. Further examination revealed that the total cumulative production showed more cumulative doublings than the individual polymer production. In the methodology this means the price decrease gets spread out over more cumulative doublings resulting in a higher progress ratio. This phenomena illustrates the importance for including a complete sector when using experience curves.

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[1] Note that cracking is not the only source of propylene. It is also a byproduct of FCC in refineries.

Ethylene has a very large share in the polymer price. Mid August 2009 prices in Asia for instance show that the ratio ethylene price to polyethylene price is 83%. For ethylene, one of the most important intermediate products for polymers currently very large plants with an annual capacity of 1.4 Mt are (coming) online. Scaling has a serious cost advantage. For ethylene scaling exponents of 0.65 are mentioned in literature. However, with current mega plants, the cost for piping becomes disproportionally high. Also the plants are operating at the limit of pumps and compressors that have proven themselves in practice.

The experience curve method with oil dummy resulted in the best fit for all the polymers except PS. The main reason for the weak fit of polystyrene is most likely the high benzene prices between 2001 and 2005 which was not accounted for. This once more emphasis the importance of correcting for the feedstock prices.

Correcting for the fluctuating feedstock price using insights from the production process did not equal the strong fit of the experience curve model with dummy variable but the results were promising and better than when not correcting for the feedstock at all. Correcting for the feedstock by looking into the production process is a topic that requires more research as the data needed for such a correction is either not readily available or shows a wide range of values. The beauty of correcting for feedstock prices with a dummy variable is that large amounts of exogenous data are not needed to do the analysis. The other methods of correcting for high feedstock prices displayed conceptual weaknesses.

The relative price models overestimated the contribution of the oil price The division by the oil price in those models created a multiplicative relation between the polymer price and the oil price, meaning that when the oil price doubles, according to the model also the polymer price. This is not how it works in practice. The oil price is only responsible for part of the costs. Although the oil-price is responsible for a relative large portion of the polymer cost it is conceptually wrong to allocate all the cost to the oil price. Introducing a dummy variable on top of the relative price only increased the overestimation of the oil price in the model decreasing the model-fit.

Conclusions and recommendations

The experience curve approach is applicable to the chemical sector, provided one takes into account effects that are not related to learning like high feedstock prices. Correcting for high feedstock prices using a dummy variable for periods of above average feedstock cost resulted in a strong model fit for the derived experience curves (R^2 up to 0.90). Based on current growth rates the polymer demand is expected to at least double between 2007 and 2020, which could relate to a general price decrease of around 17% for the bulk polymers.

Although including a dummy variable as correcting method provided good results. Further research is needed that looks into correcting for drivers that are not related to learning. Challenges lie in correcting for multiple drivers which are not related to learning and finding high quality data on process steps to make corrections based on production details.

1 Introduction

Plastics take up a very prominent place in our society. They are used in a very wide range of products and sectors. From a historic perspective this is quite impressive. Compared to the more traditional bulk materials like glass, steel and paper which have been produced for ages, the mass production of plastics only just started. Over the last decades worldwide plastic production has exploded from 1.5 million tonnes in 1950 to 260 Million tonnes in 2007. Already in the late 1980s the volume of plastics produced exceeded that of steel (Figure 1). In Western Europe alone it is estimated that we used approximately 100 kg of plastics per capita in 2005. This figure is even expected to rise to 136 kg per capita in the year 2015 (PlasticsEurope, 2008b).

Worldwide the drivers of growth in the demand for plastics are manifold. Economic growth and the increasing wealth in newly industrialized and in developing countries play an important role. The share of plastics has been increasing at the expense of the other bulk materials. This is partly a result of new needs, which can best be fulfilled by plastics (e.g., safety devices such as airbags, mulch films for agriculture and certain medical devices and implants). Another important driver is material substitution, e.g. the replacement of glass by polymers in consumer goods such as computer screens and inroads made by plastics into the traditional applications of paper/board in packaging and metals (e.g. in consumer goods and buildings). Here, the costs for production and processing of the competing materials play an important role.

The market for plastics is dominated by Polypropylene (PP), Polyvinylchloride (PVC), Polyethylene (PE) and Polystyrene (PS). Together these bulk polymers accounted in 2007 for 84% of the total 210 Mt world demand for thermoplastics[2] (Figure 2; PlasticsEurope, 2008b). Over the last four decades prices of these polymers have dropped significantly. With ongoing price decreases polymers might become competitive in existing markets that currently use more traditional materials or open up new and unexplored markets, which could increase the demand for these polymers tremendously.

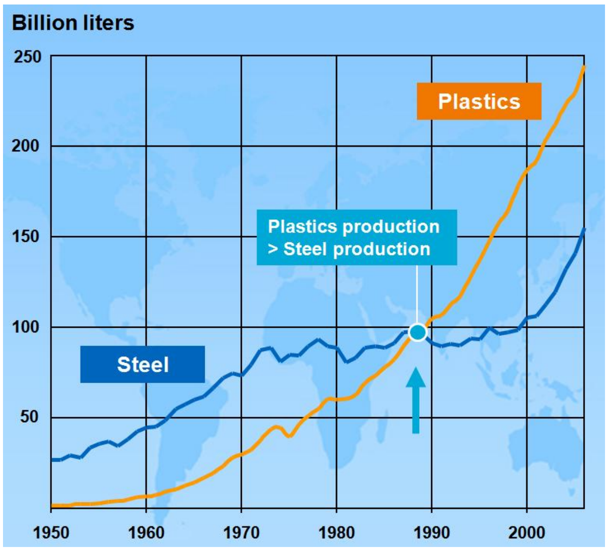

Figure 1 - Historical world production of plastics and steel.

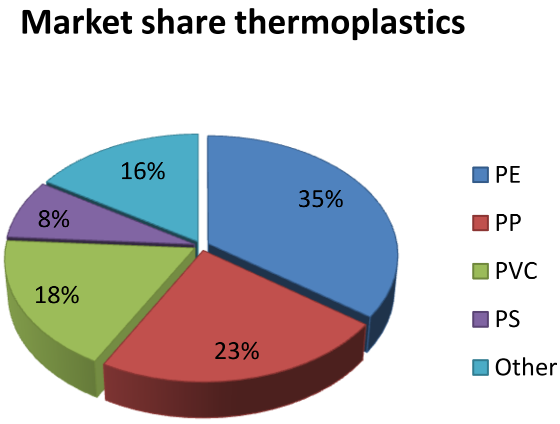

Figure 2 – Market share world thermoplastics in 2007

The experience curve method is a method that enables us to quantify these developments. In the method cumulative production is considered to be an indicator for experience in which more experience relates to lower cost and thus lower prices. A good understanding of these developments

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[2] Thermoplastics accounted in 2007 for around 80% of the total plastics demand. The remaining 20% comprises of adhesives, coatings sealants and others (PlasticsEurope, 2008b).

could be of great value to polymer producers. Experience curve analysis can, for instance, aid producers in strategic management decisions.

The experience curve methodology is especially popular in research concerning the development of (renewable) energy supplying technologies. It is thought that new technologies are developing faster eventually overtaking the conventional technologies (Junginger et al., 2008). The experience curve method can be used to determine such a turning-point.

From this line of reasoning future price developments for the bulk polymers are also valuable for bio-polymer producers. With the recently high oil prices we see the emerging bulk production of bio-based polymers. These polymers are less sensitive to high oil prices due to their renewable feedstock (Patel, 2007). Bio-polymers are a recent development which makes it impossible to use the experience curve method because time series that span decades are needed. These time series do not exist yet. In this research the focus will therefore be on bulk petrochemical polymers. Nevertheless the research will be of interest for bio-polymer producers because it will provide insight at what price their product could become competitive compared to the standard bulk polymers.

The influence of the oil price on the price of petrochemical polymers needs special attention. From the theory regarding experience curves we expect production cost to go down over time due to gained experience. This relation can however been masked when the costs are mainly determined by feedstocks which fluctuate in price over time due to reasons other than gained experience. This is the case for the bulk polymers. The main feedstock for the bulk polymers is ultimately crude oil. Since the price of crude oil is mainly dependent on geopolitical developments and supply and demand relations rather than gained experience the experience curve method has to be adapted to reveal the experience dynamic.

The main objective of this thesis is to identify how the polymer industry developed by deriving experience curves for the four main bulk polymers for the period 1970 until 2007. The experience curves will be explained by identifying the underlying drivers behind the cost reduction. Based on extrapolations of the experience curves it is tried to identify a growth potential in demand for bulk polymers in 2020.

Most of the studies using the experience curve method use regional boundaries. For instance sugar cane ethanol production in Brazil (Wall Bake 2008) and corn ethanol production in the U.S. (Hettinga, 2008). Some research has been done already regarding experience curves in the polymer industry. The Boston consulting group (1968) for instance has researched technological learning for bulk polymer industry in the U.S. And the petrochemical polymer industry in Germany was assessed with experience curves to examine the techno-economic feasibility of bio-based polymers (Crank et al., 2005). However, with current means of communication and transport, knowledge and products are no longer bound to a single region. This study is to the knowledge of the author the first time technological learning is examined for the world polymer industry as a whole.

In chapter 2 an overview of the polymer sector is given and put into context. It is tried to give the reader a feel for this vast sector by providing information on the various uses and applications of the bulk polymers and by providing information about the history and the production process of the bulk polymers. In chapter 3 some general theories will be discussed. More specific the experience curve approach will be introduced and explained here providing to the methodology. In chapter 4 an overview of the data used is given. In chapter 5 the results will be shown. In chapter 6 the results will be discussed and the chapter will contain additional analysis. Finally chapter 7 will contain the general conclusions and findings. Detailed datasets can be found in the various Appendices.

2 Context

2.1 Monomers for bulk polymers

Ethylene is very important for the polymer industry as it is used direct or indirect to produce PE, PVC and PS (Figure 3). Ethylene is created by cracking light hydrocarbons like naphtha in large steam crackers. Propylene is one of the side products in this process. Polyethylene and Polypropylene are created by polymerization of respectively ethylene and propylene. Besides polymerizing ethylene into polyethylene, ethylene is used for producing ethyl-benzene (EB) which is needed to create polystyrene. Furthermore ethylene is also used to produce ethylene-dichloride (EDC). EDC[3] is the main resource for the vinyl-chloride monomer (VCM), which in turn the main component for PVC. Due to the importance of ethylene, in Europe a network of ethylene pipelines exist since the 1970s which is still expanding (Appendix VIII).

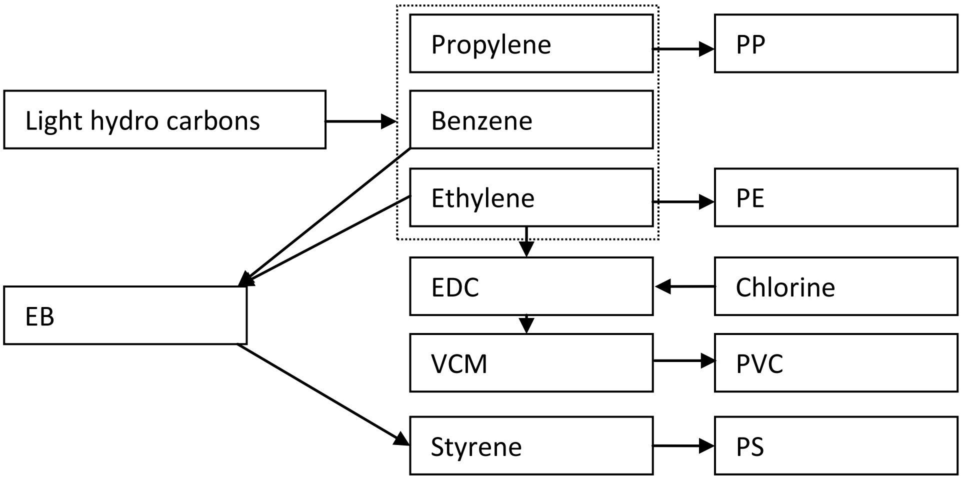

Figure 3 – Simplified overview of the main production routes of bulk polymers

In conventional steam cracking (Figure 4) light hydro carbons like naphtha, LPG and ethane are diluted with steam and heated in a cracking furnace. By quenching the gas from the cracking furnace the reactions are stopped. The resulting products and their ratio depend on the hydro carbon to steam ratio, the time in the cracking furnace, the temperature of the furnace. Heavier hydrocarbons for instance result in a wider spectrum of products and favor products as benzene.

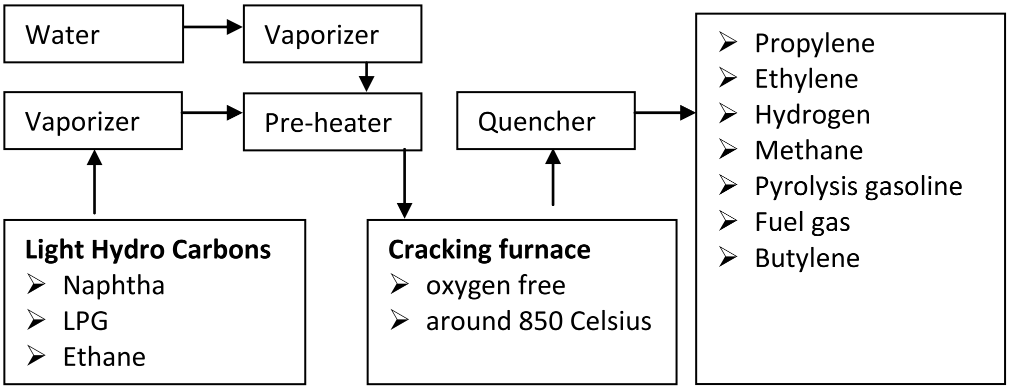

Figure 4 - Conventional steam cracking of light hydro carbons into monomers

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[3] An alternative route to produce VCM is from acetylene. This route is more polluting and energy consuming. Due to the lower capital costs, the simpler technology and the domestic availability of all the raw materials the process to produce VCM from acetylene dominates in China (ICIS, 2009a). In 2007, of the 80 VCM plants in China, 71 produced VCM from acetylene. In China VCM from acetylene production accounted for approximately 6100kt VCM and VCM from ethylene accounted for approximately 2500kt VCM (Nexant, 2007)

In North America and the Middle East mainly ethane and propane are fed into the cracking process. These light hydrocarbons yield in relatively little side products compared to naphtha feedstocks (Table 1). Less side products results in simpler and cheaper plants.

Table 1 - Ultimate yields from steam cracking (Matar et al., 2001)

	Feedstock			
Yield[1], wt %	Ethane[2]	Propane	Butane	Naphtha
H_2+CH_4	13	28	24	26
Ethylene	80	45	37	30
Propylene	2.4	15	18	13
Butadiene	1.4	2	2	4.5
Mixed butenes	1.6	1	6.4	8
C_5+	1.6	9	12.6	18.5

[1] When recycling feedstock to extinction

[2] Figures based on temperature being between 750 and 850 Celsius, pressure 1 -1.2 kg / cm^2 and a steam to hydro carbon ratio of 0.5

Over the last 15 years the growth rate in the demand for propylene has outpaced that of ethylene (Chemsystems, 2007) which stresses the conventional supply of propylene. “In 2002 conventional steam cracking was responsible for 70% of the propylene production” (Bölt and Glanz, 2002). In conventional cracking furnaces the highest propylene to ethylene ratio’s (P/E) achievable is limited to 0.65. At higher ratios the total yield drops to uneconomically levels. The ratio is hard to change as it is mainly feedstock dependent. To overcome this problem currently new on purpose propylene plants are emerging that produce propylene from propane. It is estimated that the on purpose production of propylene will rise from 5% to 30% the coming 5 years (CB&I, 2009a).

In 2006 approximately 40% of the world ethylene producing capacity used Lummus[4,5] global licensed technology (Lummus, 2009). Many existing units using this technology have been expanded in capacity with over 150%. Currently the maximum single line capacity for this technology is 1.4 Mt ethylene per year. Propylene is a side product in this process. Lummus is licensor of a technology (OCT) to create propylene via metathesis of Butenes and Ethylene. This technology can be integrated with FCC units at refineries. Integrating the technology via a revised flow scheme in traditional thermal ethylene plants could reduce the energy consumption up to 14% (Bloch, 2006) and could increase P/E ratio up to 1.1 in such plants (CB&I, 2009a)

2.2 Polymers from ethylene

In general plastics have some distinct properties which make them very attractive to use as a material. With current metallocene catalysts the properties of plastics can often be tailor-made for specific purposes and plastics are very flexible in processing. Together with increasing applications the world polymer sector has shown continuous growth over the over the last 40 years (Figure 5). Between 1970 and 2007 the average growth of the bulk polymers was 6.5% per year. This is higher than the 3.9% average growth in world domestic product in during this period (International Monetary Fund, 2009).

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[4] In China Lummus licensed technology is even responsible for 60% of the ethylene and propylene production.

[5] Since November 2007 CB&I has completed its acquisition of Lummus. Lummus is one of the most important licensors for technology in this industry.

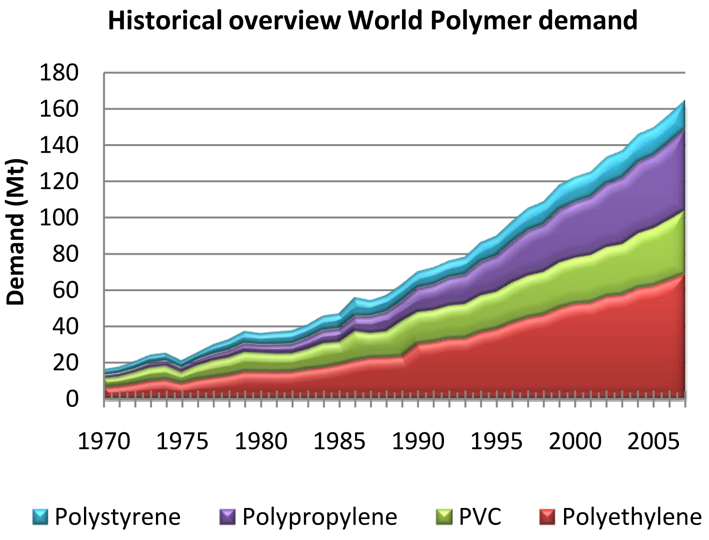

Figure 5 - Historical overview world demand for bulk polymers

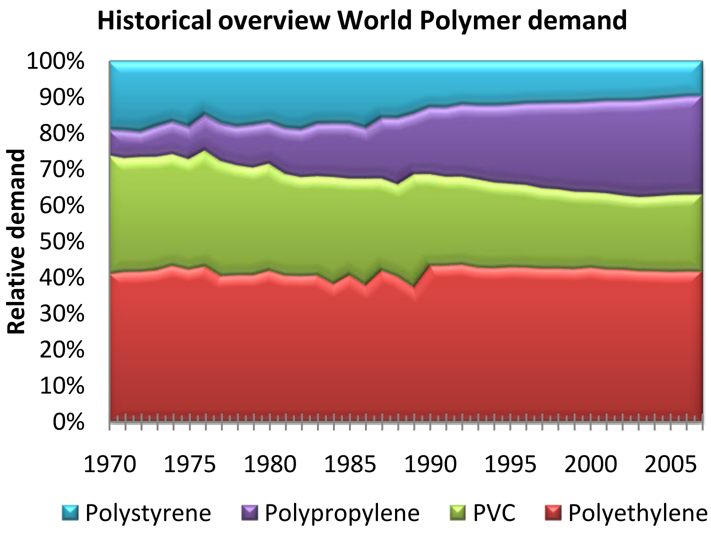

Figure 6 - Historical overview relative world demand for bulk polymer

2.2.1 Polyethylene

Polyethylene is used for a very wide range of applications. The share of polyethylene has been quite stable over the years (Figure 6). Currently it is the most used polymer in the world and available in many grades. Polyethylene with a specific gravity higher than 0.941 gram per cubic centimeter is called high density polyethylene (HDPE). Polyethylene with a specific gravity equal or lower than 0.941 gram per cubic centime is called low density polyethylene (LDPE). From 1970 until 2007 the production of polyethylene showed an average annual growth of 6.5%.

