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TNO report

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Small-scale flexible plants - Towards a more agile and competitive EU chemical industry

Full report

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Management summary

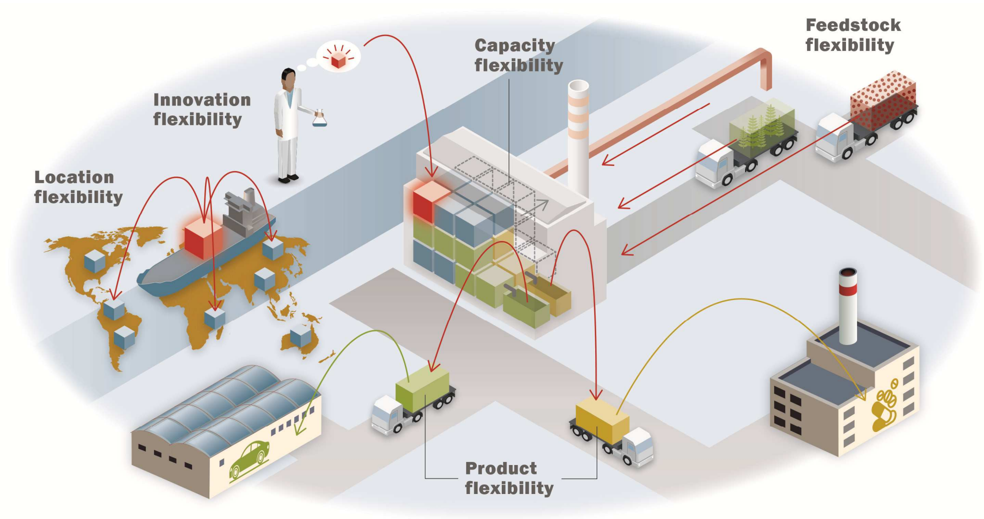
The European chemical industry is worrying about its competitive position. In the global market it has a major disadvantage on its cost position on feedstock, energy and labour. The European industry profits from growing market demand in upcoming regions like Asia, but to a limited extent. It is looking for ways to get a significant foothold in these markets. Investment levels in Europe lag behind compared to all other regions.

The strength of the EU chemical industry lies in its knowledge position and its ability to innovate. This leading position in knowledge and innovation offers opportunities to strengthen the competitive position of the industry, not only by the innovations itself, but also by mitigating the disadvantages in other areas, e.g. by reducing costs through innovation.

In the rapidly changing and highly volatile chemical market, flexibility is seen as a key element to strengthen the position of Europe. A way to implement this necessary flexibility is offered by the concept of flexible plants. This report presents a vision on the opportunities that flexible plants can offer. Industry representatives from a large number of chemical companies, covering a wide range from commodities to pharma, provided valuable input for this report during interviews. Their main drivers to implement flexible plants are to

- Shorten time to market
- Increase responsiveness to customer demand
- Enable market entry and growth in emerging markets
- Reduce CAPEX risks

Flexibility in production offers a route to new strategies reversing the negative trend of the moment. Production can be flexible in capacity, product type, innovation, location and feedstock.



Technical developments enable the implementation of flexible plants. Modularity offers opportunities to expand and adapt a plant in a flexible manner, e.g. to enlarge capacity over time. Other relevant technical enablers are process intensification and continuous processing, novel manufacturing technologies like 3D printing, and smart industry. These technological developments contribute to more flexibility in production. Meanwhile they have the potential to break economy of scale and drive down capital and operational costs.

Sound business cases are within reach when supported by business models that utilize the benefits of flexibility. More emphasis should be put on value creation. This can be realised by utilising the benefits of flexibility: increasing responsiveness to customer demand and shortening time to market. Meanwhile CAPEX risks can be reduced by implementing capacity flexibility, thus enabling market entry in emerging markets. On the cost side investments and operational costs should become less dependent on scale by implementing the technologies named above.

Currently the concept of flexible production is mainly applied in R&D and pilot setting. Recently quite some examples of successful commercial implementation were reported. The table below shows the term on which we expect the different types of flexibility to become implemented in each market segment. The arrow in the picture indicates the expansion of flexibility from higher value products to specialties (mid-term) and commodities (long-term).

	Pharma	Fine chemicals	Specialties	Commodities
Location flexibility	Short-term	Short-term	Mid-term	Short-term*
Innovation flexibility	Short-term	Short-term	Mid-term	Less relevant
Product flexibility	Mid-term	Mid-term	Long-term	Less relevant
Capacity flexibility	Less relevant	Less relevant	Mid-term	Long-term
Feedstock flexibility	Less relevant	Less relevant	Mid-term	Long-term

By joining forces in North Western Europe development and implementation in flexible production can accelerate. Therefore, it is key that companies, knowledge suppliers and governments follow the same direction together, each organisation in its own role and with its own strength. Then the way to broad adoption is open and the concept of flexible production can be implemented on a wide scale, contributing to a stronger competitive position of the EU chemical industry.

Contents

1 Change is needed to strengthen the competitive position of the EU chemical industry

The EU chemical industry is worrying about its competitive position. In this chapter an analysis is made of the competitive position of the EU chemical industry. Next we describe how its strength can be utilized to realize the necessary change and improve competitiveness.

1.1 Competitive position of the EU chemical industry

The competitive strength of chemical companies is globally determined by the following factors:

- Cost of production
- Market demand
- Financial capability
- Knowledge and ability to innovate

Cost of production
The cost of production of chemicals is mainly determined by the cost of feedstock, energy and labour. On this point Europe has a significant disadvantage compared to their competitors. The shale gas revolution in the US has led to low energy and feedstock (specifically methane and ethane) prices. The Middle East also profits from low energy and feedstock prices, due to their oil and gas reserves. And Asia is favoured by low labour costs and, in potential, has access to large shale gas reserves[1]. Price pressure is high in the chemical industry in general, though higher value products like pharma and fine chemicals are less sensitive to production costs than commodities. Therefore the disadvantage on cost is felt most in commodities.

Market demand
The chemical industry is a typically global market. End markets are very broad, varying from automotive and construction to agro and food. For this reason many chemical companies are operating globally, having a foothold in different regions.

Worldwide chemical sales increased with 14% in 2013[2]. Emerging markets in Asia and Latin America contributed significantly to global growth, which makes them very attractive for chemical companies to invest in. Chemical production worldwide valued €3156 billion in 2013, of which €527 billion in the EU and €1047 billion in China. Though EU chemical sales have also grown and almost doubled in 20 years, the EU market share in the global chemical industry almost halved during this period.

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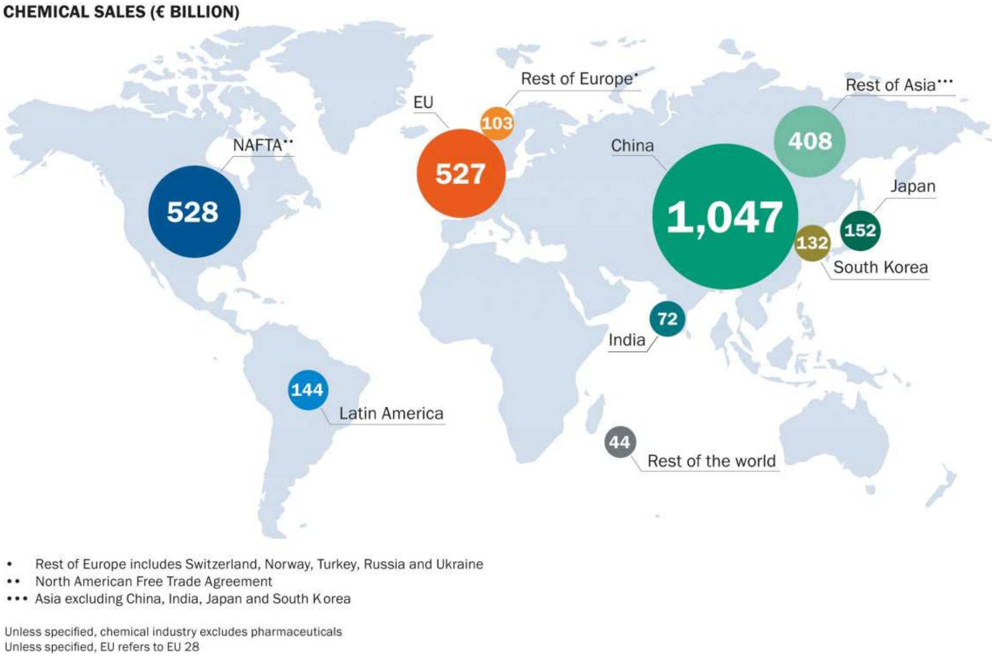
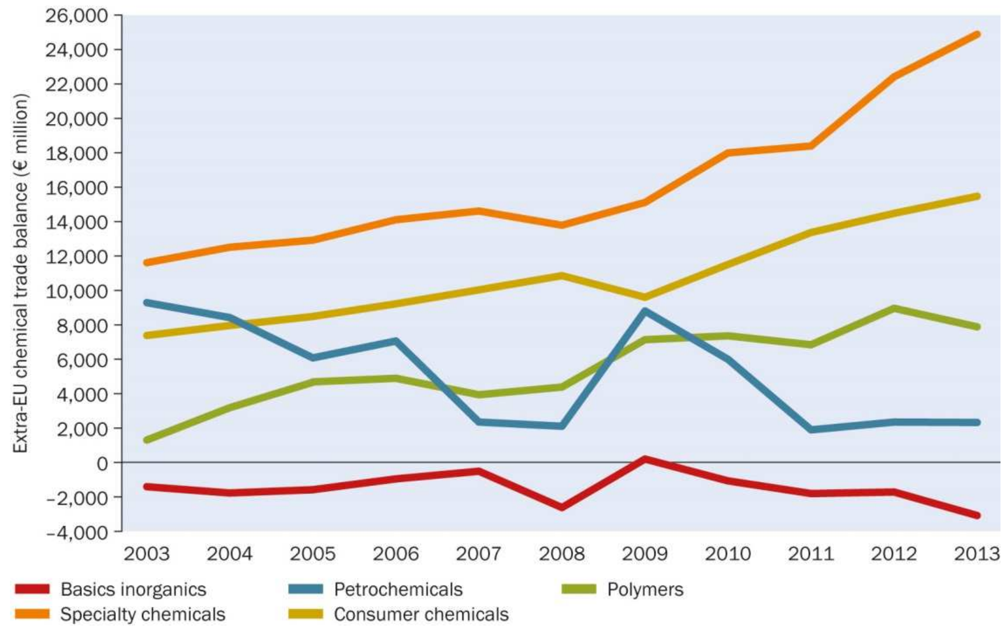
[1] *Rabobank, Een voorwaardelijke toekomst. De chemie in Nederland, 2014*
[2] *Source of the numbers and figures in this paragraph is Cefic, The European chemical industry, Facts & Figures 2013 and 2014*