From a historical point of view the bulk polymer industry started with polyethylene in the western world. In 1980 around 70% of polyethylene was produced either in Europe or in North America. This has changed dramatically with increased wealth in Asia. Especially China has invested and is still investing in PE production. In 2000 only half of PE produced came from the western world. Recently we also see a lot of investments in the Middle East for PE production. This geographical shift is quite interesting as the production is increasingly moved closer to the feedstock.

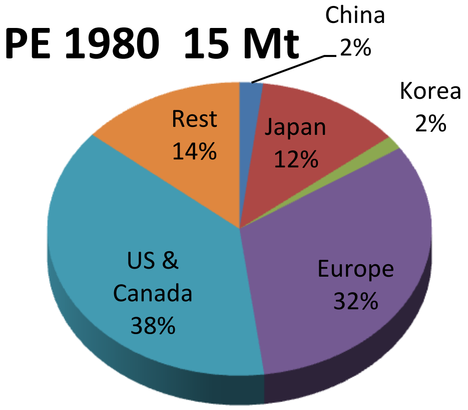

Figure 7 - World share PE Production 1980 (United Nations, 2002)

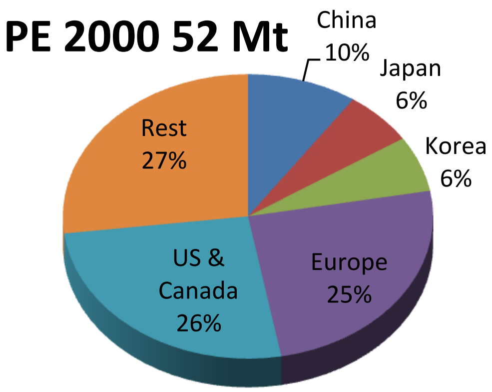

Figure 8 - World share PE Production 2000 (United Nations, 2002)

2.2.1.1 LDPE

Polyethylene was developed by accident in 1933 by Fawcet and Gibson in the research lab of Imperial Chemical Industries[6]. In their research lab they were researching the reaction between benzaldehyde and ethylene under high pressure up to 2000 atmosphere at high temperatures up to 170 degrees centigrade. When opening the reaction tube they found “a waxy solid”. Especially the moulding and electric properties of this waxy solid made the discovery very interesting to pursue. It took 6 years to make this discovery ready for commercial purposes. Mainly because at first they did not noticed the reaction had nothing to do with benzaldehyde but started because there was some oxygen in the reaction tube that initiated the polymerization (reaction 1).

$$N\ (H_2C{=}CH_2) \xrightarrow[\text{High temperature}]{\text{Initiator, Pressure}} -[H_2C{-}CH_2]_N- \qquad \text{reaction 1}$$

In 1939 Imperial Chemical Industries started the first commercial polyethylene plant (VKC, 2007). The process in that plant was very much the same as the initial discovery. Under high pressure, high temperatures and with an initiator ethylene undergoes a free-radical polymerization reaction. The resulting polyethylene had long branches and a density below 0.94 g/cm^3.

LDPE is water resistant with the ability to block fat and all kinds of aroma. It is mainly used in the packaging sector. Examples are litter bags, meat and poultry wrapping, bag in-box wrapping for liquids, stretch and shrink wrap, electrical shielding and so on. LDPE was even used as shielding in the first transatlantic telephone cable between the U.S. and Europe (VKC, 2007). LDPE can be produced either tubular or autoclave. Due to the higher conversion rate of ethylene the tubular reaction is gaining preference (ICIS, 2009c).

2.2.1.2 HDPE

During the 1940s Professor Karl Ziegler at the Max Planck Institute in Germany developed new catalysts based on organo-metallic compounds that significantly lowered the pressure needed for polymerization. Finally in 1953 Professor Ziegler discovered that especially titanium based catalysts are very effective catalysts for polymerizing ethylene at atmospheric pressure. Consequently the yield of polyethylene produced with such Ziegler catalysts increased, the density was higher, the melting point was higher and due to less branching also the tensile strength of the polymer increased. This new type of ethylene is now called High Density Polyethylene (HDPE). In 1955 Hoechst took the first HDPE plant in use. In these early days the first large volume application came from the popularity of the hoola hoop.

HDPE has a good chemical resistance and mainly used as a packaging material for both household and industrial products. In Europe HDPE it is mainly injection moulded in to crates, fuel tanks, milk canes etc.

2.2.1.3 LLDPE

From the 1950s to the late 1960s DuPont, Union Carbide and The DowChemical Company worked separately on developing copolymers of ethylene with alpha-olefins. The resulting copolymer had densities similar to LDPE, but the new polymer was far more linear (Figure 9) and had very short branches compared to LDPE. As a result a new polymer was called Linear Low Density Polyethylene (LLDP)[7].

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[6] In 2008 Akzo Nobel acquired Imperial Chemical Industries.

[7] In the 1980s experiments with incorporating higher amounts of alpha-olefins resulting in ultra-low-density polyethylene (ULDPE) and very-low-density polyethylene (VLDPE). All are created using Ziegler / Natta catalysts.

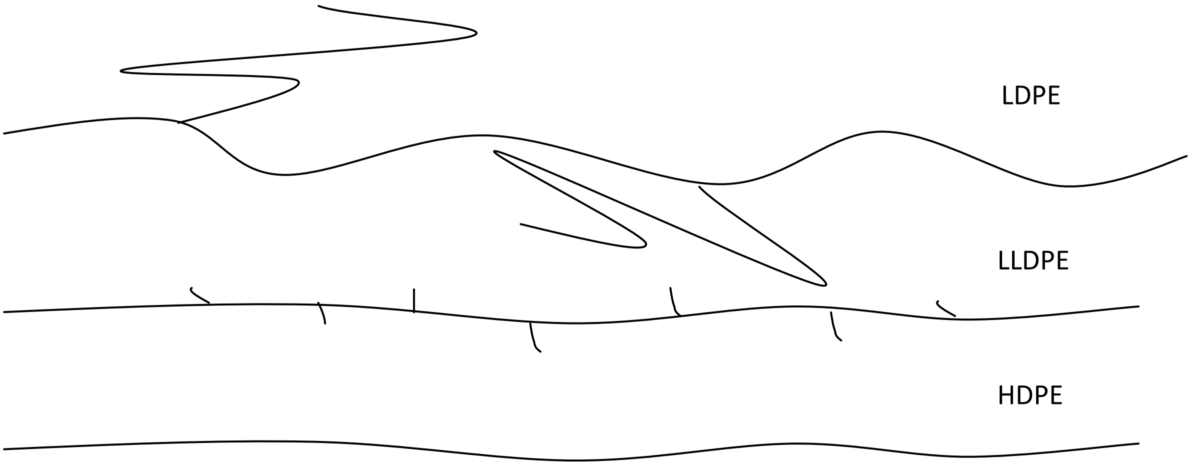

Figure 9 - PE Branching

LLDP is created by copolymerizing ethylene monomers with alkyl-branched co-monomers. The shorter chain branches than regular LDPE give it a better puncture resistance than LDPE. This is especially attractive for wrapping films. LLDPE is less clear then LDPE. Often LLDPE and LDPE are mixed to the get the right balance between clarity and puncture resistance. As LLDPE and HDPE can both be produced via a Ziegler-Natta catalyst some facilities are able to swing[8] production from LLDPE to HDPE and back depending on the demand for a specific type of PE.

2.2.2 PVC

In 2007 around two third of the 35.3 Mt PVC demand was accounted for by the construction industry. Among other things PVC in the construction industry is used for pipes, plumbing, profiles, wires, cables and tubes. As the construction sector is strongly related to the economy, PVC demand is also strongly related to the economy. From 1970 until 2007 the demand for PVC has grown 5.3% per year on average. Also for PVC a geographic shift has taken place towards Asia. In 1992 27% of the PVC production came from Asia. Based on planned expansion of capacity it is expected in 2012 about half of the world PVC production will come from Asia. The growth in Asia can for a large part be explained by the increase in PVC demand in China. Per capita the PVC consumption in 2001 in China was 4 kg per capita, in 2006 8 kg per capita and it is expected to rise to 11 kg per capita in 2011. PVC demand has remained stable in Western Europe between 14 and 16 kg per capita and around 20 kg per capita for the US. Based on US and European figures we can expect PVC consumption to increase even more (Esckilsen, 2008).

PVC is produced by polymerizing the Vinyl-Chloride-monomer (VCM). The VCM can be polymerized to PVC with a suspension or an emulsion process. The different processes yield in different size and characteristics of the PVC grains. In 2002 80% of the PVC produced in the world used the suspension process. As with the other polymers the polymerization happens in a reactor. In the 1970s typically in the reactor the VCM is inserted, de-mineralized water, a suspending agent and an initiator. The reactor is than sealed. The reactor is kept at 57 degrees Celsius and a pressure of 5 kg per cubic centimeter. After 8 hours 85% to 90% of the mass in the reactor is converted to PVC after which it is flushed down to a tank from where it goes to a centrifuge and a dryer (Saeki 2002).

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[8] SCLAIRTECH is a licensed PE swing process by NOVA chemicals. In 1999 NOVA chemicals and ABB Lummus Global made an agreement making Lummus the exclusive engineering company for the SCLAIRTECH technology (Fairley, 1999).

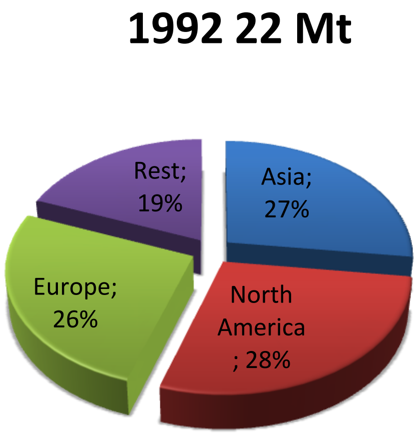


Figure 10 - World Production capacity PVC 1992

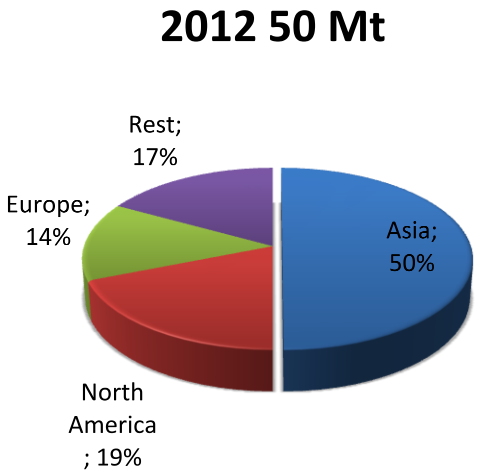
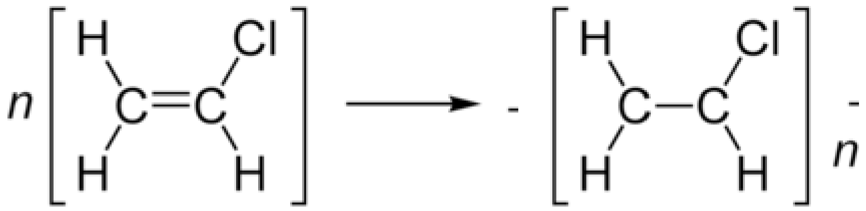


Figure 11 - Estimated World Production capacity PVC 2012



The reactor builds up a heat blocking inner skin during the process, which is called scale. This scale needs to be removed. This was done manually in the 1960s, but due to health reasons this scale soon was flushed out with water. Currently, Important licensors for PVC production are the Chisso[9] corporation and INEOS[10]. Their technology together is currently used for 25% of the PVC produced with the suspension process worldwide. Current process require a shorter residence time in the reactor (6 hours instead of 8) and also the reactor sizes have significantly increased from 20 m^3 in the 1960s to 170m^3 currently (Saeki, 2002).

2.2.3 Polystyrene

Currently polystyrene is used in many applications including food packaging, domestic appliances, electronic goods, toys, household goods and furniture. Since 1985 the relative demand for Polystyrene (PS) has been declining (Figure 6). Polystyrene has competition from PVC, glass, wood, paper and mostly from polypropylene (ICIS 2009b). Recently Poly(Acrylonitrile, Butadiene, Styrene) or ABS for short has also come into the picture as a competitor. Currently there is a 30% overproduction of polystyrene in Europe (ICIS). From 1970 until 2007 the demand for PS has grown 4.5% per year on average.

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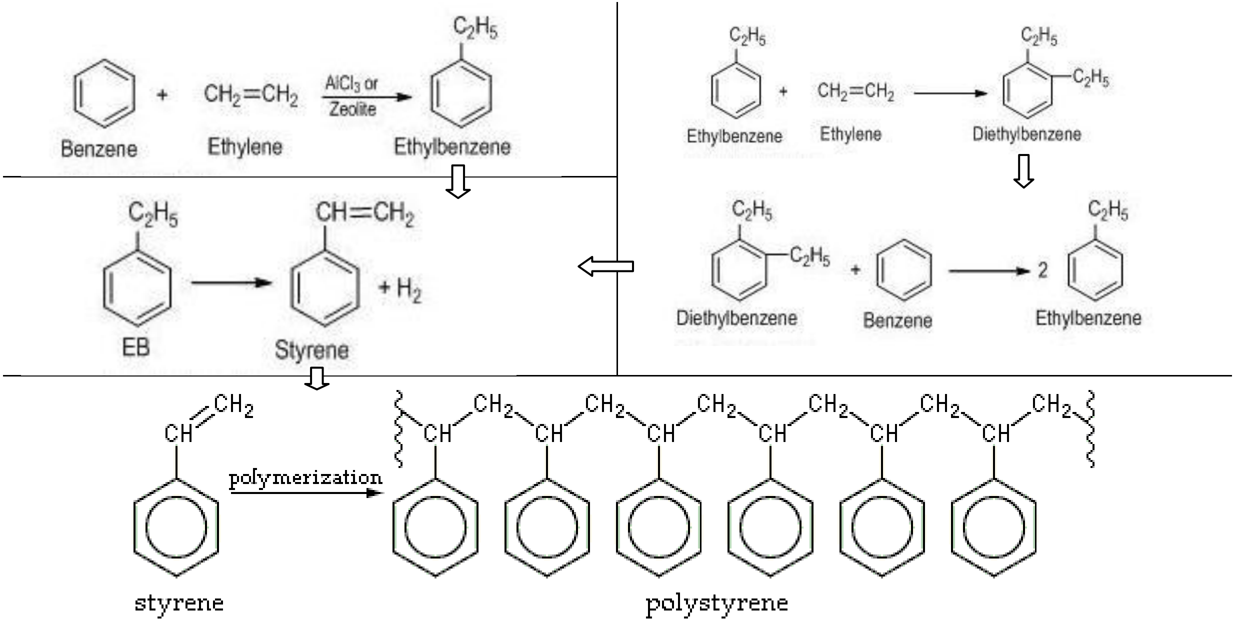
[9] The Chisso PVC process has a total installed capacity in the world of 1.5 Mt per year and a single line capacity of 125 kt per year (Chisso, 2009)

[10] The EVIPOL process by INEOS has a total installed capacity in the world of 1.5 Mt per year (INEOS, 2009)

Figure 12 - Commercial routes to polystyrene



2.3 Polypropylene

Professor Giulio-Natta extended on the work of Karl Ziegler and found several linear non-branched polymers. Among these polymers was crystalline polypropylene. PP was first produced commercially on an industrial scale in 1957. Polypropylene has a high stiffness, good tensile strength and has a good inertness towards, acids, alkalis and solvents. Polypropylene is gaining both in absolute terms as in relative terms over the other bulk polymers. From 1970 until 2007 the demand for PP has grown 4.5% per year on average.

Traditionally polypropylene has a cost advantage. Fewer steps are needed than for PS or PVC. Propylene is further more a side product in the process of ethylene production. Due to the high increase in demand more on purpose solutions for PP production are arising. These on purpose solutions are more expensive than the integrated method. For most practices, due to its properties, PP can replace PS, PVC, HDPE, ABS and some other polymers (ICIS, 2009d). Currently Basell is the most important PP producer with a 24% market share worldwide (Figure 13).

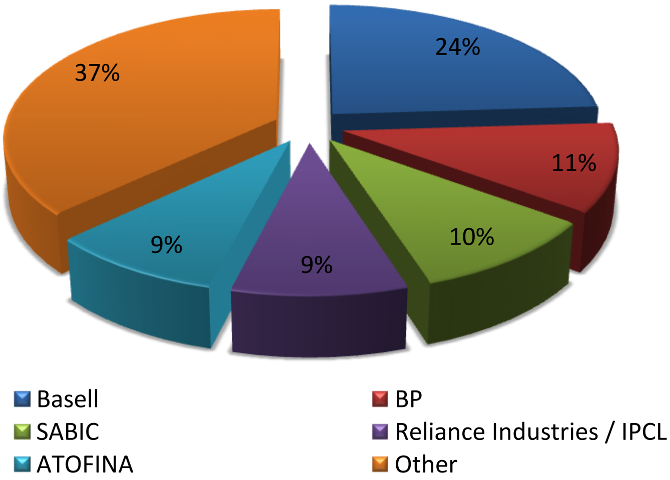


Figure 13 - World PP producers

2.4 Licensors

Much research is done concerning the production of polymers. An internet search for patents with the term “polyethylene production” reveals over 200.000 patents ranging from products and processes to catalysts for over the last 20 years in the U.S.A. alone. The company holding the patent often licenses’ the technology. Appendix XII gives an overview of the dominant licensed processes and their licensor. Both the production capacity of a single production line and the share of the technology in the world capacity are shown in the table.

3 Methodology

In this chapter some general theories regarding technological learning are discussed. The methods used to analyze the polymer sector will be explained. Eventually this leads to a set of regression models based on the experience curve method, which will be used to describe the polymer sector.

3.1 Mechanisms for cost reduction

“Operating in competitive markets makes individuals, enterprises and industries do better” (International Energy Agency, 2000). This doing better is what makes it that products get cheaper over time. To do better than the competition one has to take risks and try new things. In other words: innovate. *“Innovation is the embodiment, combination, or synthesis of knowledge in original, relevant, valued new products, processes, or services” (*Luecke & Katz, 2003). In essence innovation is creating added value by combining knowledge and resources into a new or better product within a market.

Consumers play an important role in the innovation process of polymers. To corner the market producers continuously are seeking technological innovations to meet the demand for different, new and better products. Consumers could for instance request a polymer with a higher tensile strength; better puncture resistance, less stickiness during molding, a lower price or a different melting temperature to meet their specific needs. With this information the polymer producers learn from their consumers what tomorrow’s market is. This is called **learning-by-using** in literature (Rosenberg, 1982).

Before such new product products find their way into the market usually a lot of research has to be done to search for adequate solutions that make such innovations possible. A new catalyst that allows for specific product properties might need a revised process (temperature and pressure) for instance. Bottlenecks in the process need to be removed to increase production and lower production cost. In literature this searching for solutions is called **learning by searching** *(Junginger, 2005)* and often comes with great R&D expenditures[11].

During production often new insights are gained that can benefit the production. An example is the transport optimizing of ethylene and propylene in Europe with pipelines (Appendix VIII). In literature improvements due to repetitive production are recognized as **learning-by-doing** (Arrow, 1962).
In the world industry for polymers knowledge is worth a lot. Yearly thousands of patents are registered concerning new production processes, new catalysts, and new polymers. Patented technology is often licensed to make a profit. Together with branch meetings, congresses and research by universities new technologies and knowledge diffuses over the industry. This type of learning is called **learning-by-interacting** (*Lundvall, 1992)*.

Some authors (Abell and Hammond, 1979) also recognize upscaling as a fifth mechanism for cost reductions. Bigger plants can drastically decrease the specific cost of a unit, but upscaling of a plant comes with considerable RD&D expenditures (Junginger 2005). “Also, in most cases both upscaling and mass production of a technology or production process requires many steps. During each step, experience is gained by learning-by-doing and learning-by-using, which is then incorporated in the next generation of the technology” (Junginger 2005). Upscaling is therefore considered to be covered by the four mentioned learning mechanisms.

Besides price decreases due to technological learning there are also other influences on the price, like the availability of resources, the price level of raw materials and intermediates, changing labor

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[11] To get an indication of total R&D expenditures: in 2004 Dow Chemical net Sales resulted in 40 billion US Dollars (Dow Chemical Company, 2008), in that same year over 1 billion US Dollars was put into R&D activities (Dow Chemical Company, 2004).

costs and economic conditions. Lysen et al. (2006; adapted from Ayres et al. ,2003) describe this dynamic between technological learning and the physical world within a cycle of increasing productivity. The system they describe is responsible for its own increasing productivity. Central are the declining cost when demand goes up due to price elasticity. With increasing demand more investments will be done to bring down the cost even further. The resulting lower prices will increase demand even further effectively starting the cycle over and over again. In the cycle increased competition is an incentive for lower prices. The increased demand is an incentive for increased production. The cycle of increasing productivity can off course not go on indefinitely towards lower prices. The system has some physical limits. In terms of energy efficiency there are thermodynamic limits. Limiting factors on the cycle are the availability of resources, labor, technological innovation and the size of the market. The four learning mechanisms can also be recognized in the cycle as price lowering mechanism.

In practice it is difficult to allocate cost reduction to a specific learning mechanism. Often the quantitative effect of a learning mechanism is not known or cannot be allocated due to some overlap in the learning mechanisms. In the end the combination of the different learning mechanisms together are responsible for the cost reductions. A concept measuring this aggregated effect of the learning mechanisms is the experience curve approach.

3.2 Experience Curve method

The dynamic behind the experience curve approach was first recognized by the Theodore Wright in 1936. Wright reported (Junginger 2005) that the time and thus the cost it took to create a single airplane frame by a worker decreased significantly when the worker had built more frames. Wright noted that the time it took to build a frame decreased with a fixed percentage with every doubling in cumulative frames produced by the worker. The resulting line is called a learning curve (Figure 14). One could say the experience of a worker can be represented by his cumulative production. At first the worker does not have any routine or skills. When he builds routine his performance goes up. After a while the worker has optimized his working routine to such an extent it will be very hard to do even better, hence the continued slowing in the decrease of production time. Learning curves are often presented on a log-log scale because the learning curve will result in a straight line on such a scale (Figure 15). Such straight lines can be used for linear regression.

The Boston consulting Group expanded on this concept (BCG 1968). First the overall production cost of a product was included instead of production time. The production cost now represents all learning effects in the complete process. Second the concept was applied on complete industries instead of single tasks. Even with the expansion of the concept the fixed decrease in price when cumulative production doubles was still found. The resulting straight line when plotting production cost and cumulative production on a log-log scale for an industry or sector is called an experience curve.

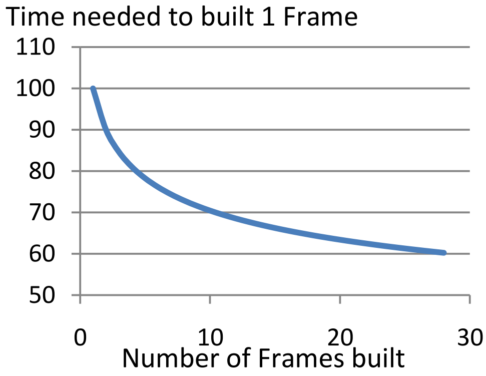

Figure 14 - Production time versus cumulative production

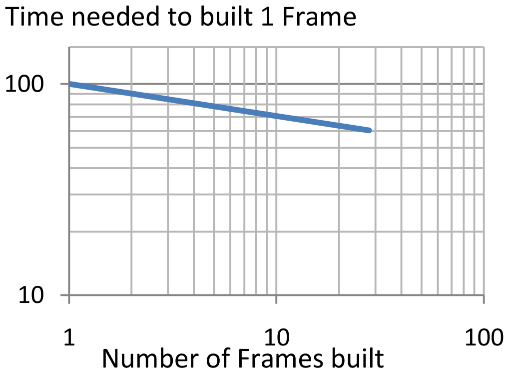

Figure 15 - Production time versus cumulative production

Experience curves can be described mathematically using a power function (1). The cumulative production (Cumpro) represents the experience gained until that point in time. The impact of experience on the original production cost (Cost_o) is represented by the learning index b. Combined this leads to the production cost (Cost_t). The linear form is represented by equation (2).

Typically the learning index has a value between -1 and 0. A learning index of -0.25 means that when the cumulative production doubles the production cost would drop to 0.84 (3) of its original value. This 0.84 is called the progress ratio (PR) and is usually presented as a percentage. A progress ratio of 84% equals a cost reduction of 16% when the cumulative production doubles. This 16% is called the learning rate (4). The observant reader would see a discrepancy in equation (1) in the units. Due to the mathematical nature of the experience curves the unit of the cumulative production (tonne) cancels out. As such the cumulative production is inserted as the number of units of cumulative production which has no unit. See Appendix IX for a detailed overview.

$$\text{Cost}_t = \text{Cost}_o * \text{Cumpro}_t^{\,b} \qquad \textbf{\textit{(1)}}$$

$$\ln(\text{Cost}_t) = \ln(\text{Cost}_0) + b*\ln(\text{Cumpro}_t) \qquad \textbf{\textit{(2)}}$$

$$\text{Progress ratio} = 2^b \qquad \textbf{\textit{(3)}}$$

$$\text{Learning rate} = 1 - \text{Progress ratio} \qquad \textbf{\textit{(4)}}$$

Cost_o : Cost of the first unit produced (€/t) at time=0
Cumpro_t : Cumulative units of production (number of units produced) at year t
b : Learning index
Cost_t : Cost per unit (€/t) in year t

As shown in equation (1) production data and cost data are needed. Information on production cost is usually secret. Commercial organizations do not want to reveal information about their margins to their competitors. For this reason prices will be used as a proxy for production costs. This implicitly assumes a stable relation between price and cost. This assumption is valid in competitive and mature markets (Figure 16). The Boston consulting Group identified four stages in the production cost to price relation development of a new product.

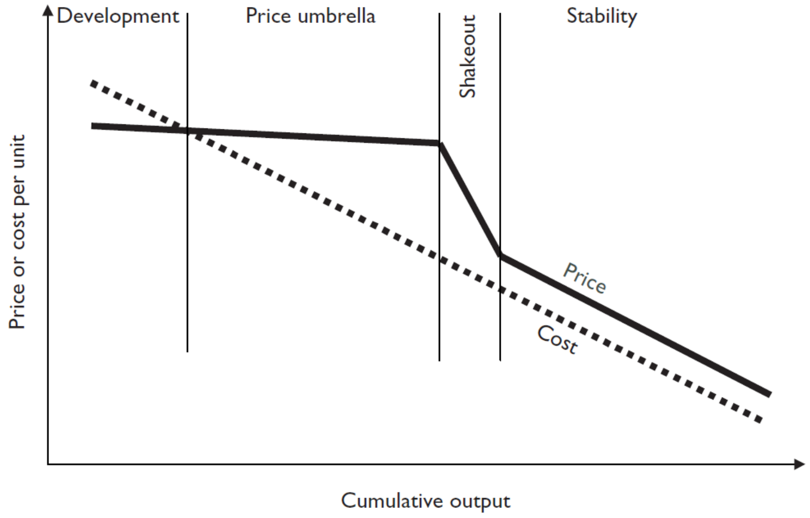

Figure 16 - Price-cost relations for a new product (BCG, 1968)

At first there is a developmental stage were the new product is still under development. At a certain point due to learning the production costs go down and more companies join in on the same product to get a piece of the profit. At this time prices are relative high. With more and more companies, the competition gets fierce leading to competition on price. Not everyone is able to meet the low prices. This leads to a shake out of companies. Eventually a stable competitive situation emerges in which the cost and price relation can be considered stable. This does however not exclude future shakeouts. Even today producers of polymers get “shaken out”, usually because they get acquired by or incorporated into another organization (For example the acquisition of Lummus by CB&I or the merger of Lyondell and Basel into Lyondell Basell). Grübler et al. (1999) describe similar stages in technological development but introduce three extra stages in the development phase (Invention, innovation and niche market commercialization).

3.3 Supply and demand

From economics we know that for certain goods a certain relation between supply and price exists called price elasticity. The lower the price of a product the more people are willing to buy the product. With an increase in demand at lower prices we can recognize the cycle of increased productivity and the drive for decreasing costs by producers. Depending on the price of a product there will be an optimum point in the price-demand relation in which profits will be maximized. When due to gained experience the cost of a product will drop, a new optimum will arise at a higher demand.

Due to scarcity demand can become higher than the supply. The market “feels” this imbalance and prices will go up to a point where demand will equal supply. This shift usually has a delay due to inertia of the market. An example to illustrate this inertia is the usage of a car. When the gasoline prices spike, people will not stop driving their car. Only after a longer period of high prices people will deviate of their current practices and alternative means of transportation will be considered. Resources like oil, ethylene, and energy are traded daily on spot markets resulting in fluctuating spot prices. To increase price stability producers can negotiate a long term contract with suppliers at a fixed price. Still increased oil prices follow trough fairly fast into the polymer prices. Correlation analysis shows that the correlation between the oil price and the polymer prices are highest when the polymer price is shifted 1 month in front compared to the oil price.

The other way around is overproduction. In this case supply will be bigger than demand. To bring the market back into equilibrium prices have to drop. With lower prices the stock will finally sell. Sometimes this can even be below cost price.

3.4 Importance of the oil price

The goal of this research is to quantify technological learning. The four bulk polymers are petrochemical products. Naphtha, which is created from crude oil, is a major feedstock for the bulk polymers. Oil-price increases like those of 1973, 1979 and the gradual increase from 2000 onwards can be observed in the polymer market as well (Figure 17). Correlation analysis shows a strong correlation up to 81% between the polymers and oil price between 1978 and 2008[12].

Such feedstock price rises can be a trigger for more resource efficient process in the long term. But the short term price follow-up has nothing to do with technological learning.

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[12] Correlations found between the Oil price and polymer price were 61% for PS, 78% for PE, 81% for PP and 67% for PVC.

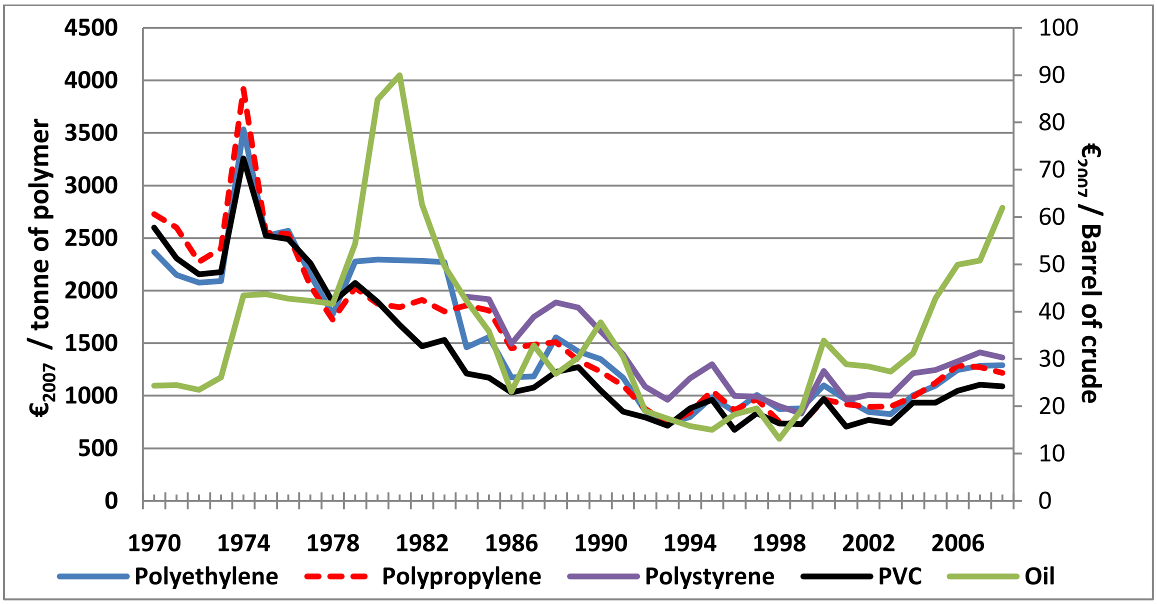


Figure 17 - Historical world average polymer and crude prices

Research has shown that “the timing of oil price increases and recession is consistent with the notion that oil price shocks may contribute to recessions” (Barsky & Kilian, 2004). During such periods of recession the demand for polymers has gone down in history. This stresses the market. It is likely less money will be available for investments in such periods, effectively lowering some learning effects.

Both due to the importance of the feedstock and the stress effect of recessions it is important to separately account for the oil price.

3.5 Regression

To analyze developments in the polymer industry linear regression will be used. First the industry data will be modeled with a regular linear regression (explained in paragraph 3.5.1) and second the linear forms of the experience curve approach will be used (explained in paragraph 3.5.2). For the regular experience curve method several methods to correct for the feedstock price will be introduced.

3.5.1 Standard regression model

To model industry developments from the price and cost data multiple linear regression is used. In multiple linear regression it is tried to relate a dependent variable (Y) to independent variables (X_1 to X_n) in a linear expression. The contribution of the independent variables is represented by scalars (B_1 to B_n). Deviations from the ideal representation are represented in an error term (u).

$$Y = B_0 + B_1X_1 + B_2X_2 + B_{..}X_{...} + B_nX_n + u \quad (5)$$

To determine how good the data fits the expression the correlation coefficient R is determined, which represents the goodness of fit. Because R in general overestimates the goodness of fit the R-square will be used for the models with a single independent variable. The R-square can vary between zero and one. A value of one represents a perfect fit meaning that the independent variables perfectly relate to the dependent variable. An R-square of zero means there is no apparent relation between the dependent and independent variable. The independent variable cannot explain the dependent variable.

For models with more than one independent variable the adjusted R-square will be used as a second control. The more variables used in linear regression the more explanatory variables there will be to account for the variation in the data. This leads to an overestimation of the fit of such a models. The adjusted R-square is not biased for the variance in the independent variables and allows for a higher degree of freedom resulting in a more accurate goodness of fit test for such models.

The basic idea behind the experience curve theory is that the cumulative production represents the total experience in a sector. When the cumulative production rises, experience is gained, which makes it possible to improve production and therefore lower prices. Using this information in a regular linear regression we would expect that the cumulative production lowers the polymer price. Such an idea can be represented in the following form:

$$\text{Price}_t = \text{Price}_0 - b\ \text{Cumpro}_t + c\ \text{Oil Price}_t + u_t \qquad (6)$$

Here the oil price would represent the costs related to the feedstock and Price_0 would represent all other costs which are lowered when experience is gained (Cumpro_t rises). Although the model (6) incorporates the basic idea of the experience curve approach it does not follow the expected power function dynamic. However, out of academic interest the model is included in this study. When valid it will also be possible to expand the model with other terms making it possible to isolate specific contributions to price decreases.

3.5.2 Experience Curve Models

To capture the learning dynamic four experience curve models are tested.

3.5.2.1 *Standard model*

To capture the learning effects the linear form of the standard experience curve model is used (equation 2 and 7).

$$\ln(\text{Price}_t) = \ln(\text{Price}_0) + b*\ln(\text{Cumpro}_t) + u_t \qquad (7)$$

3.5.2.2 *Standard Model with Oil Dummy*

Due to high correlations between the oil price and the polymer price the polymer price is most likely not representative for the learning effects in the polymer industry. To account for the oil price a Dummy is introduced to capture the effect of the oil price.

$$\ln(\text{Price}_t) = \ln(\text{Price}_0) + b*\ln(\text{Cumpro}_t) + c*\text{Dummy}_t + u_t \qquad (8)$$

Non-linear regression was thought of but that would imply good insight into the exact dynamics between all the variables is known. Also the interpretation of the results would be less straightforward.