Source: Cefic, The European chemical industry, Facts & Figures 2014

However, the European Union is still the largest trade region in the world for chemicals: import and export together accounted for 39% of global trade, still slightly more than Asia. It must be noted that this is inclusive intra-EU trade between countries. About two-thirds of total EU export of chemicals is intra-EU. This means that the internal EU market is most important for the competitiveness of the EU chemical industry. It also benefits though from growth in emerging industries, mainly in Asia and Latin America, and the EU is still a net-exporter with a trade surplus of €49 billion in 2013.

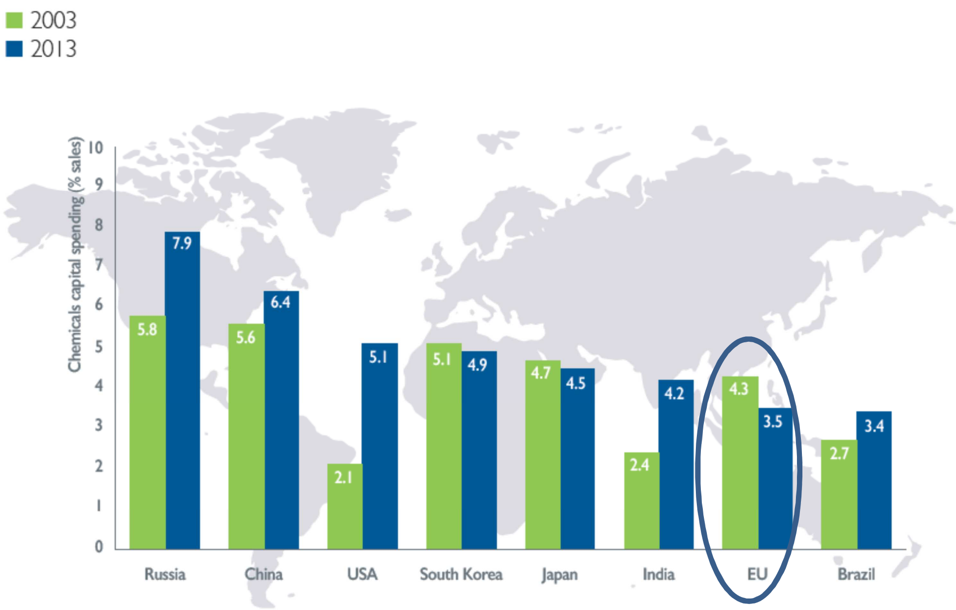
Unless these benefits from emerging industries, the Trade Competitiveness Index (TCI) is declining , which means that imports are growing faster than exports. This indicates a decreasing global competitiveness of the EU chemical industry. The contribution of petrochemicals has declined significantly, where specialties, consumer chemicals and polymers realize a growing contribution to the TCI of the EU chemical industry.



Higher value products contribute most to extra-EU chemical trade surplus
Source: Cefic, The European chemical industry, Facts & Figures 2014

Financial capability

Investments are an important factor to strengthen the competitive strength of an industry. On this point, the EU chemical industry lags behind on all other important chemical regions in the world. Although the EU realized investments of €18.6 billion in 2013, which is the highest after China (€67 billion) and the US (€24 billion), the spending intensity (capital spending as % of sales) is almost the lowest of all regions.



EU capital spending lags behind on other regions
Source: Cefic, The European chemical industry, Facts & Figures 2014

Knowledge and ability to innovate

Another important factor for the competitive strength of an industry is its knowledge position and its ability to turn this into innovation. On this point the EU chemical industry has a very strong position: it is known for its strong knowledge position. In absolute numbers, the EU chemical industry spends more on R&D than any other region, with €8.4 billion in 2013. When looking at spending intensity on R&D as a percentage of sales, the EU spent 1.6% in 2013, significantly less than Japan (4%) but close to the USA (1.7%). China has an R&D intensity that is less than half of the EU.

Concluding we can state that the EU chemical industry has a major disadvantage on its cost position. This is the main concern of the EU chemical industry at the moment, which was confirmed during the interviews (see text box below). Companies are therefore shifting their operations to low cost regions like Asia and take benefit of lower production costs. It profits from growing market demand in upcoming regions, but to a limited extent. It lags behind in investment levels. The strength of the EU chemical industry lies in its knowledge position and its ability to innovate.

Main concerns and challenges
TNO performed interviews with multiple European industry representatives, covering a wide range of segments including fine chemicals, specialties, pharma and commodities. We asked them what are currently the main concerns and challenges of their company. The following items were most prominent:

- High cost of energy, feedstock and labour in Europe, which deteriorates its competitiveness
- Doing the right investments, in the right place and in technologies that will pay back
- Gain a position in emerging markets: close to customers, by applying distributed production, preferably with limited capital expenditure
- Accelerate innovation
- Stringent regulation in EU

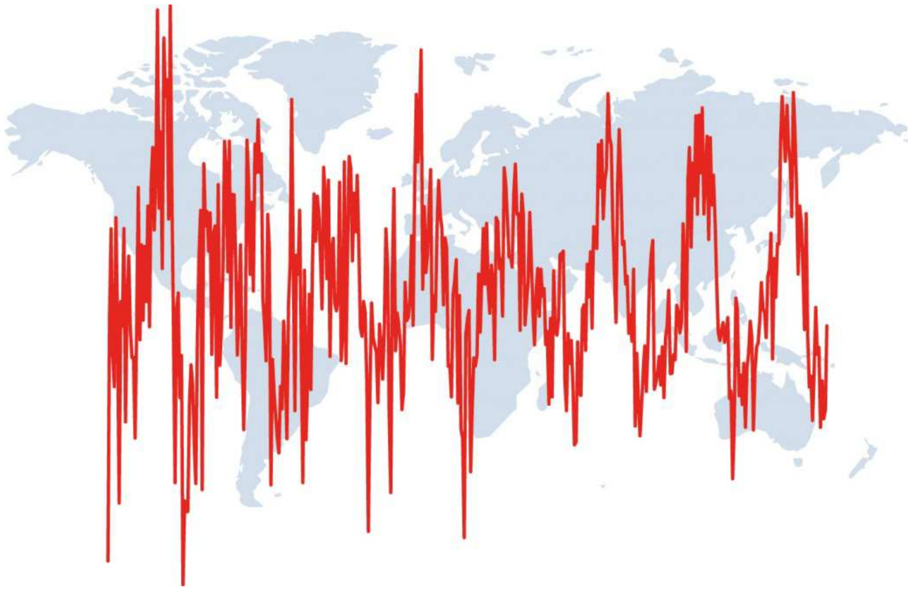
1.2 Directions for the future

In our vision the EU chemical industry should build upon its leading position in knowledge and innovation. This offers opportunities to strengthen the competitive position of the industry, not only by the innovations itself, but also by mitigating the disadvantages in other areas, e.g. by reducing costs through innovation. By utilizing this position, the EU chemical industry can stay ahead of its global competitors.

By further extending its position in specialties and fine chemicals, the EU chemical industry can mitigate its drawback on costs. In higher value products, the disadvantageous cost position on labour, energy and feedstock has lower impact than in commodities. The growing TCI of Europe for these products shows that this way is already set in. In general specialties and fine chemicals require a high level of knowledge since they are technically more complex. Innovation can ameliorate the value of these products further and makes the EU industry more attractive to invest in.

An important enabler to realize a future proof EU chemical industry lies in flexibility. A number of trends in the market have led to a growing need for instant reactions on changing market circumstances:

- Increasing volatility in demand
- High volatility in prices for feedstock and energy
- Shorter product life cycles
- Demand growth in emerging economies
- Mass customisation



Increasing volatility in a global market

Increasing volatility in demand
Demand patterns for the chemical industry have become increasingly volatile, especially for the higher value segments. This volatility is partly caused by fragile economic circumstances. Meanwhile, demand in emerging economies is still growing, and to be able to respond to this emerging demand often local presence is required.

High volatility in prices for feedstock and energy
Prices of feedstock and energy also have become increasingly volatile. The global nature of the world economy nowadays causes an interdependence between local economies[3]. It has also become more sensitive to local crises like the Arab spring and the financial and economic crisis from 2008. The price of oil more than halved during the second half of 2014.Meanwhile the European chemical industry has a

[3] See also http://www.atkearney.com/chemicals/ideas-insights/article/-/asset_publisher/LCcgOeS4t85g/content/chemical-industry-vision-2030-a-european-perspective/10192#sthash.p65YWQt2.dpuf

wish to get less dependent on oil supply from outside Europe and is looking at alternatives like bio-based feedstock.