3.5.2.3 *Relative Price Model*

Another method to capture the effect of the oil price is by using relative polymer prices in which the effect of the oil price is divided out (8).

$$\ln(\text{Price}_t/\text{Oilprice}_t) = \ln(\text{Price}_0/\text{Oilprice}_0) + b*\ln(\text{Cumpro}_t) + u_t \qquad (9)$$

3.5.2.4 *Relative Price Model with Oil Dummy*

Besides -relative prices Crank et al. (2004) also a dummy to account for economic conditions.

$$\ln(\text{Price}_t/\text{Oilprice}_t) = \ln(\text{Price}_0/\text{Oilprice}_0) + b*\ln(\text{Cumpro}_t) + c*\text{Dummy}_t + u_t \qquad (10)$$

To determine the impact of the increased experience on the prices of polymers linear regression is used to determine the learning index b. The linear form of the experience curve formula will be used for this.

3.5.3 Oil Dummy variable

Crank et al. (2005) use the dummy variable to account for bad economic conditions like the oil crisis. In that study the dummy was 1 for the period 1974 – 1985 and 0 otherwise. In this study the dummy variable will be 1 when the oil price is above 18% of the average deflated oil price for at least 3 years in a row. If these criteria are not met the dummy variable will be zero.

The restriction was chosen in such a way that the dummy highlights the first and second oil crisis and it highlights the recently high oil prices from 2005 till 2008 (Appendix V), which are all periods of recession .

Transforming equation (8) back to a power function (9) reveals how the dummy interacts with the data. In periods where the dummy is zero the data will be multiplied with one (e^{0}) not effecting the data at all. At periods where the oil price is very high the dummy will be one, increasing the price estimate with a factor e^{B}.

$$\text{Price}_t = \text{Price}_0 * \text{Cumpro}_t^{\,b} * e^{\text{DummyB}} \qquad (9)$$

3.6 Extrapolation

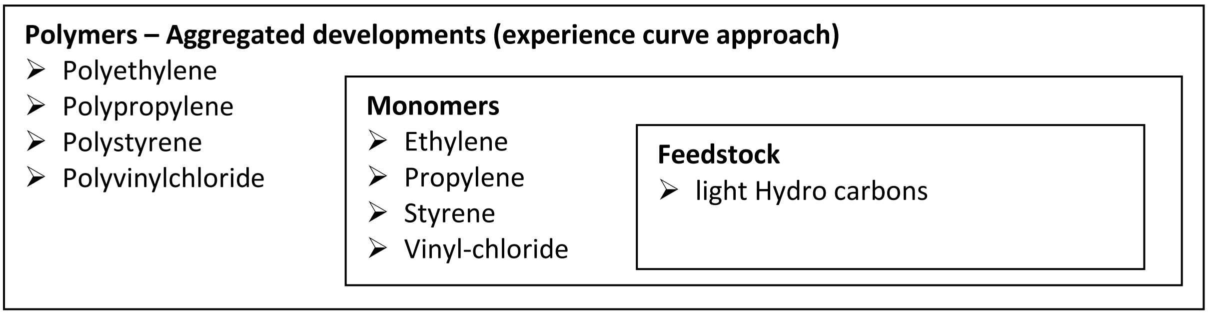
Extrapolating the experience curve gives an idea of future prices and corresponding demand. Extrapolating from a regression model has some pitfalls that need to be recognized. Extrapolating the linear regression model implicitly assumes that the linear model is also valid beyond the data series. Based on the experience curve theory and previous research (Junginger 2005) and more specifically for polymers (Crank et al., 2005) we can assume the relation between price and production is indeed linear on a log-log scale beyond the current data points until physical barriers are met.

Furthermore the regression analysis gives an expression that fits best to the data, but this does not mean this is ultimately the correct expression. In fact a confidence band exists where a whole range of expressions could be valid. A sensitivity analysis will be done to give an indication of the uncertainty. Besides the R-square also the error of the progress ratio will be used to show how good the fit of the model is, which is recommended to create a reliable forecast range (Van Sark, 2008). Multiple scenarios will be created using the standard error in the progress ration.

3.7 Applied methodology

The polymer industry can be analyzed at three stages of production (Figure 18). First, the production of the feedstocks. Second, the production of the monomers from the feedstock. And third, the production of the polymers from the monomers. The experience curve approach is used to gain insight in developments in the aggregated overall effect in all three processes that determine the developments in the polymer cost. It is tried to link specific developments in all three levels to the experience curve and if possible to quantify the contribution of these developments. Expected developments on all three stages are used to determine if the experience curve extrapolations are realistic.

Figure 18 - Polymer learning system



Polymers – Aggregated developments (experience curve approach)

- Polyethylene
- Polypropylene
- Polystyrene
- Polyvinylchloride

Monomers

- Ethylene
- Propylene
- Styrene
- Vinyl-chloride

Feedstock

- light Hydro carbons

3.8 Previous Studies

This study is not the first to develop learning curves for the polymer industry. Table 2 gives an overview of the literature found on experience curves for plastics and the progress ratios found. All authors have chosen a different implementation of the experience curve approach. Clair (1983) chose to use the value added per tonne as a dependent variable and Crank et al. (2005) used the relative price model with oil dummy to account for the direct effect of the fluctuating price of oil which distorts the experience curve. Based on the progress ratios in the overview we little regional differences in learning concerning PVC and PE. Unfortunately the analysis of Crank et al. (2005) did not include polystyrene for comparison. The progress ratio for PP shows a rather large difference of (9% point) between the USA and German region indicating a higher learning rate for the USA region.

Table 2 - Overview of literature on experience curves for plastics

Source	Product / Activity	PR in %	R^2	Data quality[1]	Geographical system boundary	Independent variable	Dependent variable	Period studied
Sallenave (1985)	Polyester	87	0.97	-[2]	One polyester manufacturer in North America	Polyester production	Polyester price	1973-1983
Sallenave (1985)	Polyester	88	0.83	-[2]	One polyester manufacturer in North America	Polyester production	Production costs for polyester	1973-1983
Clair (1983)	LDPE	64[4]	-	I	Western Europe	Cumulative world production	Value added per t produced	-
Clair (1983)	LDPE	64[5]	-	I	USA	Cumulative world production	Value added per t produced	-
Clair (1983)	HDPE	68[5]	-	I	USA	Cumulative production	Value added	-
Clair (1983)	Ethylene/LDPE integrated	65[6]	-	I	Western Europe	Cumulative world production	Value added per t produced	-
Crank et al. (2005)	PE	71	0.92	II	Germany	Cumulative German production	PE price divided by oil price	1969-2002
Clair (1983)	PS	80[5]	-	I	USA	Cumulative production	Value added	-
Clair (1983)	PP	73[2]	-	I	USA	Cumulative production	Value added	-
Crank et al. (2005)	PP	81	0.98	II	Germany	Cumulative German production	PE price divided by oil price	1969-2002
Clair (1983)	PVC	66	-	I	USA	Cumulative production	Value added	-
Crank et al. (2005)	PVC	64	0.86	II	Germany	Cumulative German	Relative PVC price per t oil	1969-2002

production

[1] Legend for symbols indicating data quality: I - cost/price data provided by producers, II - cost/price data collected from various sources, III - cost/price data (or progress ratios) not based on empirical data.

[2] No information given.

[3] Data refer to the actual polyester production in the first year of the analysis.

[4] Based on cumulative worldwide production and value added data for Western Europe.

[5] Based on cumulative worldwide production and value added data for the USA.

[6] Referring to the cumulative worldwide production of LDPE and integrated value added data for ethylene and LDPE in Western Europe.

[7] Data refer to the cumulative production since the base year of the analysis.

[9] The base year is the first year in which both price and production data is available (typically the first year of the period studied).

4 Data

This chapter gives an overview of the data that is used and its origin.

4.1 Polymer demand

In experience curve analyses it is most important to have long time series in which cumulative production has doubled at least a few times. Only then is it possible to get a good insight in the experience gained. In this research the time series consist of data ranging van 1970 to 2007. This limitation is due to the fact polymer demand data before 1970 was not available to us. Polymer demand data for 2008 was not yet available at the time of writing this thesis.

World polymer demand figures for the period 1970 - 1989 are based on production figures reported by the United Nations (2002). Because world data is used production is considered to be equal to demand. The United Nations (UN) do not report data when the data might impact the competitive position of a company. For this reason no data is reported on a country when there are less than three producers. This exclusion has a serious impact on data completeness from 1989 onwards in the UN dataset. For this reason the UN data was only used for figures from 1970 to 1989. World polymer demand figures for the period 1990 – 2007 are industry data. An overview of all the demand figures is given in (Appendix I). Table 3 gives an overview is given of the production data sources used.

Table 3 - Overview polymer production data

Production[1] Data	Source
1990 – 2007[2]	various industry sources
1970 – 2000[3]	United Nations (2002)[5]
1950 – 1970[4]	Extrapolated

[1] As the data is on a world scale, production is assumed to be equal to demand

[2] World totals annual demand for PE, PP, PVC and PS

[3] Production per country for PE, PP, PVC and PS

[4] Based on average annual growth rates 1970 - 1980

[5] The database included data on 62 countries (among others including EU27 countries, Japan, China, U.S. Canada, Korea, Russia and Brazil) Because of gabs Data is partly interpolated using linear regression. Data for 1970 – 1990 is 65% complete.

4.2 Polymer Prices

Multiple organizations keep track of daily polymer prices. Prices provided by ICIS and Plastics Information Europe are generally accepted in the industry to be the most reliable. PieWeb provided time series for polymer prices for the period 1984 – 2009 for Western Europe. Prices from before 1984 are German data from a previous study (Crank et al., 2005) or in the case of polystyrene derived from trade statistics.

ICIS has a database with world polymer prices for the period 1996 -2009. Due to budget reasons their database could unfortunately not be used for information on prices per world region.

Some price data, especially from before the 1980s is not directly available. Foreign trade statistics are used to fill in these gaps. In trade statistics in- and exports of commodities are reported both in quantity as in monetary value. Dividing the two values yields the price per unit of product. It should be noted that this includes transportation until the border.

Price[1] Data	Source
1984 – 2009	Plastics Information Europe (2009) [2]
1970 – 2003	Crank et al. (2005) [3]
1996 - 2009	ICIS[4]
1988 - 2007	CBS (2009)[5]
1988 - 2007	DESTATIS (2009)
1996 - 2006	UNComtrade (2009)[6]

[1] Price is used as a proxy for costs

[2] Nominal Price data for LDPE, HDPE, LLDPE, PVC and PS for large consumers in Western Europe

[3] Deflated price (€$_{2003}$) data for PE, PP and PVC

[4] Not used as a source due to budget reasons. Would however be a great source to gain insight in the dynamic between price relations between world regions (Asia, North America, South America, Europe, Middle East and Africa)

[5] Monthly trade statistics from 1966 – 2007 yield nominal prices in fl/ tonne and from 2001 € / tonne. Data before 1988 is too aggregated, as one figure is mentioned for all plastics (including non-thermoplastics). From 1988 onwards PE, PP, PVC and PS can be distinguished.

[6] Nominal prices in US Dollar / tonne on import and export between the U.S. and the world. Used to gain insight in the dynamics between Europe and the U.S. Region

4.2.1 Trade statistics

Over the years the nomenclature used to report foreign trade statistics changed significantly. One organization that tries to harmonize and simplify foreign trade statistics to a global standard is the World Customs Organization (WCO). Founded in 1952 as the Customs Co-operation Council they are responsible for the Harmonized System (HS) in which commodities can be reported. In 1999 already 98% of the world trade statistics were reported using this system directly or indirectly (UNSTATS, 2000). Major goods classifications like SITC, CPC and ISIC are correlated to the HS. The European Union adopted the HS indirectly by implementing the SITC classification for all their member states as of 1978. Some countries like the Netherlands already implemented the SITC classification in the late 1950s.

These classifications and their level of detail change over time due to new goods or growing markets. The SITC classification, revision 4, uses five levels of increasing detail. Appendix IV gives an example under what heading polyethylene can be found. In the Dutch foreign trade statistics reported by the Central Bureau of Statistics (CBS) from before 1988 polymers are reported in a aggregated level up to a level 2 detail, as the SITC nomenclature had only 2 levels at that time. This level of detail aggregates information of all plastics in primary forms, not just those of the main bulk polymers.

Only from 1988 onwards when revision 3 was implemented three levels of detail were used. This makes it possible to distinguish between specific polymers like polyethylene and polypropylene. A more detailed nomenclature comes with SITC revision 4 which is not yet implemented. SITC Revision 4 was introduced in 2006.

For now, level 4 details are not mandatory to report. However, the German statistical office DESTATIS provided trade statistics for Germany up to level 4 detail for the period 1988 to present. The level of detail in the data from DESTATIS for the period 1952 to 1987 varies between level 2 and level 3.

To get an indication of the international dynamics in polymer prices the United Nations (2009) database was accessed. The UNComtrade database has foreign trade statistics from the US on polymers from 1978 till present up to a level 3 detail (Appendix VIII).

4.3 Deflating – Consumer Price index

In this study all prices are given in 2007 Euros. Most of the source data had to be converted to Euro 2007 by deflating the data using various consumer price indices. Equation (10) shows how price data from year x is deflated to 2007 prices.

$$Euro_{2007} = \frac{Euro_x}{Index_x} Index_{2007} \quad (10)$$

Various price indexes are used throughout this research. For deflating the polymer prices the Harmonized Index Consumer Prices for the chemical industry is used (Eurostat 2009).

4.4 Exchange rates

Some data like oil prices were available in a different currency. Historic exchange rates from Plastics Information Europe (2009) and the European Central Bank were used to convert the foreign currencies to 2007 Euros.

5 Results

In this chapter the model results are presented. The model with the best fit is used to plot experience curves which are put into context by presenting de drivers that where identified.

5.1 Model results

In Table 4 the results are shown for each model and for each polymer. The standard experience model with oil dummy gives the best fit for all the polymers with the exception of polystyrene. Due to the good fit the standard experience model with oil dummy is used for future extrapolations and graphs in this study. Why the standard experience model with oil dummy performs best will be discussed in (paragraph 6.1).

Table 4 - Model Results

Model		**Coefficients**						**Learning specifics**		**Fit**
		Constant	Std.	**b**	Std.	**c**	Std.	PR%[a]	N[b]	R-Square
Standard regression	PE	1610.92	193.43	-1.225E-6	0.0	12.621	3.975	x	4.21	0.62
	PP	1509.387	236.796	-2.201E-6	0.0	11.418	5.288	x	6.21	0.42
	PVC	1940.504	199.136	-2.33E-6	0.0	7.577	3.866	X	3.61	0.63
	PS	982.180	93.157	-1.886E-6	0.0	18.992	2.594	X	3.50	0.76
Standard Experience	PE	15.372	0.875	-0.414	0.045	X	x	75.1± 2.3	4.21	0.71
	PP	12.681	0.496	-0.297	0.027	X	X	81.4± 1.5	6.21	0.77
	PVC	17.742	0.882	-0.550	0.046	X	X	68.3± 2.2	3.61	0.80
	PS	15.624	2.186	-0.442	0.114	X	X	73.6± 5.8	3.50	0.41
Standard Experience with Oil dummy	PE	14.660	0.531	-0.384	0.027	0.410	0.051	76.6± 1.5	4.21	**0.90**
	PP	12.314	0.398	-0.281	0.022	0.291	0.061	82.3± 1.1	6.21	**0.86**
	PVC	17.118	0.666	-0.523	0.034	0.304	0.055	69.6± 1.6	3.61	**0.89**
	PS	19.783	2.048	-0.661	0.107	0.451	0.119	63.2± 4.6	3.50	**0.65**
Relative Price	PE	9.315	1.084	-0.305	0.049	x	X	80.9± 2.7	4.21	0.42
	PP	7.543	0.810	-0.205	0.044	X	x	86.7± 2.6	6.21	0.37
	PVC	11.257	1.539	-0.394	0.080	x	X	76.1± 4.2	3.61	0.39
	PS	14.482	2.661	-0.554	0.139	x	x	68.1±6.6	3.50	0.40
Relative price with oil dummy	PE	9.856	0.968	-0.305	0.049	-0.312	0.92	80.9±2.7	4.21	0.56
	PP	8.085	0.688	-0.228	0.037	-0.429	0.105	85.4±2.2	6.21	0.58
	PVC	12.112	1.339	-0.432	0.069	-0.417	0.112	74.1±3.5	3.61	0.55
	PS	10.935	2.892	-0.366	0.151	-0.385	0.169	77.6±8.1	3.50	0.49