Shorter product life cycles

Product life cycles have become shorter due to the velocity of innovation nowadays, rapidly changing and increasing customer requirements and intensified competition. This trend is mainly visible in end user products and high value products like fine chemicals and pharmaceuticals[4].

Demand growth in emerging economies

The chemical industry in emerging markets have realized impressive growth figures last years, especially in Asia and Latin America. Though there are challenges like falling oil prices and local overcapacity and economies are slowing down[5], they are still very attractive to invest in. Many industry representatives indicated during the interviews that they want to create a foothold in these regions.

Mass customisation

Customer demand is getting more and more personalized. Nice examples of mass customisation are Mymuesli (personalized muesli bars), MyTwinn (personalized dolls) and NIKEiD (personalized shoes), and a more traditional example are the paint mixing machines at Do-It-Yourself stores. While responding to highly differentiated demand patterns, mass production efficiency should be maintained. To maintain this efficiency often a fixed solution space for customers is defined, i.e. Mymuesli has a choice of 80 cereals that can be mixed.

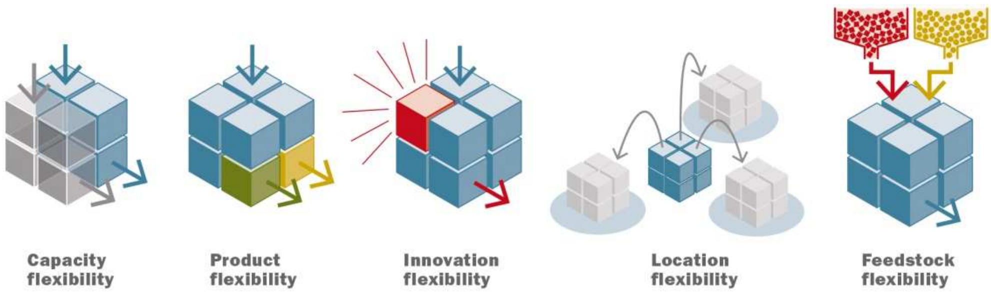
Flexibility is key for many aspects of doing business. It covers a wide range from internal organisational aspects and flexibility in the supply chain to flexibility in technology. In this report we will focus on small-scale flexible production.

[4] http://www.rolandberger.at/media/pdf/Roland_Berger_Studie_Chemicals_2030_20111117.pdf
[5] http://cen.acs.org/articles/93/i2/Chemical-Outlook-2015-Region.html#3

2 Flexible production meets the needs of the industry

The era of major new commodity chemical plants being built in Europe is over. The industry is increasingly looking for decentralized, flexible production capacity, especially for high value products. To meet the flexibility needs of the industry, an ideal plant would have the following properties:

- **Capacity flexibility**: a plant should be able to produce small volumes in a cost efficient way. When local demand grows or prices of feedstock or energy drop, it should be possible to scale the plant up or down easily.
- **Product flexibility**: a plant should be easily adaptable to switch to another product.
- **Innovation flexibility**: small-scale plants that are used in R&D and pilot setting should be very easily adaptable to try out innovative products and processes.
- **Location flexibility**: the plant should be moveable from one place to another.
- **Feedstock flexibility**: the plant should be able to handle different kinds of feedstock.

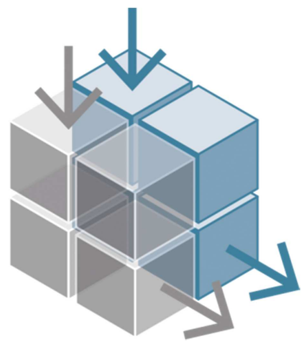


No plant exists yet that can meet all these criteria. In practice, the needs of the industry often have an emphasis on one or two types of flexibility. Also the technology is not far enough yet to combine different types of flexibility, and investments would be so high, that production would not be cost efficient. However significant steps in the right direction have been made and first implementations of the different kinds of flexibility have popped up in the market.

2.1 Flexibility types

Capacity flexibility

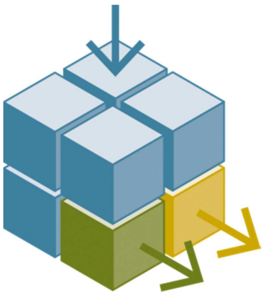
Besides using its existing large-scale centralized and highly efficient plants the industry can benefit from distributed, small-scale production. This enables companies to create a foothold closer to market demand, especially in emerging economies, without the financial risk of huge investments in large-scale plants. When local demand increases, such a plant can be scaled up to produce higher volumes. Small-scale



production offers the possibility to produce close to the customer, resulting in more customer intimacy and responsiveness and less transport costs. A small-scale plant can be implemented in relatively short time, especially when using modular technology. This will lead to a shorter time to market. Other benefits of small-scale production are smaller stocks and less use of working capital. Small-scale distributed and capacity flexible production may also be applied to reduce logistic costs.

Currently low capacity flexible production in some cases appears to be economically attractive already in specialties. For commodities it is generally not cost efficient yet, since economies of scale play a dominant role in commodities. However we expect it to become relevant for commodities also on longer term.

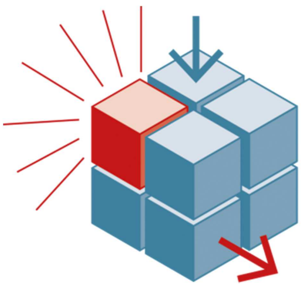
Product flexibility



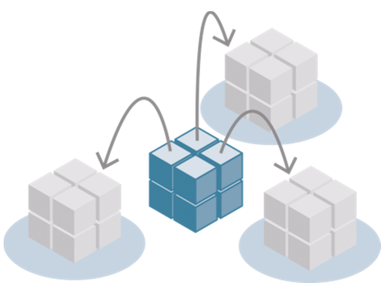
Product flexibility makes it possible to produce different products, or variations of a product, with the same equipment. This type of flexibility meets the need for greater responsiveness to customer needs and mass customisation. For example customers may need different quality plastics, that vary per week. Another trend that makes product flexibility relevant is the shortening of product life cycles. When demand for a product decreases because newer products replace it, a plant with product flexibility characteristics can be adapted to produce a new or adapted product relatively easy. This will shorten time to market significantly. Product flexibility is mainly interesting for higher value products, e.g. specialty plastics, food ingredients or lifestyle products. Also in pharma steps towards product flexibility are visible (see the example of Pfizer below). In commodities the competition is focused on cost and less on innovation. Product flexibility is less relevant in this market segment.

Innovation flexibility

This type of flexibility resembles product flexibility, but focusses on innovation and applies mostly in R&D and pilot setting. By making pilot plants very easily



adaptable, modifications to products or new products can be tried out rapidly. The same applies to process innovation. This will accelerate product and process innovation considerably and shorten time to market. Since this flexibility type explicitly builds on Europe's strength in knowledge and innovation, it is very important to the EU industry. Like product flexibility, it applies mostly in higher value products.



Location flexibility

Location flexibility makes a plant, or parts of the plant, moveable from one place to another. Also this kind of flexibility is already applied in a commercial environment in some cases. Transportable plants can be applied in the following situations:

- Local production close to customers. Production can be synchronized to local demand: when production is enough (to meet timely demand, or enough stock is created), the plant can be moved to another region or country. In this way not only a shorter time to market is realized, but also logistic costs can be minimized.
- Production of products that are seasonal. E.g. pesticides can be produced half a year in Europe, and the rest of the year somewhere in the southern hemisphere. This principle can also be applied for bio-mass (see feedstock flexibility).
- When it is preferable not to build the plant onsite, e.g. for safety reasons: a chemical site is a risk full environment to build on and special licenses are needed which is time costly. The elements of the plants can be built in a less vulnerable environment and only need to be assembled after transport.[6] In this way also implementation times can be reduced when building offsite.

Location flexibility is especially interesting for small-scale production, both in pharma and fine chemicals and will become viable for application in specialties within a few years. The concept is also applied for R&D purposes: a transportable pilot plant can be moved between different plants worldwide and accelerate product development locally. Building a transportable plant offsite is also interesting, and already being applied in commodities, for safety reasons.

[6] For an example, see http://www.uhdenora.com/skid_mounted_plants.asp and https://petrochem-projects.creatavist.com/petrochem-projects-2014

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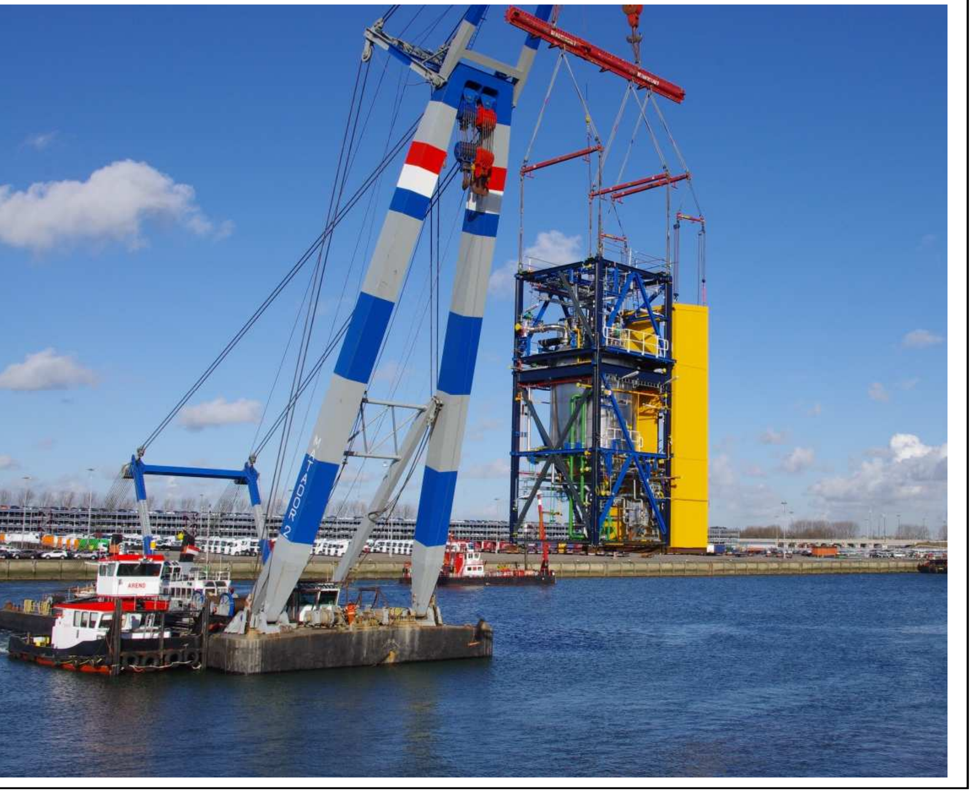
Off-site building by Tebodin

In 2014 Tebodin delivered a project for Huntsman Rotterdam that was built off-site in a modular way. The purpose was to minimize the necessary construction work at site and hence reduce the safety risks. Divided in 4 modules, all built outside the Huntsman site, the units were shipped, transported and safely placed within 48 hours. This meant that the time-top-production was drastically decreased.



Portable plants by Pfizer

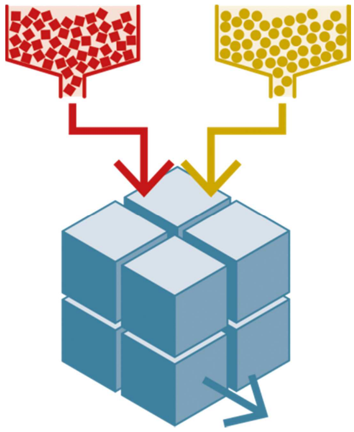
Pfizer, together with partners, developed a concept for Portable Continuous Miniature and Modular Manufacturing. In the concept, formulation is done in a moveable cleanroom that can be transported to customer sites. Active ingredients will still be produced in the US, to minimize technology transfer. The concept should result in a shorter time to market, more responsiveness to customer demand (6-8 months from order), operational flexibility (multiple products and scales) and lower upfront investments and operational costs.

Pfizer

Source: Presentation of Michael K. O’Brien, Ph.D. at ISBioTech Flexible Facilities & Systems, Rosslyn, Virginia March 14, 2013

Feedstock flexibility

Feedstock flexibility enables a plant to use different kinds of feedstock. In the following situations feedstock flexibility may apply:



- Switching from one feedstock to another in the process of formulation or production of end user products. This may apply when novel materials are brought to the market. Another driver is less dependency on specific feedstock suppliers. In case of e.g. a price raise or a feedstock shortage the plant can quickly switch to another feedstock without losing quality.
- Use of different, e.g. bio-based, feedstocks. Bio-mass forms an interesting alternative to traditional feedstock to create greener products. The use of different kinds of bio-mass next to each other can be applied in the future. Think of the conversion of e.g. glucose, wood, and straw.

Feedstock flexibility will often combine with location flexibility. Because it is not desirable to transport waste streams or bio-mass the plant should be located at the feedstock source. When streams are limited in size or seasonal a transportable plant can be located timely at one feedstock source, and after some time be moved to another source.

2.2 Business drivers for flexible plants

During the interviews we asked companies for their main drivers to implement small-scale flexible production. The main drivers that were named are the following:

- *Shorten time to market*
  Shortening the time to market is an important issue for many chemical companies. Many interviewees indicated this as a main driver to implement flexible plants.
- *Increase responsiveness to customer demand*
  Being able to react better and faster to customer wishes is also an important driver for flexible plants, especially to pharma and fine chemical companies. Product and innovation flexibility can play a role in developing new or adapted products. Capacity flexibility can also play a role here, to react better on volatility in volume demand. When combined with small-scale distributed production, it becomes possible to create a foothold closer to customers and increase customer intimacy.
- *Enable market entry and growth in emerging markets*
  Due to rising demand in emerging economies, many businesses want to entry those markets. Uncertain market circumstances however make it risky to make high investments here. Capacity flexibility makes it possible to create a foothold with limited CAPEX risk. Chemical companies can do a relatively small investment in a small-scale plant and scale up when market demand grows.
- *Risk reduction:*

- *Financial* risk reduction was named by a significant number of companies. They want to create a foothold in new markets, but at limited CAPEX risk. Small scale, capacity flexible plants are important to realise this.
- *Security of supply* is mainly important in pharma, where one cannot afford to run out of stock.
- *Reduce feedstock and energy dependency* is also a wish of a number of companies. Feedstock flexibility can play an important role on this point.

Besides these main drivers, some other drivers were named:

- *Cost reduction*
  The cost position of the EU compared to other regions was named as a main concern. Some interviewees see chances to reduce costs by implementing flexible production, mainly on logistics.
- *Cope with decentralisation of feedstock and energy*
  To handle decentralized feedstock and energy sources location flexible plants are important.
- *Production of hazardous materials on location*
  To avoid transport of hazardous products a small scale plant on e.g. customer location can be a solution.
- *Easy integration of technology*
  Flexibility is seen by some interviewees as an enabler to change to other systems quite easily, and to make installation and transport of equipment easier. Location flexibility is interesting in case of mergers/take-overs.

The table below gives an overview of the importance of the different types of flexibility to realise the main business drivers:

	Shorten time to market	Increased responsiveness	Market entry in emerging economies	Risk reduction
Capacity flexibility	Important	Important	Important	Important
Product flexibility	Important	Important	Not relevant	Important
Innovation flexibility	Important	Important	Not relevant	Relevant
Location flexibility	Relevant	Relevant	Relevant	Relevant
Feedstock flexibility	Not relevant	Not relevant	Not relevant	Important

Relevance of the different types of flexibility for the main business drivers

3 Technological developments enable flexible production

The implementation of flexibility into chemicals production is very much dependent on technology in order to adapt to uncertainty in future demand, the increase of volatility and the need for more flexibility in innovation and processing. Common technological challenges for achieving the different types of flexibility are how to break the economy of scale and drive down capital and operational costs for smaller production units and also how to increase operational value generation to make a sound business case for flexibility.

Multiple technical developments are ongoing, both in academia and industry, that can potentially address these challenges. The most promising developments are the following:

- Modularity
- Process intensification and continuous processing
- Equipment manufacturing technologies
- ICT and smart industry

They are described below and will for sure be seen more and more in practice, by themselves and in combinations. The table below gives an indication of the relevance of the technical developments for each type of flexibility.

	Modularity	Process Intensification & Continuous Processing	Equipment Manufacturing technologies	ICT & Smart Industry
Capacity flexibility	Relevant	Important	Relevant	Relevant
Product flexibility	Relevant	Not relevant	Relevant	Relevant
Innovation flexibility	Important	Relevant	Relevant	Not relevant
Location flexibility	Important	Relevant	Relevant	Important
Feedstock flexibility	Relevant	Not relevant	Relevant	Relevant

Relevance of technology developments for the different types of flexibility

3.1 Modularity

Modular design is an approach that subdivides processes into separate parts (modules) that can be independently created and then be connected either in parallel (to enable increase in capacity by numbering up) or in series to connect two process steps (such as reaction and separation). So numbering up or down the modules guarantees short development and response times with regards to flexibility in capacity. On top of that the modules can be connected in a skid or container which would give the opportunity to move the process to another location thus providing geographical flexibility.

Making modules by simply scaling down unit operations from full-sized plants will in most cases not work as these unit operations will become relatively expensive due to the disadvantageous economy of scale. To compensate this the modular unit operations need to be far more efficient in for instance space-time-yield and/or selectivity. During the last decade a breakthrough was attained on continuous flow reactors. Examples are micro reactors, tubular reactors, plate reactors and stirred tank reactors in series. Many of these flow reactors can be supplied in the form of modules or stacks which allow for fast numbering up and down approaches to attain fine-tuning of the production capacity.

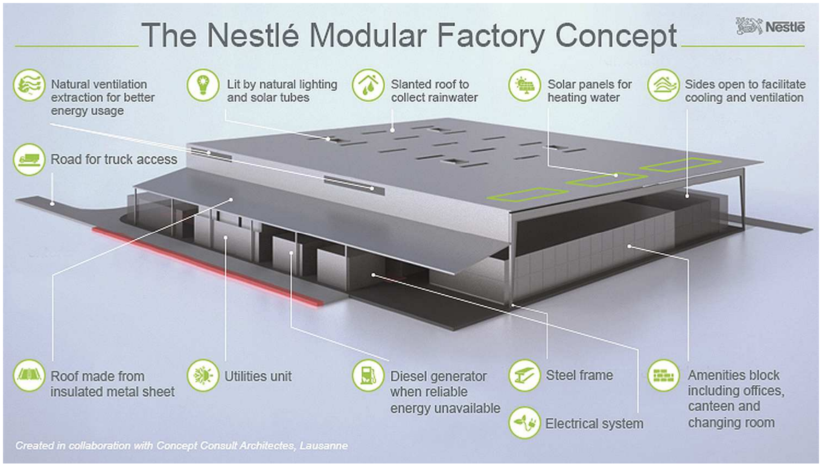
The principle of designing and manufacturing modules is not new. There are inspiring examples of plants that were designed as turn-key modules or skids, which are assembled at the site of the equipment manufacturer, transported to the site of the client where they are connected and integrated in the plant infrastructure. In flexible, decentralised production the concept of modularity is expanded in the sense that not only the plant consists of modules (skids), but the skids itself also contain modular equipment/components and in some cases even the components are modular with multiple structures, tubes or channels that can be put in parallel or in series.