X Not relevant

a Uncertainty intervals indicate the regression error only, representing the 95% confidence band of progress ratios

b Number of cumulative doublings in cumulative production from 1970 - 2007

5.2 Experience curves

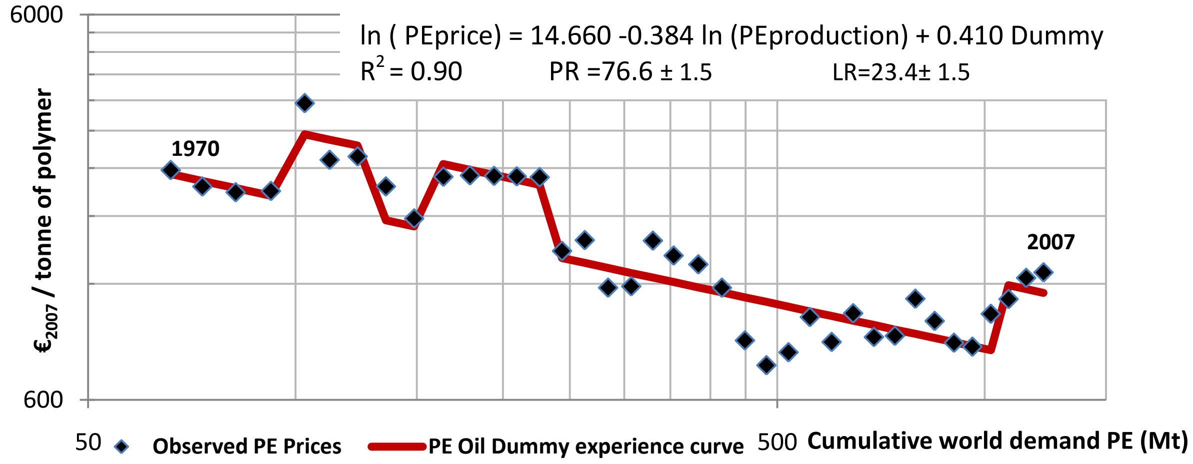


Figure 19 - Learning Curve PE

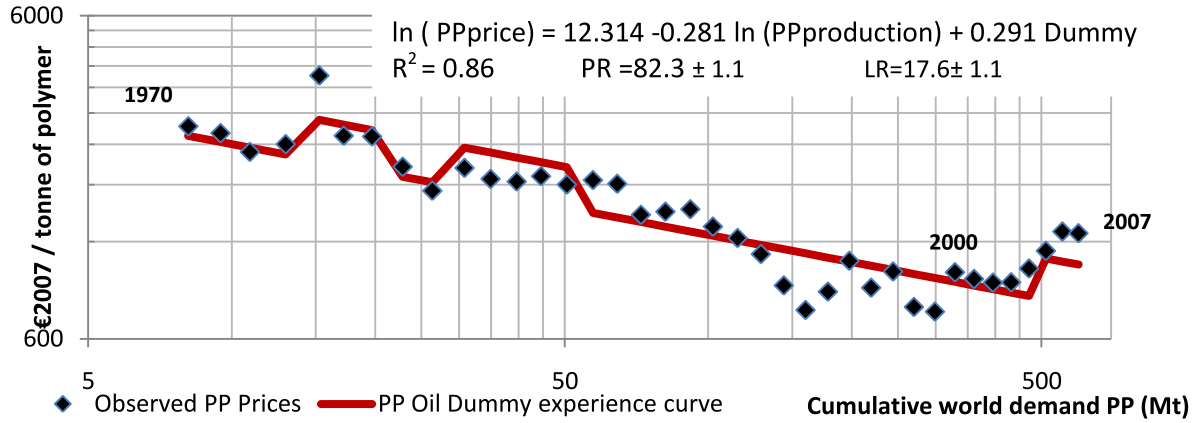


Figure 20 - Experience Curve PP

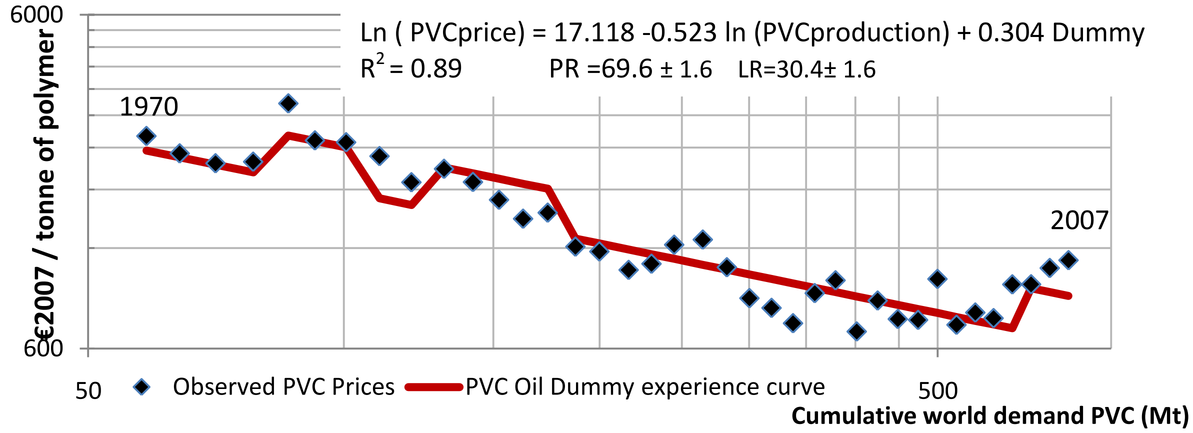


Figure 21 - Experience curve PVC

5.3 Cost breakdown

Ethylene cost is the mayor part off the polyethylene cost. As ethylene costs are mostly energy related the price of PE is mainly energy related. For example in mid august 2009 the ratio in ethylene to high density polyethylene price was 0.83 (ICIS 2009d). In Figure 22 an indicative cost built up for HDPE production in Germany in 1986 is given to explore the costs in more detail. In this example 70% of the production cost exists of raw material cost, which is mainly ethylene. For ethylene the cost are split up in the stacked bar, showing the relative high share of naphtha in the price at that point in time. Since 1986 the production capacity of new plants has increased. The example plant has capacity of 100 kt HD PE per year. New plants due in 2013 in Iran and Saudi Arabia (Total Petrochemicals, 2009) will have capacities between 200 kt and 300 kt annual (Townsend Solutions, 2009). Costs like O&M and plant depreciation cost are most likely lower for these plants due to scaling advantages.

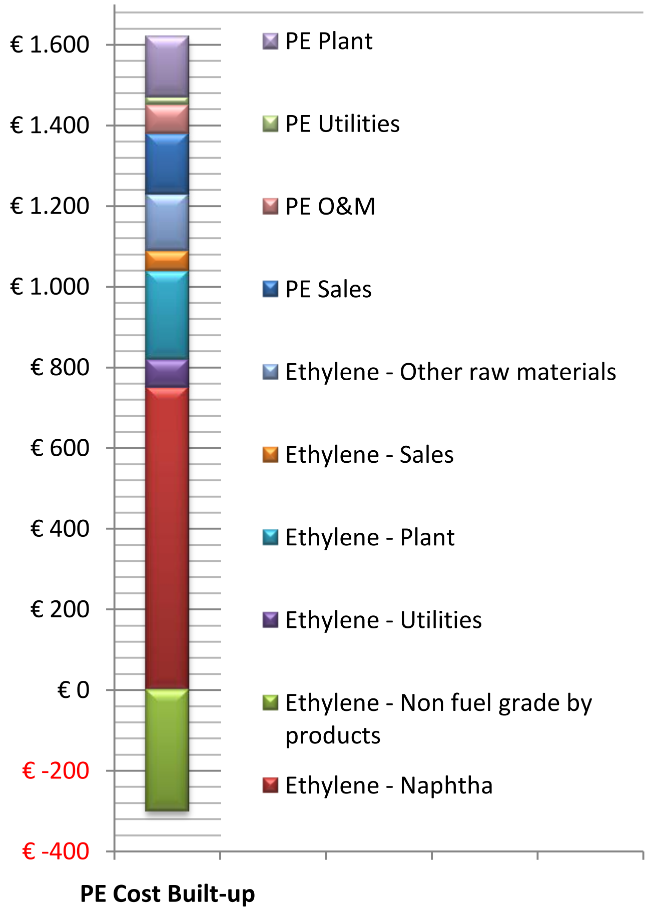


Figure 22 – Indicative Cost built-up of polyethylene for a typical 1986 German HDPE plant

5.4 Explaining the curves – drivers for learning

5.4.1 Scaling

5.4.1.1 Polyethylene

With ethylene to polyethylene price ratios of up to 0.83, ethylene related cost are shown to be the main price determinant for polyethylene. Ethylene production has scaled to enormous proportions. In 1953 in the whole of the USA 1.8 Mt of ethylene was produced (Boston Consulting Group, 1968). Currently such quantities can be produced almost exclusively by a single plant in one year. During the 1950s an average ethylene plant produced 70kt ethylene per year on average. This gradually increased over time to 200kt for large facilities in the 1960s. During the 1990s large ethylene plants reached annual maximum capacities of 1 Mt ethylene (Meyers, 2004).

A random sample on 48 planned projects in 1994 showed that on average a new plant in 1994 had a capacity of 400kt. The smallest plants planned had a 125 kt capacity. The biggest plant planned had a capacity of 0.9Mt (Chemical Week, 1994). A typical ethylene unit currently processes 500kt to 1.1Mt ethylene a year. The largest single-unit ethylene plant built within the last ten years in North America is the joint venture between Nova and Dow (Joffre, Alberta, Canada), with an annual capacity of 1,3 Mt built at a reported cost of $$_{USD}$750 million"(SRI Consulting, 2009). Figure 23 gives an overview of the increased plant capacities over time.

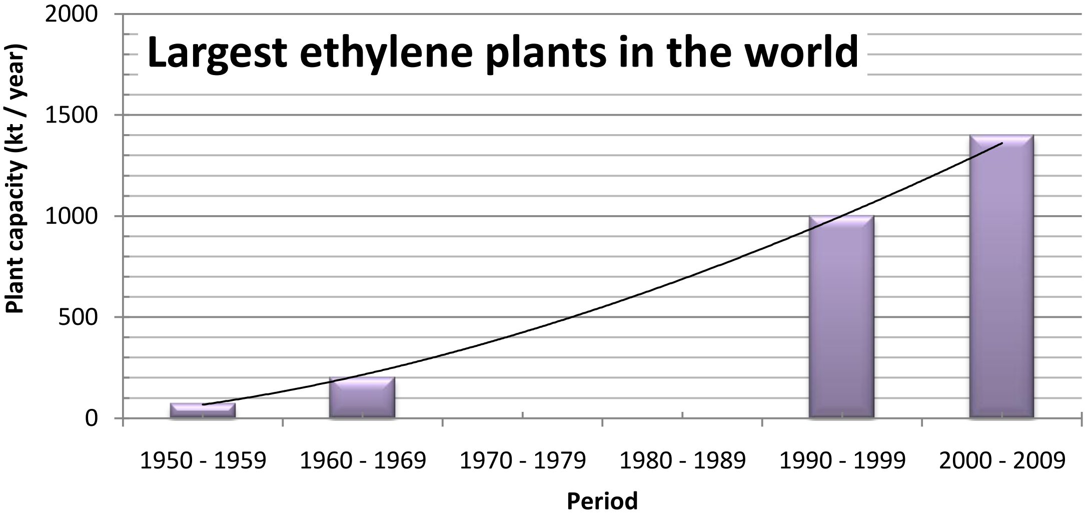


Figure 23- Ethylene plant capacity

Upscaling of ethylene plants has a considerable cost advantage. Meyers (2005, p644) reports a scaling factor of 0.65 for ethylene plants. This implies that when the capacity of an ethylene plant doubles the turn-key price for the ethylene plant only goes up with 57%. This effectively means a cost reduction of 21.5% in the capital cost for ethylene. Based on Figure 22, this relates to a price decrease of up to 3% for polyethylene.

Due to the cost advantage there is a strong tendency for bigger and bigger plants. Future plants are expected to have even higher capacities to reduce specific-costs. However there are some design issues for mega plants. In ethylene plants heat-pump compressors are used with casings that that do not exceed sizes that have already been proven in services. Also the cost for piping, valves and fittings becomes disproportionally high. And extra safety requirements are needed for the large hydrogen facilities need (Meyers 2005). Today's ethylene plants have cracking furnaces up to 230 kt/ a capacity. Up to 8 furnaces can be used in current references designs, making the limit for current technology 1.8 Mt ethylene annually in a plant.

5.4.1.2 Polypropylene

Currently Basell's Spheripol process is the dominant way for creating polypropylene. The process exists now for 27 years and has been upscaled over time. Articles from 2002 report plant sizes of 160 kt / a. Currently, new plants can produce around 500 kt/a (ICIS 2009d).

Even though the plants have been scaled up in a relative short time PP shows the least learning. This could be explained by the increasingly high demand for PP resembled by the high number of cumulative doublings. The high demand has led to more on purpose solutions to fabricate propylene from propane, which are more expensive than the traditional production from a naphtha feedstock.

This switch towards a more expensive process is illustrated in Figure 20 in which all data points from 2000 onwards lie above the experience curve.

5.4.1.3 PVC

The experience curve for PVC (Figure 21) shows a progress ratio of 69.6% which means the price of a tonne of PVC went down 30.4% at each cumulative doubling of world PVC production. This is in line with the regional results of Clair (1983) and Crank et al. (2005). A lot has changed since 1970. The reactors where the actual process takes place has been scaled up from 20 m^3 in the 1960s to 170 m^3 currently (Vinnolit, 2009). The manual reactor cleaning has been replaced by an automated flushing system which reduces the time the reactor is not in use.

5.4.2 Energy and material efficiency

During the 1970s there was a strong incentive due to the oil crisis to produce reduces costs. On average the specific energy requirement for ethylene dropped 40% to 50% on average between the 1970s and the 1980s. More specific the thermal efficiency of cracker heating increased from 82% to approximately 92% (Meyers, 2004 p6.5).

In 2004 energy cost accounted for approximately 70% of the processing cost for ethylene produced in typical naphtha- or ethane based plants (Ren et al., 2006). Almost all the energy used in the production process comes from the fuel grade by-products. It is estimated that the energy cost for ethylene production can go down 20% by using state of the art naphtha cracking (Ren et al., 2006). Due to the linkages of ethylene with the bulk polymers these reductions will follow through in all the bulk polymers.

5.4.3 Environmental and health concerns

Although PVC has shown tremendous growth in the past, in the future PVC might be phased out due to various health issues. PVC that warms up during a fire smolders releasing toxic fumes of hydrochloric acid and burning PVC releases carcinogenic dioxins. Rare lever diseases and some forms of cancer have been linked to a relative large portion of workers in PVC plants. Additives like plasticizers used in toys can be harmful to the human reproductive system when leaching out of the PVC product. And stabilizers used in PVC production can contain heavy metals like lead (Ackerman & Massey, 2003)

Several initiatives have already been taken to phase PVC out. Germany has even banned the disposal of all plastics in landfills in 2005. Sweden has been enforcing restrictions on PVC since 1999. Soft PVC toys have been banned in Europe since 1999. Singapore has declared electrical shielding of PVC cables chemical waste, making it impossible to import electrical wires with PVC shielding. Japan passed a law enforcing all manufactures to recycle all packaging material in 2000. All manufactures quickly adopted non-PVC packaging (Ackerman & Massey, 2003) because PVC needs to be sorted[13] out from the other bulk polymers before recycling, which is expensive.

There are also several market initiatives reducing the use of PVC. Several car manufactures[14] have been eliminating PVC from the car interior or have been removing PVC from the car completely. There are also many examples from supermarkets and hospital initiatives (Ackerman & Massey, 2003).

For the polystyrene market a similar risk applies. A potential danger for PS market is the suspected neurotoxicity and carcinogenic properties of styrene (EPA, 2009), which is especially relevant because PS is used in food packaging. Some initiatives have been emerging to reduce the use of PS.

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[13] PVC needs to be sorted out because it needs a different recycle process because of the large portion of additives and chlorine in it.

[14] General-Motors, Daimler-Benz, Opel, Peugot and BMW have banned PVC from their car interior.

Today more than 30 cities and counties in California U.S have restrictions on styrene and polystyrene products (Turner, 2009). The suspected toxicity might reduce future demand for PS.

Environmental issues can however also have a positive effect polymer demand. For instance, in an effort to meet new European regulation (European Parlement, 2008), which limits the average emissions of new cars in the EU to 130 gram CO_2 per kilometer, it is expected that polymer demand will grow in the automotive industry to make cars lighter and thus more efficient while still meeting ever increasing safety standards. Already the automotive industry accounts for 8% of the plastics demand in Europe (PlasticsEurope, 2008a). In 2007 SMART already started providing their cars with polypropylene body panels reducing the overall weight of the car with 15% (Smart, 2009).

5.4.4 Decoking

The cracking of light hydrocarbons into ethylene takes place in a tubular cracking furnace. This reactor should withstand the high temperatures of 750 to 900 degrees centigrade, the high stress-strain relationship and carburization. To satisfy these conditions metal alloys are used in the furnace. Such alloys tend to promote coke formation on the inner surface of the tube which is not desirable. The coke layer for instance influences the heat transfer but also lowers the fluid pressure in the cracker lowering the plant’s capacity (Hájeková 2008).

To remove coke layers production is stopped once in a while. The coke is removed by burning it off in a pyrolysis run (Albright et al., 1990). Since the 1960 the time between decoking runs has increased. Currently the leading licensor Lummus has pushed decoking cycles over 50 days by decreasing the residence time in the furnace from a few seconds in the 1960s to 100ms today (CB&I, 2009b). The reduction of the number of pyrolysis runs has led to an increase in efficiency, which in turn lowers cost.

5.4.5 Feedstock influences

Correcting for the oil feedstock by using a dummy variable very much improved the fit of the models. However, the learning curve for polystyrene still shows a weak fit. This is an indication other effects that are not related to technological learning are present in the data.

One of the effects revealed is the feedstock price Benzene. Between 2001 and 2005 benzene, one of the feedstocks for styrene, almost six folded in price from €135 /tonne to €1000 / tonne (ICIS, 2009b). As already shown for the oil price, such high price fluctuations in the feedstock need to be accounted for to accurately determine learning effects.

Since 1984 the relative market share of polystyrene is declining. Also polystyrene has been overproduced in Western Europe since 1985 (ICIS, 2009b). The high feedstock prices for Benzene made matters even worse for polystyrene. Other polymers like PP can often replace PS and thus gained market share over PS

New developments in the PS market revolve around new production routes to styrene. Using methanol and toluene (ExSyM process by Exelus) as a basis it is expected styrene can be produced cheaper than with the regular route with ethylene and benzene (Chemsystems, 2009).

6 Discussion

In chapter five the experience curves were presented together some insight in the drivers responsible for the curse of the curve. In this chapter the results are discussed in a broader context. Possible improvements on the methodology and topics for future research will be put forward. Also the experience curves will be extrapolated to provide a 2020 forecast.

6.1 Model performance

The idea behind correcting for the oil price is that the oil price is a significant price determinant for polymers while it does not represent any learning effect because the oil-price is mainly determined by geopolitical conditions rather than technological innovations.

Except for polystyrene[15], correcting for the oil feedstock price by using a dummy variable significantly increased the fit of the experience curves (R-square increased 9% to 18% point). The other methods of correcting for the oil price performed less convincing. The standard regression model and the relative price models were found to have some conceptual weaknesses.

It seems the relative price models were overestimating the effect of the oil price. The division by the oil price in those models created a multiplicative relation between the polymer price and the oil price, meaning that when the oil price doubles, according to the model also the polymer price doubles (see box). This is not how it works in practice. The oil price is only responsible for part of the costs. Although the oil-price is responsible for a relative large portion of the polymer cost it is conceptually wrong to allocate all the cost to the oil price. Introducing a dummy variable on top of the relative price only increased the overestimation of the oil price in the model decreasing the model-fit.