Multiple examples on modular processing are already seen in the market ranging from R&D activities by the European F3 Factory consortium, through commercial implementation of modular factory concepts by Nestlé (see text boxes below). We expect that this is only the beginning of a movement towards the widespread use of modularity in many sub-segments of the processing industry.

Modular factory concept by Nestlé

A simple but nice example of modularity has been elaborated by Nestlé. The company has created a blueprint for a flexible modular factory, that can be built in half the time (<12 months) of a traditional factory, and at 50-60% of the cost. It enables Nestlé to rapidly create a foothold in countries in Africa and Asia, getting closer to their customers and raw material sources.

The factory is made of ready-to-use elements, that can be assembled on site. If needed, the factory can be moved or expanded. The factory will fulfill relatively simple processes like mixing dry goods, e.g. Maggi bouillon cubes.



Nestlé

Source: http://www.nestle.com/media/newsandfeatures/modular-factories

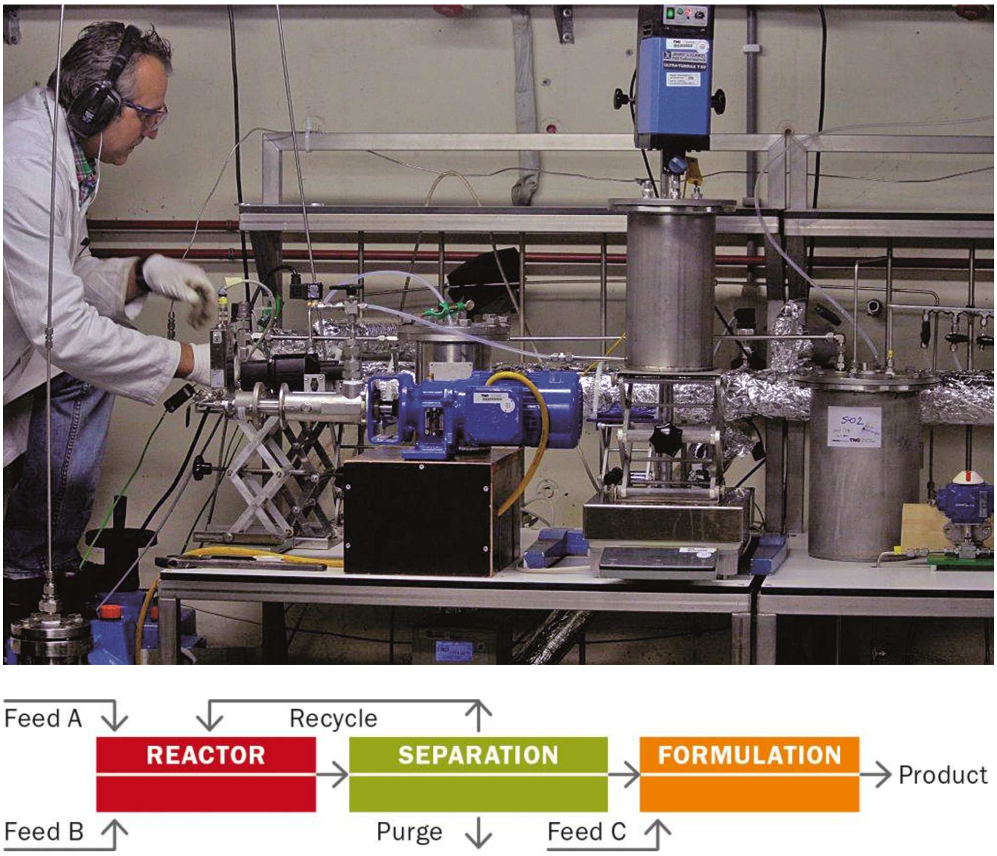
F3 Factory project
In the F3 Factory project a standardized, modular, continuous demonstrator plant in a container has been developed. It is based on "plug and produce" modular chemical production technology to deliver new manufacturing concepts that can significantly decrease process development time through the standardisation, modularisation and application of novel process intensification technologies.
The building blocks in F³ Factory are called Process Equipment Assemblies (PEAs). They include intensified continuous chemical reactors, downstream equipment, storage units, pumps or combinations of these components and can be easily installed, connected or removed. PEAs can fulfill tasks like feed, reaction, separation or purification.

Bayer's Process Equipment Container Unit installed at INVITE
Source: http://www.f3factory.com

3.2 Process intensification and continuous processing

Process intensification is an approach in chemical engineering that can be described as 'a strategy for making dramatic reductions in the size of a chemical plant to achieve a given production objective' (Ramshaw, 1995). This approach is enabled in the last decades by enormous scientific and technological advances in reactor engineering, separation technology and inline process analysis and control, combined with systems engineering approaches towards chemical plant design. When employed correctly, process intensification and continuous processing offer a huge increase in productivity at much lower operational and capital costs and a much smaller plant footprint compared to employing traditional methods and technologies. In addition the intensified process can be easier run under novel/extreme operating conditions such as high p and/or T to further enhance the productivity rate and/or to change the yield and product purity. Process Intensification and continuous processing address a number of the key requirements for flexible production.

Whereas the conventional production of fine and specialty chemicals is done in batch, flexible production requires continuous processing. The modular flow reactors introduced in the previous section have in common that they are all operated in continuous mode and lead to a much better and more controlled heat and mass transfer. There are plenty of examples that this approach indeed boosts efficiency with improvements of the volumetric capacity with a factor of 10-1000 compared to the reference, which is often a batch stirred tank reactor. This means for instance that process steps that in the references took hours are reduced to minutes or in extreme cases even seconds. Important side effects of fast and better controlled reactions are that the product quality increases and that less unwanted by-products and waste is produced, whereas the recycling of materials and energy integration and optimisation in the process is much easier and more effective in continuous processes. These last effects contribute to decreasing the operational costs, which is a crucial point for compensation of the worse economy of scale for small, decentralized production.



Photograph of a continuous flow chemistry research installation in the CoRIAC project and a schematic representation of full continuous processing

Despite of these impressive improvements of the efficiency that are possible after the introduction of continuous, intensified processes it has not fully matured in the fine and specialty chemical segments yet due to the higher (perceived) cost of capital, the technological uncertainties and lack of knowledge concerning application in those segments. The next section will give examples of modern manufacturing technologies that can help to reduce the costs of modular process equipment.

It must be noted that batch processing has created an image of being extremely flexible. In reality the flexibility of the batch reactor is often based on accepting that it is used outside the optimal operating window with suboptimal control of function like mixing or heat exchange. In addition continuous processes operate in or around steady state. This opens the opportunity for automation and remote controlled plants with a minimum of operators. Nevertheless the implementation of continuous intensified processes in chemical industry still seems to be in the early adopter phase, which is evidenced by a slowly but steadily growing amount of showcases of continuous processes replacing the traditional batch processing, e.g. in pharmaceuticals and specialty plastics production.

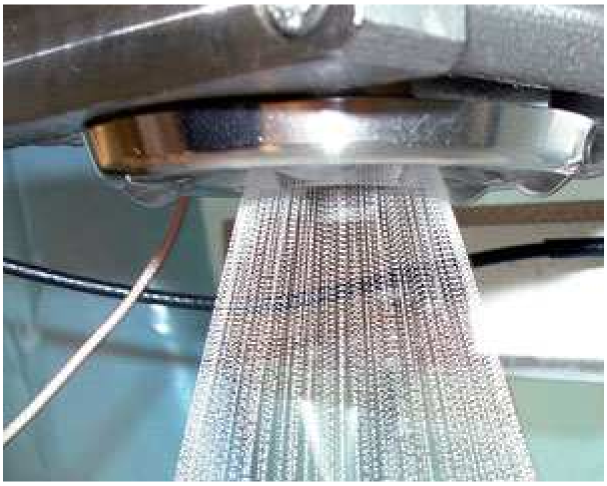
Most processes are not ready after the reaction or conversion step. The stream leaving the reactor does in most cases not meet the requirements of the end product as it may still contain impurities introduced via the raw materials, process aids like solvents or catalysts, unreacted raw materials or side products. So, in many cases one or more separation steps will be needed to remove these components and bring the product to the quality or specification needed for the application. It makes no sense if only the reactor is continuous or modular; also the separation and purification steps need to become modular. In some cases the process will also contain a formulation step in which the chemical product is brought in the form that is needed in the formulated end product such as powders or concentrated solutions for products like detergents or agrochemicals or tablets and stable suspensions for pharmaceuticals. Development status and track record for modular separation and formulation are at the moment far less developed than for modular reactors. The further development of separation and formulation modules is an important target and stepping stone to pave the path towards modular production.

Important wishes and demands for separation technologies in decentralised, flexible production based on Flow Chemistry principles are that they are:

- Modular by principle (e.g. membranes) or by strong intensification (e.g. HiGee),
- Highly selective also for complex mixtures to reduce the number of separation steps,
- Mild separations (e.g. based on molecular affinity) to minimize energy consumption.