Box – multiplicative relation

Equation (9) shows the relative price model, which can be rewritten as equation (11). Equation (11) reveals a multiplicative relation in which the polymer price doubles when the oil price doubles.

$$\ln(\mathrm{Price}_t/\mathrm{Oilprice}_t) = \ln(\mathrm{Price}_0/\mathrm{Oilprice}_0) + b*\ln(\mathrm{Cumpro}_t) \qquad (9)$$

$$\mathrm{Price}_t = \mathrm{Price}_0 * \mathrm{Cumpro}_t^{\ b} * \mathrm{Oilprice}_1/\mathrm{Oilprice}_0 \qquad (11)$$

The standard regression model does not capture the learning dynamic in which the price drops a fixed percentage with every doubling in cumulative production. Interesting is the fact that this model in contrast to the experience curve models gives a modest fit ($R^2 = 0.76$) for polystyrene. Due to the relative decrease in demand since 1985 and the structural overproduction, prices most likely do not represent the effect of increased experience but rather that of a stressed sector. Furthermore the used series is rather short due to the lack of data. For this type of analysis longer time series with more cumulative doublings are preferred in order to capture to learning dynamic to its full extent. Like the man working on the airplane frame, most experience is gained early. Early price data in line with the available price data is lacking. In paragraph 6.4.3. it is explored if extending the time series with early data from the Boston Consulting Group (1968) improves the model fit.

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[15] PS is the only exception, with equation (7) having a better fit than equation (8) (by 11 percentage points). It should, however, be noted that the times series for PS are shorter than for the other polymers and that the R^2 values are lower for PS. This could be due to the absence of data from before 1984 or the hard market conditions for PS from 1985 onwards

6.2 Data

6.2.1 Price data

The price data used in the analysis is for Western Europe (Plastics Information Europe, 2009). To get an indication of how representative this data is for the world a comparison was made with US prices. High quality price series for different world regions are available at ICIS or Chemsystems which use data from Chemical Market Associates. Unfortunately the price for the data was well above the budget for this research. For the comparison prices were derived from data (Appendix XII) available in the UNComtrade database (United Nations, 2009).

In Figure 24 the price developments of PE prices in US and in the EU, as used in this study, are plotted for the period 1996 – 2006. In the figure one can see the dynamics in the US and in the EU differ. The correlation is modest with .64. The dynamics between the US and European price data differ and the US price was most of the time higher than European prices. On average PE was 12% more expensive in the US than in Western Europe.

The difference between the data used in this study and the trade statistics can to some extent be explained by intrinsic difference in the data reported. Trade statistics can include some special or high performance polypropylene variants. These special polymers are more expensive than the regular bulk polyethylene. Furthermore the dataset in this research is representative for large consumers. Trade-statistics will also include smaller consumers. Furthermore, trade-statistics will also include transportation cost until the border of the receiving country which can vary over time. A comparison with high quality data will most likely result in smaller differences and a higher degree of correlation. Comparing regional trade statistics among each other already shows the same dynamic between all world regions (Chang 2008), which strengthens the idea that there are intrinsic differences between data derived from trade statistics and those resources which are in industry generally accepted as of high quality. For PE the regional price differences diminished since 1997 with the exception of the US prices which are in general higher than in the rest of the world (Chang, 2008).

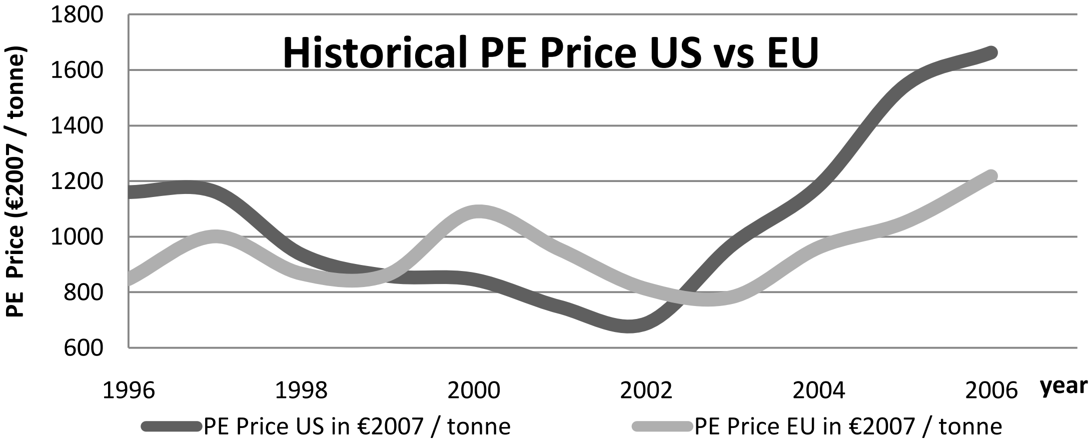


Figure 24 - Historical PE Trade Prices US and EU spot prices

6.2.1.1 *Exchange rates*

The price data from Plastics Information Europe was daily data. Trade statistics however report trade in a monetary value per year. This provides an intrinsic discrepancy between the high quality data from Plastics Information Europe and trade statistics. Applying daily exchange rates to prices and then averaging over a complete year usually yields a different number than applying an average exchange rate to an average price.

6.2.2 Production data

The United Nations (2004) database includes production data on polymer production for 58 out of the 195 countries in the world. It is unknown to what extent production data from those missing countries would have contributed to the total production. Assuming they produce polymers at all. Although production data was not reported for each UN country the grand totals seem in conformation with the grand totals in world demand as reported by the industry.

6.3 2008 effect

Due to the recession polymer demand dropped drastically in the second half of 2008. Compared to 2007 the world demand for HDPE for example decreased by 2.1%. In 2008 world PVC demand even dropped by 8% in comparison with 2007. It is expected that polymer demand will have recovered in 2011 (ICIS 2009a & Chemsystems 2009).

In the experience curve methodology prices are related to demand. The increase in demand relates to a higher production rate which in turn results in an increase in experience gained in time. With the decrease in demand the buildup of experience will go less fast. As a result lower prices will be reached later in time than would be expected in the first place. Because the experience curve approach is production related and not time related the approach remains valid for periods of recession as can be seen in the curves for the first and second oil crisis (see paragraph 5.2).

During periods of low demand the production capacity of plants cannot be maximized. As structural costs now need to be spread out over fewer products one would expect a price increase. Because periods of recession usually coincide with periods of a relative high oil price, the dummy variable (although unintended) most likely also corrected for the increase in structural cost that accompanied a recession.

6.4 Sensitivity analysis

The aim of this paragraph is to assess sensitivity of the derived progress ratios for the various assumptions and methodological issues. First the range in progress ratios will be examined; second the sensitivity for early experience will be examined. Third the used time series will be extended with early data from the Boston Consulting Group (1968) and finally the range in progress ratios will be used to make a 2020 extrapolation based on the expected developments in polymer demand.

6.4.1 Range in Progress Ratio

The error reported for the learning index resulted in a range of progress ratios that can be considered valid. This range provides the smallest possible range over which sensitivity studies should be done (Van Sark, 2008). The range (Table 5) will be used as an input for the 2020 forecast (paragraph 6.4.4). For polystyrene the range is quite broad due to the relative weak fit of the model (R^2 of 65%).

Table 5 – Range of progress ratios based on standard error

Polymer	**Progress Ratio**			**R^2**
	Smallest	**Medium**	**Highest**	
PE	75.1	76.6	78.1	0.90
PP	81.2	82.3	83.4	0.86
PVC	68.0	69.6	71.2	0.89
PS	58.6	63.2	67.8	0.65

6.4.2 Sensitivity for early experience

In the experience curve method cumulative production is used as proxy for experience. Until now 1950 was considered to be the year when polymer production started and cumulative production before 1950 was considered to be zero. However, prior to 1950 polymers where already produced. For instance with the discovery of polyethylene in 1933. As such, the building of experience in the polymer sector has started long before 1950. One could even say experience for large scale polymer production is to some extent due to experience with the early oil refineries in the 1900s

Because world production data from before 1970 was not available no exact figure could be given for the built up cumulative production up to 1970. To still gain insight in the sensitivity of the progress ratios for early experiences the production data from before 1970 was estimated based on growth rates from 1970 to 1980.

The sensitivity for the early experience will be examined with two scenarios. The first scenario considers experience being built from 1900 onwards (Refinery scenario). In this scenario the assumption is that experience from early refineries contributed to the total polymer experience. The second scenario considers experience being built from 1930 onwards (invention scenario). In this scenario the assumption is that early polymer production, even though not mass produced contributed to the experience for current mass produced bulk polymers. The base scenario with no experience from before 1950 will function as a comparison. The average annual growth rate in demand for 1970 until 1980 is used for the extrapolation. Table 6 gives an overview of the sensitivity of the progress ratio for early experience.

Table 6 - Sensitivity for pre 1970 experience

Polymer[1]	**Base scenario** Cumulative production 1950 -2007		**Invention scenario** Cumulative production 1930 -2007		**Refinery scenario** Cumulative production 1900 -2007	
	PR%	R-Square	PR%	R-Square	PR%	R-Square
PE	76.6 ± 1.5	**0.90**	75.8± 1.5	**0.90**	75.7±1.5	**0.90**
PP[2]	82.3 ± 1.1	**0.86**	82.2± 1.3	**0.86**	82.2±1.3	**0.86**
PVC	69.6 ± 1.6	**0.89**	68.1± 1.7	**0.89**	67.8±1.8	**0.89**
PS	63.2 ± 4.6	**0.65**	62.2± 4.8	**0.64**	61.9±4.8	**0.64**

[1] The average annual growth rate PE,PP,PVC and PS for 1970 to 1980 (respectively 8.6%,13.6%,7.2% and 7.1%) is used for extrapolation

Extrapolation of the demand prior to 1950 hardly makes any difference. In the worst case the progress ratio changes with 1.8% point for PVC, which is still within the error range of the base scenario. Because there is little change throughout the three scenario's we can conclude the base scenario included enough doublings in cumulative production to derive experience curves which are little sensitive to a change in early experience.

6.4.3 Sensitivity for including BCG Data

The Boston Consulting Group where the first to apply the learning curve approach to complete industries. In their studies they used the experience curve method on the US LDPE, PP, PVC and PS industry. In this example the BCG data (Appendix X) is used to complete the time series from 1942 to 1968. Using real data to complete the time-series (Table 7) yield no significant differences. The results are in fact almost identical.

Table 7 - BCG scenario

Polymer	Base scenario Cumulative production 1950 -2007		BCG scenario[1] Cumulative production 1942 -2007	
	PR%	R-Square	PR%	R-Square
PE	76.6 ± 1.5	**0.90**	76.6± 1.4	**0.90**
PP	82.3 ± 1.1	**0.86**	82.3± 1.3	**0.86**
PVC	69.6 ± 1.6	**0.89**	69.6± 1.6	**0.89**
PS	63.2 ± 4.6	**0.65**	63.3± 4.7	**0.65**

[1] Not all data starts in 1942. See Appendix X for details.

6.4.4 2020 Price forecast

According to PlasticsEurope (2007) the annual consumption of plastics per capita in Western European and NAFTA countries has the potential to grow from 100 kg per capita in 2007 to 140 kg per capita in 2015. This equals an annual growth in demand of 5.0% in which the rapidly growing demand in Asia and Eastern Europe is not yet included. In 2007 the bulk polymer demand in Western Europe has grown 3% on average (PlasticsEurope, 2008b). World polymer demand figures used in this research show on average a growth of 4.7% for the bulk polymers in the last decade.

In order to give a price forecast for 2020 a low (2%), medium (5%) and high (8%) growth scenario is created. Together with the confidence band in progress ratios, nine estimates for each polymer were made (Table 8). Cumulative production for all polymers is expected to at least double with the low, medium and high growth rates between 2008 and 2020.

Table 8 - Future price estimates for 2020 and the sensitivity for PR and annual growth rate

	Assumed annual growth rate in demand	2%	5%	8%
	Estimated Cumulative World demand 2020 (kt)	2247900	2497206	2814715
PE	PR 75.1%	333	320	304
	PR 76.6%	596	573	547
	PR 78.1%	1067	1027	984

	Assumed annual growth rate in demand	2%	5%	8%
	Estimated Cumulative World demand	1267036	1428933	1635119
PP	PR 81.2%	388	374	359
	PR 82.3%	616	596	573
	PR 83.4%	977	947	915

	Assumed annual growth rate in demand	2%	5%	8%
	Estimated Cumulative World demand	1241420	1369372	1532327
PVC	PR 68.0%	233	221	208
	PR 69.6%	476	452	426
	PR 71.2%	971	925	876

	Assumed annual growth rate in demand	2%	5%	8%
	Estimated Cumulative World demand	622544	680467	754235
PS	PR 58.6%	69	64	60
	PR 63.2%	600	566	529
	PR 67.8%	5244	4991	4715

[1] The dummy variable was assumed to be 0 for the year 2020.

The forecast is quite robust for change in the average annual growth, showing price differences of less than 6.5% when comparing with the medium growth scenario. Although for PE, PS and PVC the change in progress ratio is rather the small the model is highly sensitive for the slight change in progress ratio. For PE, which had a high model fit ($R^2 = 0.90$), the difference between the low and the high learning scenario even yield in differences of a factor three.

Due to the weak fit for polystyrene forecasting with the high progress ratio resulted in a price that is 80 times higher than when forecasting with the low progress ratio. Although the model result for PS shows a large uncertainty, the model was in line with the early data reported by the Boston Consulting group (1968).

6.5 Limits to growth

Theoretically, based on the experience curve expression experience curves have two asymptotes. When production is near zero units the production cost would go towards infinity and when infinite units are produced the price would go towards zero. These extremes are not possible in the physical world. Production is never infinite small and prices have a minimum due to physical constraints like a maximum efficiency, operational costs, raw material cost, thermodynamic limits etc. Also the market cannot absorb an infinite number of units. As such we need to be careful with extrapolating experience curves and check if extrapolations still comply with physical limits and expected innovations.

6.6 Correcting for the feedstock

In this study four methods of accounting for the oil feedstock were included, which all used an approach that did not require detailed exogenous data on the production processes to correct for the feedstock price. One could also think of a method in which first the contribution of the feedstock price is researched into great detail by analyzing the production processes and then correct for its exact contribution. This paragraph explores the possibility of such a correction for polyethylene. The concept would be the same for other polymers.

6.6.1 Allocation

Crude oil lies at the basis of polyethylene production. Crude oil is processed at an oil refinery into a wide range of products like among others petrol, naphtha, diesel and propane. The first challenge is the method of allocating the crude to these products. One could allocate a fraction of the crude oil to naphtha based on mass. However, given the large range of products and byproducts from the oil refineries it would be a true nightmare, to gather information on all relevant mass flows for all the refineries in the world, to come to a world average allocation based on mass. Supposing one would manage to do an allocation based on mass the result would most likely not representative for the world market. All the products have their own fluctuating market prices which also need to be taken into account.

In addition to the mass flows one would also need detailed time series on price for all the products from refineries in the world to make to make a weighted allocation based one economic value. Assuming one would also mange to do such an economic allocation the same challenge will come up in the production of ethylene. When naphtha is cracked besides ethylene also a wide range of by-products are created with their own market prices. This would require the same mass and price information, which is not readily available.

To circumvent the allocation problem one could allocate the feedstock to the polymer based on the energy content of the feedstock. One would need to gather data on process energy in the production steps leading to the polymer. The energy of the production processes will be allocated to the main product (the polymer studied). Based on the calorific value of the end product and the total process energy, the energy related (oil) cost in the polymers can be calculated. This approach limits the amount of data needed to a more amount. Figure 25 gives an overview of the energy built up in the polymer process.

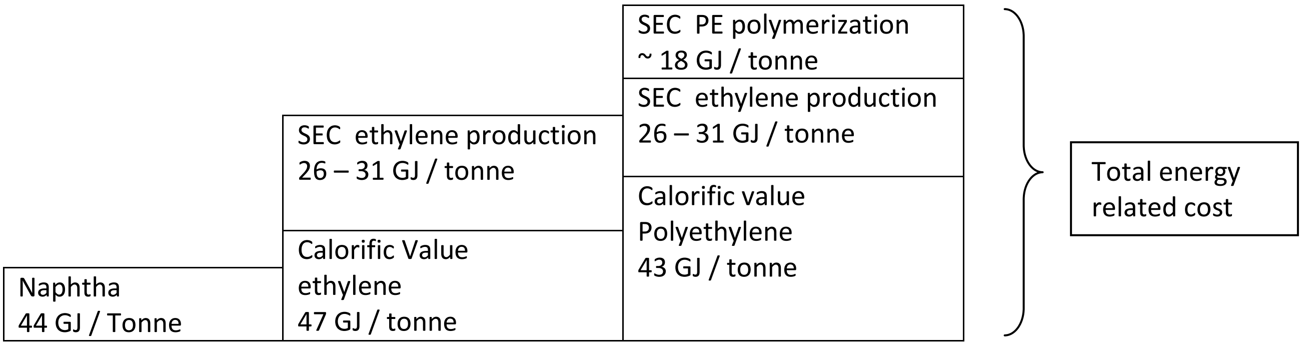
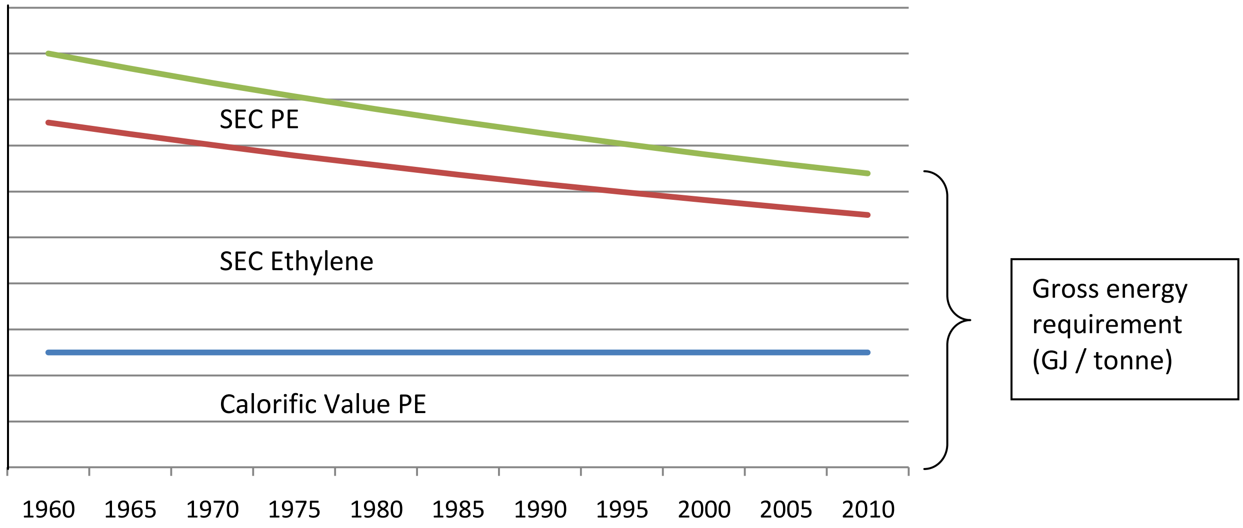


Figure 25 - Buildup energy requirement PE

The reported average calorific values of naphtha, ethylene, and polyethylene differ depending on the source (Tréanton, 2004). The specific energy consumption for producing ethylene and polyethylene values are not readily available over time. Ren et al. (2008) report SEC values for ethylene between 26 and 31 GJ / tonne for 2005. Since SEC values are not available for every year an assumption was made about the change in SEC over time. In this example we assumed an efficiency increase in SEC of 1% per year. Note that this 1% per year is related to learning and thus this assumption directly effects the experience curve results

Based on the SEC values, the calorific value of polyethylene and the assumption for the SEC change over time we can model the total related energy content over time.