Example of modular separation technologies: modular membrane extraction (pertraction) process for waste water treatment implemented by TNO at Invisita, the Netherlands

It is envisioned that the development of efficient modular separation and formulation technologies can get a kick start by borrowing technologies originally developed for other markets or applications than modular flexible processing. The figure above shows a membrane process for waste water treatment and a tubular crystallizer used in the (bulk) petrochemical industry as examples of modular separation processes that can be adapted to be introduced in flexible decentralized plants. The figure below shows an example of a modular formulation technology which started by exploring the potential of 3D printing in food industry but which may create a fast path for the production of monodisperse particles in chemical products like pharmaceuticals, detergents or catalysts.



multi-nozzle monodisperse printing

3.3 Equipment manufacturing technologies

The previous section postulated and illustrated that it is not difficult to find examples with impressively high volumetric productivities in continuous flow chemistry processes. However, this will only contribute to building a positive business case when the advantages of the small intensified equipment is accompanied by a cost benefit compared to the reference, which is often the batch reactor/process. So the challenge or hurdle is whether we can decrease the (investment) costs of equipment for intensified continuous production. The potential game changer on this point is the use of novel inexpensive mass production technologies. These technologies should be able to produce complex parts that can resist process environmental conditions, are relatively easy and low-cost to make and that can be changed easily in geometry.

A first example of a suitable breakthrough production technology is 3-D printing, officially known as additive manufacturing. 3D printing is “the process of joining materials to make objects from 3-D model data, usually layer upon layer”[7]. It is said that the technology has the potential to become the biggest single disruptive phenomenon to impact global industry since mass production lines were introduced. The freedom to create forms that were not possible with other production methods, and the fact that an idea can go directly from a design file to a product, creates

[7] ASTM International (2012). ASTM F2792-10.

possibilities for application in the chemical industry. The flexibility of the technology enables the creation of different shapes rapidly and inexpensively.

Example of a 3D printed metal part

Another interesting breakthrough manufacturing technology is injection moulding and extrusion of ceramics. The ceramic parts can be assembled to create almost inert reactors that can withstand high p and/or T or in membrane modules for modular separations like dewatering, microfiltration or ultrafiltration. The current use of ceramic membranes for micro-, ultra-filtration or pervaporation in industry illustrates the potential, but it is important to note that the operating window is often not determined by the ceramic membranes themselves but by the gaskets and the potting, which in many cases determine the inertness and maximum operating temperature and pressure of the module. So, these limits could be widened if the joints can be made in such a way that the use of materials with a low temperature, pressure or chemical resistance can be avoided.

The fact that gaskets and pottings are often limiting the operating window and/or the inertness towards chemicals is not restricted to ceramic modules but also to polymeric modules. Also here promising developments are arising by avoiding gaskets or special pottings (typically using an industrial glue or resin) by direct welding of polymeric components.

3-D printing and injection moulding or extrusion have been introduced successfully for polymers and later also for ceramics and metals. For metals (hydro)forming and embossing could be alternative manufacturing technologies to create easily replicable and cost efficient metal parts for reactors or separators.

Most reactors are suited for liquid reactions. If the reaction is multi-phase like gas-liquid, solid-liquid or gas-liquid-solid the number of suitable reactors drops readily. In most cases the basic hurdle is that the reactors were not designed for multi-phase reactions or they are intrinsically not-suitable. For instance, solids in processes have a size which is equal or even bigger than the size of the channels in most micro-reactors. There is a need to re-design or re-invent reactor concepts to make them suited for multi-phase processes as most reactions in fine and speciality chemicals will involve multiple phases.

Next to the innovations in manufacturing or production technologies the adoption of a new design philosophy could help to further decrease the investment costs of modular, flexible plants. The leading principle behind this could be to try to reduce the costs of the modular process equipment by making use of the shorter life cycles of higher added value products. It is interesting to explore whether modules/components will become cheaper if they will be designed and manufactured for a much shorter life time than we currently apply for the equipment in large single purpose chemical plants. The extreme case would be the use of single use modules/components. That this idea is maybe already closer than a first glance would disclose could be found in the increasing use of single use bags in fermenters (biological reactors) for red biotechnology in the production of pharmaceuticals. On top of the potentially lower production and manufacturing costs of single use modules/components can be further enhanced by a strong reduction of the cleaning and costs and time which would also contribute to improve the product flexibility.

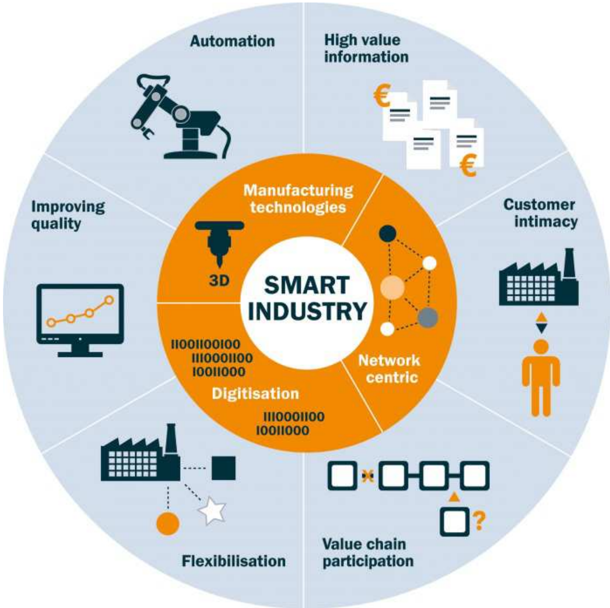
Single-use reactor bags in biotechnology (Sartorius Stedim Biotech S.A.)

3.4 ICT and smart industry

Smart industry, also called Industry 4.0 or Internet-of-Things, integrates ICT and internet into production. As information technologies progress, production plants will for sure be made more intelligent, more efficient and more flexible. The batch to continuous transition described before does not only require development of hardware, but also of software. There is a need for predictive and holistic process models for monitoring and control of continuous, remote controlled plants. The models are crucial for safety of operation as well as for intrinsic control of the product quality which is monitored by the sensors and in-line process analytical tools.

By integrating sensors and ICT in flexible production more insight in the condition of assets is gained and this information can be used to implement condition based maintenance, preventing downtime, increasing safety and making maintenance more efficient. All these aspects contribute to increasing the robustness and the productivity, whilst decreasing maintenance costs.

ICT can also create shorter response times in the value chain. By automated monitoring and communication across the value chain responses on changes the value chain, like increases in demand, changes in customer needs, or volatility of feedstock and energy prices, will become faster and dedicated. This will for instance pay off in the reduction of the amount of products that are kept in stock.



Visualisation of the concept of 'smart industry'

Last but not least, ICT/Smart Industry creates the opportunity to design and operate remote controlled plants. As precursor the automation of maintenance and management of plants is already taking place. Remote controlled/operated plants will strongly reduce the amount of personnel on location which will strongly reduce the operational costs of small, flexible production plants. The ongoing development of advanced sensors and Process Analytical Tools is essential to reach the ultimate end-point of remote controlled plants. This development is supported by the booming use of Big Data, which means that the possibilities to handle and analyse incredible amounts of data fast and reliably are expanding rapidly. This will mean that monitoring and controlling a decentralised plant by the data from a large amount of sensors is or will become in reach. Secondly, smart analysis and interpretation of data opens the opportunity for soft sensors and/or chemometrics, which are both examples of possibilities to collect information on parameters that are not directly measured but can be deduced or derived from information embedded in large data sets.

4 Business models should support the benefits of flexibility

The concept of flexible modular plants will impact the way in which the industry does business. This does not only concern the technology but even more the business model of companies. Business models should support the envisaged benefits. Nowadays most business models in the chemical industry are driven by cost efficiency and large-scale production. For high value products new business models are emerging, that put more emphasis on value than on costs. To support the business benefits of small-scale flexible plants, a further adaptation of business models should take place.

To describe the way business models will be affected the Business Model Canvas is a good tool. The Business Model Canvas method is developed by Alex Osterwalder[8] and describes a business model by nine basic building blocks. Osterwalder defines a business model as follows:

"A business model describes the rationale of how an organisation creates, delivers and captures value."

Below we will describe the way in which each element of the business model will be *impacted* by the introduction of small-scale flexible production. The highlights are shown in the picture below:

Changes in business models due to flexible production mapped on the business model canvas.

Customer Segments: downstream integration and production closer to customers

This field forms the start of every business model. It describes who are the main customers that an organisation creates value for.

[8] Alex Osterwalder, "Business Model Generation", 2010

Customers will be impacted by flexible production in the following way:

One of the drivers for distributed production is the wish to produce closer to customers, e.g. in emerging markets. This illustrates how small-scale flexible production can create a possibility to reach new customers. In the meantime the ability to produce near the customers will result in more customer intimacy and greater responsiveness to customer demand for existing customers. For chemical companies this creates a possibility for downstream integration in the value chain. The ultimate form of customer responsiveness is mass customisation, where the chemical company produces products (in most cases in cooperation with partners) for individual end customers, tailored to his wishes.

Especially product flexibility supports this trend towards a more demand driven production by making it easier and less expensive to adapt the product. Also location flexibility is important: it enables timely production on a certain customer location.

Value Propositions: Better tailored to customer needs and accelerated product innovation

The center of the business model is the value proposition. It describes the value that is delivered to the customer segments. The value proposition should respond to the customer's needs, and/or alleviate his pains.

As described above, small-scale flexible production makes it possible to better respond to changing demand of customers, with a shorter time to market. This will lead to higher value products and increase the pace of product innovation. In the case of mass customisation the product will be tailored to the individual needs of the end user.