Based on the calorific value of crude oil (GJ / tonne) and its price (€ / tonne) we can now calculate the amount in € / GJ for each year that is related in cost to energy. Combined with the Gross energy requirement (GJ / tonne) we can calculate the crude oil cost for PE for each year (GER * € / GJ crude)[16]. For sound experience curves we would like a stable feedstock price. As such the fluctuating crude oil related costs need to be subtracted from the polymer price to remove the effect of feedstock fluctuations on the price. To simulate stable energy prices, the cost related to the gross energy requirement will be recalculated with a stable average energy price.

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[16] The gross energy requirement for PE was found to be 92 GJ / tonne in 2005. The calorific value for crude oil differs between regions. 45.7 GJ/ tonne was found as the weighted average calorific value of crude oil (Scott et al. , 2005).

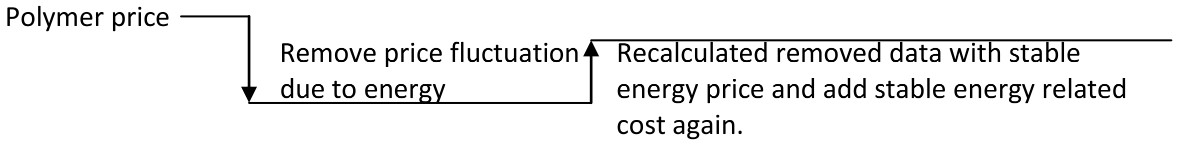

Figure 26 - Graphical representation feedstock correction

The regular experience curve methodology can now be applied to the new price series.
In Figure 27 an overview is given of the price series before and after the correction in relation to the oil price fluctuations.

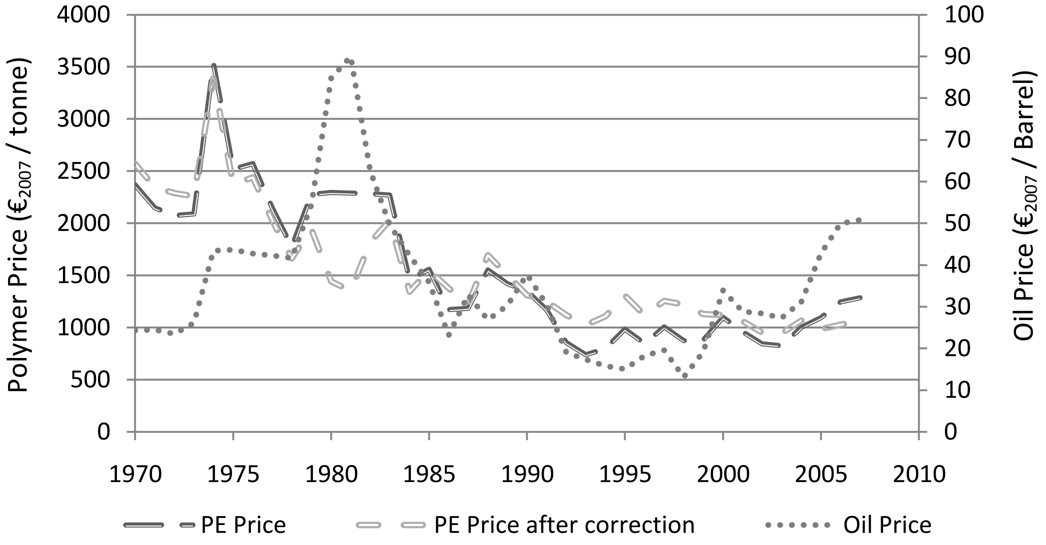

Figure 27 - Graphical overview of prices with feedstock correction

The results for the progress ratio are presented in Table 9 along with the result of the experience curve method with dummy correction and the standard experience curve approach.

Table 9 - Results PR using energy correction

Correction Method	**PR**	**R^2**
Experience Curve with dummy correction	76.6± 1.5	**0.90**
Experience Curve with energy correction	78.3± 1.5	**0.83**
Experience Curve without correction	75.1± 2.3	**0.71**

The energy correction resulted in a better fit than when not doing any correcting for the feedstock (R^2 increased from 71% to 83%). However, the Experience curve model with dummy still performs the best (R^2 = 0.90). In the energy correction an increase of 1% per year in energy efficiency was assumed for process related energy. This increase is however not stable over time. For instance during the first oil crisis producers where very much triggered to produce more energy efficient which led to a relative high decrease of the specific energy in the cracking process. To further perfect the energy correction more research is needed regarding the specific energy requirement over time and also more insight is needed in the calorific values of chemicals.

6.7 Linked sectors

All the bulk polymers have crude oil at the basis. Some processes are even linked until the production of the monomer. Even the polymerization steps are quite the same. As such one could argue the sector for one polymer is linked to the other polymers in terms of experience. Knowledge gained in the production of one polymer can often be used in the production of another polymer. The swing production of LLDPE and PP, were almost the same process is used to produce both polymers, is the ultimate example of this linkage.

Based on this linkage in experience one might expect that the progress ratios for the bulk polymers would lay close together. However, the results for PE, PVC, PP and PS show a range in progress ratio's form 63.2% for PS to 82.3% for PP. The low progress ratio for PS could be due to a stressed sector, but the low progress ratio might also be due to the properties of the experience curve method.

This will be illustrated with a fictional example. Let us assume a fictional Product A and Product B which use the same technology to produce. Table 10 contains a fictional time series. First the time series for A and the weighted average for A and B were chosen and second the data for product B was included accordingly.

Table 10 - PR dependence in linked products, an illustrative example

Year	Cumulative Production A	Cumulative Production B	Cumulative Production Sector	Price A	Price B	Weighted average Price[1]
1	1	0	1	100		100
2	3	1	4	80	52	73
3	8	3	11	70	26	55
4	28	7	35	51	15	44
PR				87%	64%	86%
N[2]	4.8	2.8	5.1			

[1] Because price developments are related to cumulative production, prices were weighted based on cumulative production

[2] Number of doublings in cumulative production

At the bottom of Table 10 the progress ratios are given for the derived series. Notice that PR for the weighted series is mainly determined by the product with the largest share in cumulative production. In a linked sector in terms of experience it is possible for products with a low share in cumulative production to can catch a ride on the experience gained for the other products and thereby showing high learning rates.

Let us now examine the results for a weighted average analysis on the bulk polymers. Table 11 shows progress ratio's for two generic polymers. Generic polymer1 was constructed using weighted average prices based on weights related to the cumulative production. Generic polymer 2 was constructed using weighted average prices based on weights related to annual production. The fit of the generic polymer2 is lower than generic polymer 1 which strengthens the idea price developments are related to cumulative production.

Note that the progress ratios of both generic polymers are higher than those of the bulk polymers. This is because the number of doublings in cumulative production increased when summarizing the cumulative production. As a result price decreases are spread out over a larger number of cumulative doublings, effectively showing a higher progress ratio.

Table 11 - PR generic polymer

Standard Experience with Oil dummy	PR%	N	R^2
Polyethylene	76.6 ± 1.5	4.21	**0.90**
Polypropylene	82.3 ± 1.1	6.21	**0.86**
PVC	69.6 ± 1.6	3.61	**0.89**
Polystyrene	63.2 ± 4.6	3.50	**0.65**
Generic Polymer1	83.4± 1.0	7.40	**0.89**
Generic Polymer2	82.4± 1.2	7.40	**0.88**

This same dynamic can be observed in the experience curves from previous studies. In the literature overview (table XX) for instance PVC consequently shows lower progress ratio's than the polymers which are produced in larger quantities. Also the various grades of PE show a smaller progress ratio than the progress ratios PE in general.

7 Conclusions and recommendations

7.1 Main conclusions

The main objective of this thesis was to identify at what rate the polymer industry builds up experience by deriving experience curves for the four main bulk polymers for the period 1970 till 2007. Underlying drivers behind the cost reductions would be identified. And based on extrapolations of the experience curves it was tried to identify a growth potential in demand for bulk polymers in 2020.

Based on the strong fit of the experience curves we can conclude that the experience curve method is applicable for energy demanding products, provided one corrects for effects that are not related to technological learning (such as fluctuating oil prices). In this research it was found a correction using a dummy variable for periods with very high feedstock prices gave the best model fit (R^2 up to 0.90).

Progress ratios for the bulk polymers varied between 63.2% for PS and 82.3% for PP. Most likely the low progress ratios for PVC and PS are the result of cross-polymer experience building. Experience gained with polymers that have a high market share can directly be adopted for polymers with a low market share. The result is that polymers with a low market share gain experience faster than one would expect based on the cumulative production.

Including all the polymers in the experience curve approach by deriving an generic polymer resulted in a progress ratio of 83.4± 1.0% for the complete polymer industry. Based on current growth rates the polymer demand is expected to at least double between 2007 and 2020, which could relate to a general price decrease of around 17% for the bulk polymers.

Major drivers for the observed price developments are the fluctuating and increasing energy prices. Especially the first oil crisis triggered producers to work more energy efficient. Also the continues upscaling contributed to lower prices for polymers. Although environmental and health concerns hampered the PVC and PS market it provided an opportunity for the PP market to take their place. Polyethylene held a very stable market share over time.

7.2 Recommendations for Future research

7.2.1 Experience curves for each process step

In this research experience curves where derived for the polymers in aggregated form, meaning the curve represents experience gained both in the refinery, monomer and the polymer part of the production chain. Deriving experience curves for those three process steps individually might provide valuable insight into the contribution of the three parts of production. This division might also make it possible to research the linkage in experience between Bio-polymer and petrochemical polymers in the polymerization step.

7.2.2 Supply demand relations.

Supply and demand issues can have a distorting effect in determining progress ratios when using prices as a proxy for cost. Based on price elasticity high demand can lead to high prices and oversupply van lead to below cost prices. If the high prices are related to the feedstock one might consider a correction. Like demonstrated using a dummy variable at very high prices gives a good fit. One could also consider a correction based on the energy content of the products (like explored in the paragraph 6.6). However, it becomes very difficult to correct for supply and demand issues when supply and demand issues are directly affecting the price of the product of interest. At such point the assumed cost versus price relation is not stable anymore and prices cannot be used as a proxy for cost anymore. Such problem might be the case for polystyrene which has been overproduced for the last decade in Western Europe. The only way to correct for polymer prices which are out of bound due to supply and demand issues in the polymer market itself would be to revert back to real cost information, which is subsequently not readily available due to the sensitive nature from a competitive point of view. Distorted feedstock prices can be corrected for by including a dummy variable or a correction based on process details.

7.2.3 Feedstock corrections

Considering the promising results based on the assumption of a 1% efficiency increase in the specific energy consumption for polyethylene it might be worthwhile to do further research in the development of the specific energy consumption in the production of polymers over time. Not only would the results provide the possibility to do feedstock corrections more precise, it would also be possible to correct for multiple feedstocks.

7.2.4 Linked sectors

New products tend to have high learning rates. This could be due to a link in experience to other products which have a far higher cumulative production. As such it is essential for sound experience curves to have a great understanding of size and boundaries of the industry or sector in question. It is therefore recommended prior to deriving experience curves to research which products or sectors are comparable or closely related in terms of experience. In this research in mass 85% of all thermoplasts was accounted for.

7.2.5 Experience curves for other materials.

Using the methodology used in this thesis it is most likely possible to derive experience curve for other products that have to cope with drivers which are not related to learning. Including a dummy variable provides a correction that does not need large amounts of exogenous data. The dummy could for instance be used to correct for temporally high feedstock prices, periods of recession or other short term effects that are not related to learning. Note that using more than 1 dummy variable is not advised because too much variation in the data will be subscribed to the dummy variable. Correcting for multiple drivers not related to learning could be done by either deriving experience curve for each intermediate and or doing a correcting based on the process details.

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Appendix I – Polymer demand data

World Polymer Demand (kt)

Year	Polyethylene	PVC	Polypropylene	Polystyrene
1970	6668	5331	1156	3072
1971	7344	5527	1365	3366
1972	8616	6533	1442	4035
1973	10229	7594	2061	4367
1974	11025	7824	2292	4251
1975	8941	6434	1908	3826
1976	11008	8154	2525	3774
1977	12162	9523	3141	5156
1978	13400	9952	3514	5944
1979	15261	11098	4435	6586
1980	15200	10695	4137	6116
1981	15057	10397	4694	6834
1982	15257	10271	4956	7100
1983	16674	11207	5914	7077
1984	17570	13561	6779	7883
1985	19220	12563	7135	8[illegible]6
1986	21310	16500	7833	10843
1987	22849	13831	9053	8528
1988	23076	14588	10415	9014
1989	23686	19754	10580	9193
1990	30435	17830	12920	8985
1991	31450	17800	13780	9350
1992	33250	18540	15100	9185
1993	33515	19125	15920	9630
1994	36840	20480	18260	10640
1995	38610	20770	19490	10900
1996	41990	22410	21940	11500
1997	44760	23440	24590	12265
1998	46360	23860	25880	12580
1999	50085	25350	28890	13600
2000	52440	25560	30350	13830
2001	53030	26480	31790	13780
2002	56380	27490	34675	14680
2003	57340	28110	36275	14970
2004	61040	30370	38990	15360
2005	62365	31900	40025	15200
2006	65575	33450	42400	15330
2007	68780	35300	44665	15980

Data from various industry sources

Data partly interpolated and derived from United Nations (2002).

Appendix II – Polymer Price Data, Cumulative Production and Oil Price

The following table shows the price of different polymers over time. Prices are in 2007 euro. Nominal prices (Plastics Information Europe, 2009) were converted using Consumer price indices (Appendix III) and currency exchange rate (VI). The cumulative production is based on the data from Appendix I. Prices are annual averages representative for normal grade polymers for large consumers (above 25t per order) in Western Europe.

	Euro 2007 / Tonne	**Cumulative tonnes**	**Euro 2007 / Tonne**	**Cumulative tonnes**	**Euro 2007 / Tonne**	**Cumulative tonnes**	**Euro 2007 / Tonne**	**Cumulative tonnes**	**Euro 2007 / Barrel**
Year	**PE Price**	**PE Production World**	**PP Price**	**PP Production World**	**PS Price**	**PS Production World**	**PVC Price**	**PVC Production World**	**Oil Price**
1970	2369	65860676	2729	8106839		33967274	2600	58570410	**24.34**
1971	2148	73204659	2599	9471745		37332873	2306	64097037	**24.50**
1972	2075	81820462	2273	10913623		41367927	2154	70630149	**23.50**
1973	2091	92049740	2403	12974992		45735048	2178	78223951	**26.10**
1974	3534	103074712	3919	15267243		49986348	3256	86047717	**43.42**
1975	2519	112015594	2550	17175699		53811925	2523	92481235	**43.67**
1976	2570	123023444	2538	19700678		57586372	2490	100635026	**42.74**
1977	2148	135185488	2045	22841521		62742296	2263	110157697	**42.27**
1978	1775	148585254	1723	26355130		68686431	1889	120109963	**41.68**
1979	2277	163845919	2028	30789967		75272911	2073	131207778	**54.40**
1980	2114	179045955	1875	34927197		81388680	1893	141902940	**84.81**
1981	1952	194103300	1841	39620745		88222399	1674	152299442	**89.95**
1982	1789	209360725	1912	44576256		95322185	1469	162570115	**62.62**
1983	1627	226034851	1801	50490646		102399157	1532	173777600	**49.62**
1984	1464	243605115	1457	57269490	1943	110282349	1212	187339072	**42.29**
1985	1575	262825382	1527	64404356	1919	118417861	1172	199902360	**35.87**
1986	1193	284135482	1134	72237119	1494	128761041	1032	216402577	**23.10**
1987	1190	306984749	1171	81289697	1751	137288626	1077	230233221	**32.85**
1988	1550	330060878	1563	91704989	1887	146302606	1228	244820768	**26.86**
1989	1463	353747337	1339	102284765	1839	155495848	1272	264574937	**30.31**

	Euro 2007 / Tonne	**Cumulative tonnes**	**Euro 2007 / Tonne**	**Cumulative tonnes**	**Euro 2007 / Tonne**	**Cumulative tonnes**	**Euro 2007 / Tonne**	**Cumulative tonnes**	**Euro 2007 / Barrel**
Year	**PE Price**	**PE Production World**	**PP Price**	**PP Production World**	**PS Price**	**PS Production World**	**PVC Price**	**PVC Production World**	**Oil Price**
1990	1390	384182337	1267	115204765	1614	164480848	1051	282404937	37.72
1991	1239	415632337	1042	128984765	1394	173830848	849	300204937	30.50
1992	874	448882337	821	144084765	1085	183015848	794	318744937	19.00
1993	725	482397337	765	160004765	960	192645848	714	337869937	17.35
1994	787	519237337	819	178264765	1166	203285848	879	358349937	15.83
1995	996	557847337	961	197754765	1300	214185848	960	379119937	15.00
1996	847	599837337	851	219694765	1000	225685848	675	401529937	18.24
1997	1001	644597337	1019	244284765	992	237950848	835	424969937	19.56
1998	867	690957337	887	270164765	902	250530848	735	448829937	13.09
1999	862	741042337	915	299054765	830	264130848	731	474179937	19.20
2000	1090	793482337	1116	329404765	1237	277960848	969	499739937	33.89
2001	954	846512337	977	361194765	963	291740848	706	526219937	28.86
2002	812	902892337	910	395869765	1009	306420848	769	553709937	28.41
2003	783	960232337	908	432144765	1000	321390848	740	581819937	27.31
2004	961	1021272337	1089	471134765	1214	336750848	934	612189937	31.19
2005	1052	1083637337	1186	511159765	1246	351950848	934	644089937	42.80
2006	1219	1149212337	1296	553559765	1328	367280848	1045	677539937	49.93
2007	1276	1217992337	1305	598224765	1412	383260848	1103	712839937	50.79
2008	1287		1301		1364		1090		61.96