Flexibility in the production process and location enables a transition from selling products towards offering services: the user pays for a service like cleaning pipes, treating water, etc. instead of buying the chemicals to fulfill these tasks. In the case of selling products the producer wants to sell as much as possible of the product, while the client wants to decrease the use of the product. By selling services, also called chemical leasing, a common interest is created, resulting in less waste and economic benefits for both. The ability to tailor te product to the specific customer's needs is an important requirement to realize this.

A new value proposition that is specifically enabled by the concept of location flexibility and small-scale production, is a small-scale plant at the customer site. The plant can be remotely managed by chemical company.

Feedstock flexibility enables the use of renewable sources, which leads to more durable products. For many customers nowadays this is a value in itself.

Customer Relationship: more customer intimacy

This field describes how the relation with the customer is established and maintained. This may vary from a dedicated personal relation to an automated service.

To utilize the benefits of flexibility greater responsiveness to customer demand will be realized. So flexible production will in most cases come together with more customer intimacy. Insight in changing customer needs should be brought directly into the product innovation process. In case of downstream integration producers may get a direct relation with end customers, especially in case of mass customisation.

Channels: distributed production can reduce logistic costs

This field describes which channels are used to reach the customer segments. These channels may differ for the different channel phases: awareness, evaluation, purchase, delivery and after sales.

Distributed production is seen as an important manner to reach customers in emerging economies. When producing closer to the customer, less transport will be needed. In the special case of production on customer location no transport is needed at all. Distributed production, combined with capacity flexibility and sometimes also with location flexibility, may thus reduce logistic costs drastically[9].

Revenue streams: higher value will result in higher margins

This field describes the revenue streams that are generated.

Product flexibility will lead to greater responsiveness to customer needs and thus higher value for the customer. This will lead to higher margins. Combined with small-scale production a transition will be visible from large-scale, low margin production to smaller scale production with higher value and higher margins.

In case of chemical leasing the revenue model will not be based on a price per unit of product (i.e. kg), but on a reward for the service delivered.

Product, volume and location flexibility will allow companies to adapt quickly to market demand. To optimize revenue streams a new management strategy, optimizing production based on local market demand will be needed.

The impact of flexible plants on revenues will be elaborated further in the next chapter.

Key resources: plants will get flexible

This building block describes what resources are required for the value propositions, the distribution channels, etc. Examples are FTEs, knowledge and intellectual property, machinery, feestock, etc.

Actually the flexible plant is a resource itself. But implementation of the concept will also impact other resources:

Higher educated personnel is needed to implement innovations and utilize flexibility to maximize profit. Knowledge on the concept and the possibilities it offers is key. Not only technical knowledge, but also economic and logistic knowledge is needed. Knowledge is a very important asset for chemical companies. To protect knowledge, some companies that are implementing the concept of flexibility just do

[9] This was one of the results of the “Economy of Chain” ISPT project. For more information see http://www.ispt.eu/economy-chain-factories-containers/

formulation distributed and keep the rest of the production process in their home country.

Supporting management and information systems will be needed to optimize the process from translating customer demand into production and logistics planning. Especially in pharma ensuring reliability of supply over time should be ensured and supported by planning systems.

Key activities: not only production will be impacted

This field denominates the activities that are required to create the value proposition and run the business model. Think of production, management of IT systems, etc.

Of course production will get impacted when it becomes flexible. But also activities and processes around it will be impacted and should get more flexible.

Flexible plants will get more automated and sometimes be managed remotely, which means less operators are needed.

To bring flexible production into practice market intelligence will get of major importance. The same applies to production planning and logistics. Cooperation throughout the value chain will get more important to cope with volatility together and to align the whole process from feedstock delivery to delivery to end users.

When production gets distributed compliance to local regulation will get an issue. The chemical industry experiences regulation as a burden already. The innovative nature of flexible production will make this burden be felt even more.

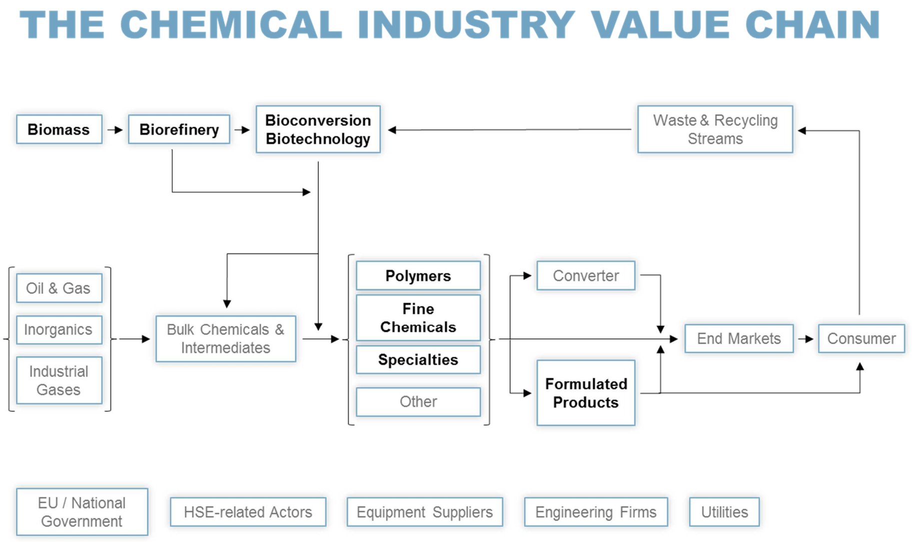
The internal culture and processes of companies should support the flexible nature of production. A working culture is required that easily adapts to change. Unnecessary complexity in internal processes should be removed, making it possible for management to respond quickly to changing market circumstances.

To reduce CAPEX risks, new business models like BOOM (Build-Own-Operate-Maintain) may be applied.

Key partnerships: closer cooperation throughout the value chain is needed

This field describes what partners are essential to offer the value proposition to the envisaged customer segments.

In the picture below the chemical industry value chain is presented. Not only the companies that are involved in production are relevant, but also governments (regulation, policy), equipment suppliers and engineering firms are involved.



The concept of small-scale flexible production is mainly relevant for fine chemicals, specialties, polymers and formulation. In longer term it will also be applied in bulk chemicals and intermediates. It will however have impact on the whole value chain and the cooperation between partners:

- Distributed production will bring chemical companies closer to their customers. These may be formulation or conversion companies, but also end markets and in some cases end users (this may apply for mass customisation). Also more responsiveness to customer demand is created by the concept of product flexibility, that will accelerate the product innovation process. This will require closer cooperation with end markets, or result in downstream integration.
- Also on the supply side of the value chain tighter integration is desirable. Suppliers should react fast to changing demand of chemical companies, due to changes in demand of end users, or due to changes in feedstock and energy prices. Distributed production may lead to integration of local partners into the value chain. Also in case of bio-based production new partnerships will emerge e.g. between the suppliers of bio-mass and the producers of bio-chemicals. New business models like BOOM (Build-Own-Operate-Maintain) may be applied to reduce CAPEX risks.
- Equipment suppliers and engineering firms will play an important role to implement the technical concept of flexibility. They should be involved more in the development of solutions and standards than they are now.

Cost structure: CAPEX risk reduction and OPEX reduction

In this last elements the most important costs to realise the value proposition are handled. They are mainly based on the key resources and key activities. Some costs will be fixed (like initial investments) and other variable.

The impact on costs will be elaborated in the next chapter.

5 Sound business cases are a challenge, but within reach

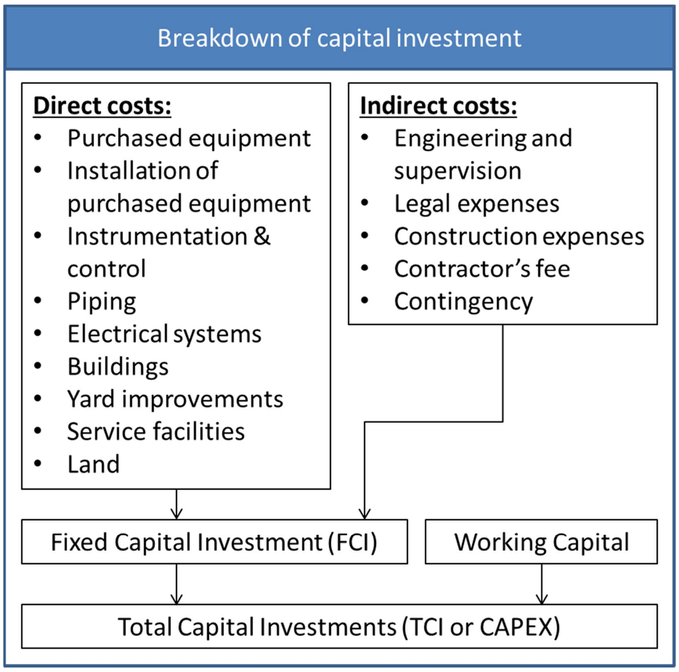
The shift towards more flexible production concepts offers opportunities to strengthen the competitive position of the chemical industry in Europe. However, for this to become reality, a sound business case needs to be realised.