Appendix III – Consumer price indices - Europe

Jul-84	Jan-89	Jan-93	Jan-97	Jan-01	Jan-05
aug-84	Feb-89	Feb-93	Feb-97	Feb-01	Feb-05
sep-84	mrt-89	mrt-93	mrt-97	mrt-01	mrt-05
Oct-84	apr-89	apr-93	apr-97	apr-01	apr-05
nov-84	May-89	May-93	May-97	May-01	May-05
dec-84	jun-89	jun-93	jun-97	jun-01	jun-05
Jan-85	Jul-89	Jul-93	Jul-97	Jul-01	Jul-05
Feb-85	aug-89	aug-93	aug-97	aug-01	aug-05
mrt-85	sep-89	sep-93	sep-97	sep-01	sep-05
apr-85	Oct-89	Oct-93	Oct-97	Oct-01	Oct-05
May-85	nov-89	nov-93	nov-97	nov-01	nov-05
jun-85	dec-89	dec-93	dec-97	dec-01	dec-05
Jul-85	Jan-90	Jan-94	Jan-98	Jan-02	Jan-06
aug-85	Feb-90	Feb-94	Feb-98	Feb-02	Feb-06
sep-85	mrt-90	mrt-94	mrt-98	mrt-02	mrt-06
Oct-85	apr-90	apr-94	apr-98	apr-02	apr-06
nov-85	May-90	May-94	May-98	May-02	May-06
dec-85	jun-90	jun-94	jun-98	jun-02	jun-06
Jan-86	Jul-90	Jul-94	Jul-98	Jul-02	Jul-06
Feb-86	aug-90	aug-94	aug-98	aug-02	aug-06
mrt-86	sep-90	sep-94	sep-98	sep-02	sep-06
apr-86	Oct-90	Oct-94	Oct-98	Oct-02	Oct-06
May-86	nov-90	nov-94	nov-98	nov-02	nov-06
jun-86	dec-90	dec-94	dec-98	dec-02	dec-06
Jul-86	Jan-91	Jan-95	Jan-99	Jan-03	Jan-07
aug-86	Feb-91	Feb-95	Feb-99	Feb-03	Feb-07
sep-86	mrt-91	mrt-95	mrt-99	mrt-03	mrt-07
Oct-86	apr-91	apr-95	apr-99	apr-03	apr-07
nov-86	May-91	May-95	May-99	May-03	May-07
dec-86	jun-91	jun-95	jun-99	jun-03	jun-07
Jan-87	Jul-91	Jul-95	Jul-99	Jul-03	Jul-07
Feb-87	aug-91	aug-95	aug-99	aug-03	aug-07
mrt-87	sep-91	sep-95	sep-99	sep-03	sep-07
apr-87	Oct-91	Oct-95	Oct-99	Oct-03	Oct-07
May-87	nov-91	nov-95	nov-99	nov-03	nov-07
jun-87	dec-91	dec-95	dec-99	dec-03	dec-07
Jul-87	Jan-92	Jan-96	Jan-00	Jan-04	Jan-08
aug-87	Feb-92	Feb-96	Feb-00	Feb-04	Feb-08
sep-87	mrt-92	mrt-96	mrt-00	mrt-04	mrt-08
Oct-87	apr-92	apr-96	apr-00	apr-04	apr-08
nov-87	May-92	May-96	May-00	May-04	May-08
dec-87	jun-92	jun-96	jun-00	jun-04	jun-08
Jan-88	Jul-92	Jul-96	Jul-00	Jul-04	Jul-08
Feb-88	aug-92	aug-96	aug-00	aug-04	aug-08
mrt-88	sep-92	sep-96	sep-00	sep-04	sep-08
apr-88	Oct-92	Oct-96	Oct-00	Oct-04	Oct-08
May-88	nov-92	nov-96	nov-00	nov-04	nov-08
jun-88	dec-92	dec-96	dec-00	dec-04	dec-08
jul-88					Jan-09
aug-88					feb-09
sep-88					
oct-88					
nov-88					
dec-88					

Copyrighted
Source: Plastics Information Europe (2009)

Appendix IV – Heading of PE in SITC Rev 4 Nomenclature

Polyethylene with a specific gravity of less than 0.94 in primary form can be found in the SITC Revision 4 classification under 57111 where:

Level 1: 5 - CHEMICALS AND RELATED PRODUCTS, N.E.S.
Level 2: 7 - PLASTICS IN PRIMARY FORMS
Level 3: 1 - POLYMERS OF ETHYLENE, IN PRIMARY FORMS
Level 4: 1 - POLYETHYLENE, HAVING A SPECIFIC GRAVITY OF LESS THAN 0.94, IN PRIMARY FORMS
Level 5: 1 - POLYETHYLENE, HAVING A SPECIFIC GRAVITY OF LESS THAN 0.94, IN PRIMARY FORMS

Appendix V – Usage of the Dummy variable (Graphic)

Figure 28 shows the dummy usage graphical. The dummy variable equals one when the oil price is 18% above average for three years in a row. In all other cases the dummy variable equals 0.

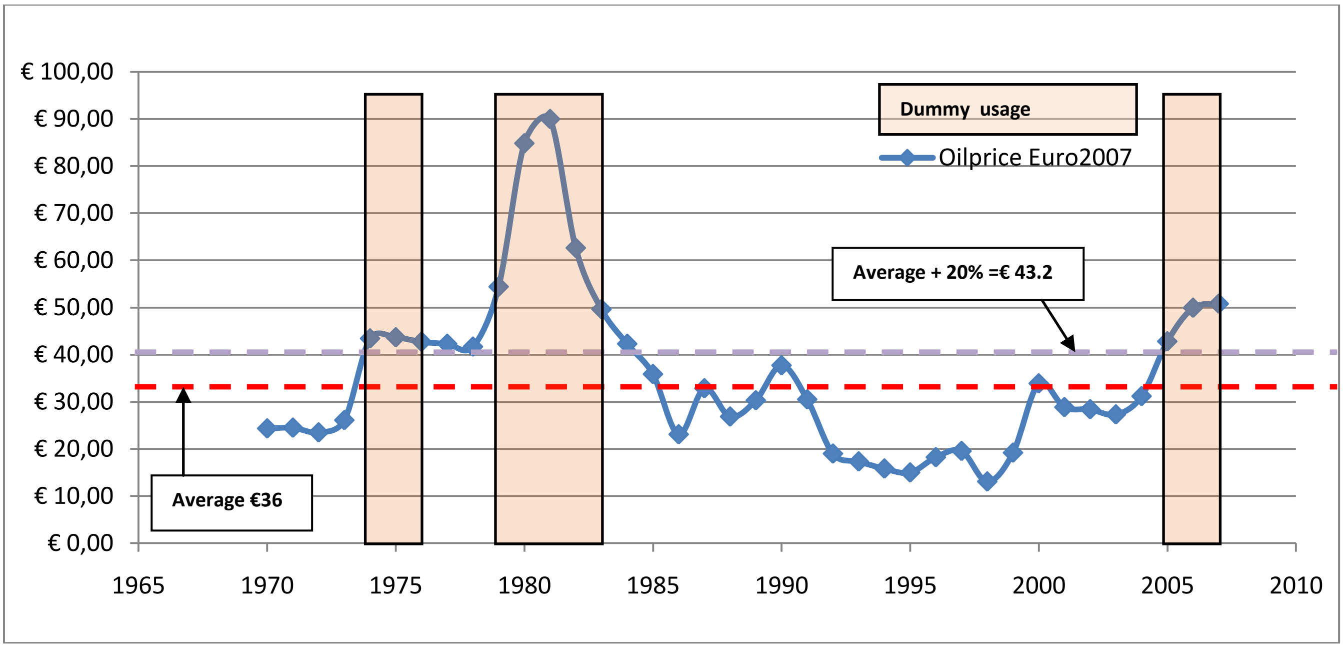

Figure 28 - Dummy usage

Appendix VI – Exchange rates and dummy vector

Year	Euro/ USD
1991	1.177100
1992	1.255133
1993	1.183667
1994	1.207917
1995	1.170842
1996	1.300158
1997	1.129283
1998	1.113000
1999	1.066842
2000	0.924033
2001	0.895650
2002	0.944908
2003	1.130900
2004	1.243333
2005	1.244633
2006	1.255658
2007	1.370642
2008	1.469183

Source: Plastics Information Europe (2009)

1970	0
1971	0
1972	0
1973	0
1974	1
1975	1
1976	1
1977	0
1978	0
1979	1
1980	1
1981	1
1982	1
1983	1
1984	0
1985	0
1986	0
1987	0
1988	0
1989	0
1990	0
1991	0
1992	0
1993	0
1994	0
1995	0
1996	0
1997	0
1998	0
1999	0
2000	0
2001	0
2002	0
2003	0
2004	0
2005	1
2006	1
2007	1

Appendix VII - Trade Statistics – United Nations

Export PP from USA to EU

	$	kg
1978	2909306	4800435
1979	675977	546609
1980	3075887	1518243
1981	3092528	2973639
1982	3298326	2621351
1983	5626978	4667043
1984	5609241	4833029
1989	29078659	22188096
1990	30745744	26469073
1991	43192917	47086590
1992	50500332	60701238
1993	73446133	99274661
1994	111859912	127828386
1995	156059376	152093552
1996	131864609	129322534
1997	158455498	167808403
1998	139194361	176134370
1999	135320298	165378228
2000	144162253	163690039
2001	126046361	149837443
2002	139329520	149287209
2003	170779164	151380400
2004	222554863	211704963
2005	269407177	186364737
2006	258216452	175329076

Source: United Nations (2009)

Import PE from World to USA

	$	kg
1989	379257324	460005198
1990	515420671	689609555
1991	421892951	609243993
1992	416811776	689320113
1993	499951647	847830398
1994	703330919	1071361857
1995	1008304384	1126312320
1996	994055108	1309534276
1997	1128911978	1276253861
1998	917838300	1267298146
1999	1059836246	1513647872
2000	1238595907	1513484562
2001	1310586534	1732684990
2002	1089303471	1636012827
2003	1355441492	1704368875
2004	1550991469	1732058936
2005	2011885623	1683229121
2006	2213671481	1695423088

Export PS from USA to World

Period	Trade Value $	Net Weight (kg)
1978	91,576,360	109,898,560
1979	187,385,936	182,293,680
1980	252,639,360	212,300,288
1989	457,727,309	321,923,867
1990	517,264,661	350,423,691
1991	550,252,738	397,118,945
1992	539,854,062	407,935,664
1993	600,719,574	465,012,635
1994	663,031,152	501,274,299
1995	793,181,568	521,774,816
1996	804,069,020	597,323,512
1997	830,643,051	650,467,985
1998	785,797,617	615,988,008
1999	761,988,193	612,123,420
2000	867,290,379	625,419,849
2001	757,300,835	543,519,619
2002	785,249,904	613,789,050
2003	859,426,288	629,457,851
2004	1,031,183,536	681,568,948
2005	1,149,984,447	644,526,182
2006	1,353,220,340	719,803,098

Appendix VIII – Ethylene and Propylene Pipelines in Europe

Ethylene and Propylene pipelines in Europe today and in the future (Association of Petrochemical Producers in Europe, 2009)

Appendix IX - Experience Curves Mathematics

In the experience curve expression (1) the price at time t ($Price_t$) is dependent on the initial price ($Price_0$) which goes down depending on the Cumulative Production ($CumPro_t$). How fast the price is going down is dependent on the learning index b.

$$Price_t = Price_0\ {CumPro_t}^b \qquad (1)$$

Progress Ratio

In experience curve studies the progress ratio used as an indicator for the rate of price decreases. The progress ratio shows the remaining percentage of the original price when the cumulative production doubles. When the Cumulative production doubles (2) the price changes (3) with 2^b, which is called the Progress ratio (4).

$$\frac{Price_1}{Price_2} = \frac{\cancel{Price_0}\ {CumPro_1}^b}{\cancel{Price_0}\ (2\ CumPro_1)^b} = \frac{\cancel{{CumPro_1}^b}}{\cancel{{CumPro_1}^b}\ \ 2^b} \qquad (2)$$

$$Price_2 = Price_1 2^b \qquad (3)$$

$$\mathrm{PR} = \frac{Price_2}{Price_1} = 2^b \qquad (4)$$

Production at the starting price.

Let us examine the experience curve for the starting price point (t = 0).

$$Price_0 = Price_0\ {CumPro_0}^b \qquad (5)$$

To make the equation (5,6) valid either the learning index has to be zero of the cumulative production has to 1. A learning index of zero is not a valid solution as that would mean cost would be stable and there would be no improvements (learning) at all. As such $CumPro_0$ equals one. $Price_0$ therefore equals the price of the first unit produced. Note that the point where t equals zero is theoretical as experience can be gained prior to the first production. For example the production of crops for thousands of years contributes to some extent to the experience currently available in the production of the feedstock for bio-fuels.

$$\begin{aligned} {CumPro_0}^b &= 1 && (6) \\ CumPro_0 &= 1 && (7) \end{aligned}$$

Absence of units

The observant reader might think there is a conflict of units as the cumulative production in tonnes is multiplied with the price. This conflict is not the case. To determine the learning index between two points the following formula (8,9) can be used.

$$\frac{Price_2}{Price_1} = \frac{\cancel{Price_0}\ {CumPro_2}^b}{\cancel{Price_0}\ {CumPro_1}^b} = \left(\frac{CumPro_2}{CumPro_1}\right)^b \qquad (8)$$

$$Price_2 = Price_1 \left(\frac{CumPro_2}{CumPro_1}\right)^b \qquad (9)$$

The cumulative production in this study is in tonnes. As the cumulative production in point t=2 gets divided over point t=1 the unit (tonne) is divided out. Suppose $Price_1$ would be $price_0$ than $CumPro_1$ would be $CumPro_0$ and equal one (equation 7), bringing back equation (1). To be complete equation 1 actually should look like (9):

$$Price_2 = Price_0 (\frac{CumPro_{\ 2}}{CumPro_{\ 0}})^b = Price_0 (\frac{CumPro_{\ 2}}{1})^b = Price_0\ CumPro_t{}^b \qquad (10)$$

Because in equation (1) CumPro_t is devided by one tonne, CumPro_t is defined as the number of units of cumulative production instead of cumulative production. This is to note that the unit has been divided out which is most common in studies dealing with experience curves.

Appendix X - BCG Data

	US Cumulative Production (kt)				Price (Euro$_{2007}$ / tonne)			
	LDPE	PP	PVC	PS	LDPE	PP	PVC	PS
1943				9525				9631
1944				14515				9810
1945				24948				9275
1946			166468	58060			9382	8026
1947			228157	104326			8365	7313
1948			306628	167829			8294	5975
1949			409594	254012			8793	7045
1950			557011	362874			8240	7580
1951			743438	476272			8133	7402
1952	120202		904917	589670	10006		7955	7313
1953	181437		1102229	703068	8882		7883	7134
1954	276691		1281852	805126	8169		7562	7045
1955	459035		1520895	941204	7669		6671	6510
1956	715769		1809834	1111301	6885		6082	5975
1957	1036912		2122359	1247379	5868		5315	5262
1958	1395250		2420369	1349437	5707		4816	4994
1959	1885130	11340	2830870	1564894	5618	7366	4388	4281
1960	2388617	29937	3255432	1689632	4816	7081	3977	4370
1961	2987359	73936	3698592	1859729	3924	6492	3246	3567
1962	3708571	139706	4249707	2063845	3549	5565	3032	3478
1963	4502358	229064	4878386	2336001	2996	4833	2996	3032
1964	5391399	352895	5620917	2585477	2782	3942	2782	2765
1965	6416518	522538	6454166	2948350	2729	3567	2747	2675
1966	7604930	773375	7433925	3311224	2658	3121	2515	2800
1967	8856845	1068210	8405520	3719457	2283	3121	2283	2586
1968	10349164	1465103	9491874	4399846	1908	3068	2194	2283

Figures based on BCG 1968. Deflated by using Appendix XI. 2009

Appendix XI – Consumer Price Indices USA

YEAR	CHIP
1943	16,90
1944	17,40
1945	17,80
1946	18,20
1947	21,50
1948	23,70
1949	24,00
1950	23,50
1951	25,40
1952	26,50
1953	26,60
1954	26,90
1955	26,70
1956	26,80
1957	27,60
1958	28,60
1959	29,00
1960	29,30
1961	29,80
1962	30,00
1963	30,40
1964	30,90
1965	31,20
1966	31,80
1967	32,90
1968	34,10
1969	35,60
1970	37,80
1971	39,80
1972	41,10
1973	42,60
2007	202,42
2008	211,08
2009	211,14

Source: Inflation data (2009)

Appendix XII - Licensors

Product	Licensed Processes	Licensor	Maximum Single Line capacity	World Capacity	Source
PP	Spherizone	Lyondell Basell		3 Mt / a	LyondellBasell 2009
PP	Spheripol	Lyondell Basell	500 kt / a	20 Mt/ a (50%)	LyondellBasell 2009
PP	Novolen	CB&I Lummus Technology			
PP	Unipol PP	Dow Chemical	550 kt / a	Expected for 2011: 17% (11 Mt / a)	The Dow Chemical Company, 2009
LDPE, MDPE, HDPE	Spherilene	Lyondell Basell			LyondellBasell 2009
LDPE	Lupatech	Lyondell Basell	400 kt/ a	6 Mt / a	LyondellBasell 2009
Ethylene	Combination of various licensed technologies	CB&I Lummus Technology	1.4 Mt / a	40%	Lummus 2009
Propylene	Catofin	CB&I Lummus Technology	650 kt/a	emerging	
Propylene	OCT	CB&I Lummus Technology			
PVC	Chisso	Bulk Process EVC[17]	125 kt / a	1.5 Mt / a	
PVC	EVIPOL	Ineos		1.5 Mt /a	
PVC	Vintec suspension	Vinnolit			
PS		Shell Arco Nizhnekamsk			
EB	EB One EB Max process	Lummus Badger Licensing LLC			Chemsystems 2009a

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[17] In 2005 EVC becomes fully owned by INEOS and is renamed INEOS Vinyls.