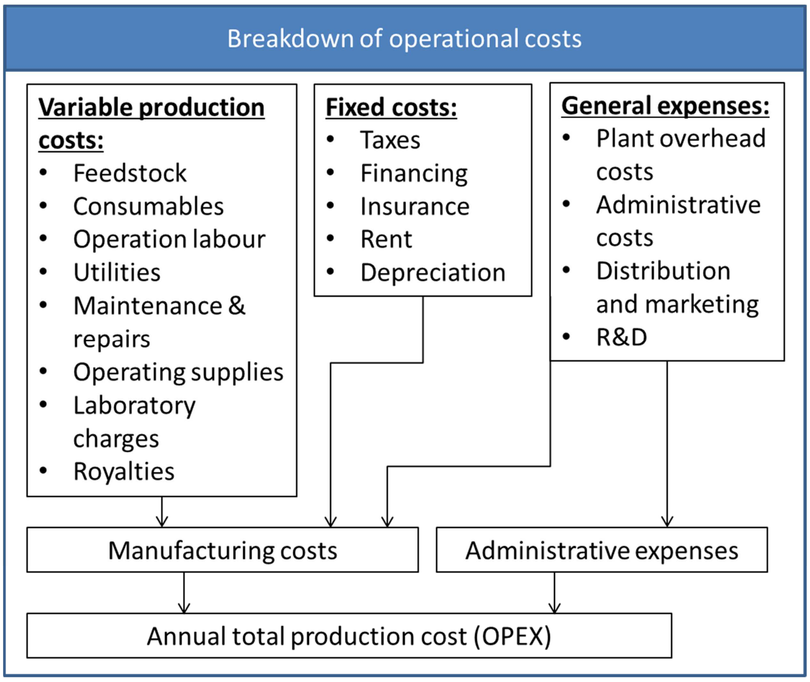
This is a challenge, since the economies of scale will favour one larger-scale dedicated plant compared to multiple small-scale flexible units. On the other hand, large-scale, dedicated plants are often not flexible enough to allow chemical companies to react to market changes (e.g. demand levels, price volatility), developments in resource availability and innovation at the desired speed. In the meantime, the first commercially and financially successful examples of small-scale flexible production have already been implemented. In this paragraph we will look at possible ways to realise a sound business case.

The opportunity to reduce capital costs per unit of product by increasing capacity has fuelled the Chemical Industry's tendency towards building large-scale installations. Economies of scale can affect cost levels both at unit operation and plant level, therefore making flexible production modules by simply scaling down unit operations from full-sized plants will in most cases not work.

As expected, the absolute contribution of the capital cost components for a given process varies depending on the capacity level. Besides that, the scaling factors can differ for each cost component and can also depend on capacity level. This means that the relative contribution, and thus importance, of the different cost components of the capital investments is subject to change for different capacity levels. For example, in most processes purchased equipment[10] and piping make up the largest part of the direct costs of the capital investment for a new plant. However, it has been observed that, when scaling down the capacity of a plant, the relative contribution of certain cost aspects, such as instrumentation, can increase, making them increasingly important.

[10] Purchased equipment refers to the main equipment units of a process, namely: (1) processing equipment, (2) raw material handling and storage equipment and (3) finished-products handling and storage equipment. [Source: Plant Design and Economics for Chemical Engineers, M.S. Peters, K.D. Timmerhaus & R.E. West (2004)]





Source: Plan Design and Economics for Chemical Engineers, Peters, Timmerhaus, West (2004)

This brings us to one of the main challenges around the implementation of smaller-scale flexible production concepts: how do we tackle the negative effects of economies of scale?

One part of the answer can be found in lowering capital investment and operational costs by rethinking the way a chemical plant is set up. The other part lies in leveraging the benefits of flexibility by increasing revenues and reducing costs and investment risks in a way that they can outweigh the increased investment costs per unit of product.

By combining the chances for reducing the cost of flexible plants and the opportunities for increased revenues and margins, positive business cases for flexible production will become within reach in many cases and will result in increased return on investment.

5.1 Lowering CAPEX and OPEX by rethinking plant setup

Up until now, plants have generally been built with a lifetime of 20-30 years in mind. Therefore, both the process design principles and the financial and decision making models assessing existing and future investments are geared towards longer evaluation periods. Anticipating on the volatility in the chemicals market, flexible plants should be designed and, therefore, evaluated based on shorter lifetime periods. This calls for a new way of thinking in terms of process design and equipment manufacturing technologies, as well as financial and decision making models that can ensure profitability.

In this report a number of technological developments were discussed, that will have significant impact on CAPEX and OPEX, besides their benefits for e.g. product quality and time to market. They can contribute significantly to overcome economies of scale drawbacks of small-scale flexible production. In the table below their impact on CAPEX and OPEX is presented and elaborated in the text below it.

Techology	Impact on CAPEX	Impact on OPEX
Modularisation and Standardisation	– Price reduction of standard elements, when produced in larger volumes/quantities. – Easier installation and integration of elements. – Reuse of elements. – Offsite production of plants will reduce implementation times.	– Reduced maintenance and repair costs; part of the plant can continue production during maintenance.
Process intensification an continuous processing	– Reduction of footprint.	– More efficient production: reduction of costs for raw materials, energy and waste. – Enables further automation of processing.
Equipment manufacturing technologies	– Lower cost for equipment, especially for small-scale production. – Low cost rapid prototyping.	–
ICT and Smart industry	– Less spare parts and product in stock due to sensor/in formation based maintenance and production planning	– Less labour cost due to remote controlled plants. – More robustness and efficiency of production will reduce costs. – Condition based maintenance will prevent downtime and reduce maintenance costs.

Modularisation and Standardisation
Achieving a high-level of standardisation in the design and construction phase of plants can lower overall capital investment and accelerate the implementation of smaller-scale, flexible production of chemicals. Standardisation can reduce equipment cost due to economies of scale during equipment manufacturing and allow easier integration and re-purposing of unit operations. Overall, this can lead to reduced project time during construction, more efficient use of assets and, finally,

lower capital investment, making smaller-scale, distributed production or step-wise capacity expansions more attractive.

Modular production concepts are generally seen as a costly alternative to the traditional plant construction approach. Such modules can refer to one functional unit that contains an entire plant or process unit (skid) or modular equipment components (e.g. reactor or separation units). Despite the higher costs of the modules, the related cost benefits can often outweigh them, making them an attractive solution.

Modules at plant and process unit level are generally fabricated off-site and can be delivered as one functional unit. This enables simpler and more efficient installation of the purchased equipment and can expedite project delivery, yielding cost benefits during the construction phase of a plant. Such benefits are very important when considering scaling up or expanding an existing process in a step-wise manner. In addition, modular production lines have the potential to reduce cost for maintenance and repairs (calculated as hours lost), since production can still continue for part of the modules (as opposed to a complete shut-down).

Process intensification an continuous processing
Process intensification can reduce the size of a chemical plant dramatically. Reduction of the footprint of a plant will lead to lower CAPEX needs for e.g. location and plant building. Equipment manufacturing technologies will drive down cost for equipment. Continuous processing will lead to lower OPEX by realising more efficient production through reuse of materials, reduction of energy use and lower formation of waste. It also enables further automation of processing, because they operate in or around steady state.

Equipment manufacturing technologies
Innovative equipment manufacturing techniques like 3-D printing enable the production of complex equipment components at low cost. They will reduce the negative effects of economies of scale at lower capacity levels. In R&D setting they can be applied for low cost rapid prototyping.

ICT and Smart industry
Employing higher levels of automation within chemical production plants can significantly reduce OPEX. Remote-control systems reduce the need for (often highly skilled) personnel at every production location. Especially in the case of distributed small-scale production it can offset the negative effects of economies of scale. A good example of such a case is that of AkzoNobel[11] where small-scale chlorine production units are operated on the end-user's site from a central unit using remote-control systems.

By implementing sensors and making production more intelligent, more insight in production and the condition of assets will result in more efficient and robust production. Sensor information can be used for condition based maintenance, which will prevent downtime and reduce maintenance cost, because problems will be reported at an earlier stage. It may also reduce the need for e.g. spare parts. When ICT is implemented across the value chain, supply chain management will enable better and faster reaction on changes in demand. This will reduce the need for high levels of product stock.

[11] [11] https://www.akzonobel.com/ic/products/remote_controlled_chlorine_production/

5.2 Leveraging the benefits of small-scale flexible production

The benefits of small-scale flexible production will directly impact the competitive position of chemical companies and give them strategic advantages. They will have positive effects on revenues, but can also reduce CAPEX and OPEX in some cases. Overall, combining flexible production concepts with strategic production planning and advanced logistics can help realize the benefits of flexibility and eventually lead to improved profitability. In the table below the main benefits of flexible production, named by the interviewees, are presented. For each benefit, its impact on revenues and costs are described.

Benefit	Impact on revenues	Impact on costs
Shorten time to market	– Offers opportunities to capture market share before the competitor does. Higher margins on innovative products.	– Shorter implementation times in general reduce CAPEX and OPEX needs for projects.
Increased responsiveness to customer demand	– Will lead to more loyal customers, that are prepare to pay a higher price, and less churn. – A better image will result in more market share. – Easy upscaling of capacity when customer demand increases.	– When adapting production volumes to actual demand more quickly, lower stock is needed.
Market entry in emerging economies	– More revenues by broadening market reach.	– Distributed production, close to customers, offers opportunities to reduce logistic costs.
Risk reduction	– Low CAPEX, small-scale production offers opportunities to create a foothold in markets where otherwise investments would be too high. – Security of supply will ensure revenues and reduce customer churn.	– Lower CAPEX risks in uncertain market conditions. E.g. by stepwise capacity expansion when demand increases (see graph). – Reduced feedstock and energy dependence will lower the risk of price increases.

Shorten time to market
Flexibility in implementing new production technologies or adjusting existing facilities to a new process will contribute to shorter time-to-market and a stronger competitive position. This will result in higher revenues in two ways:

- It will offer a company the opportunity to capture market share before the competitor does. Revenues will take off earlier and will be higher due to a larger customer base.
- In general margins on innovative products are higher, especially when competitors have not brought their alternatives to the market yet. When the innovation has a high added value for potential customers, readiness to pay will be high.

Implementation times may be reduced by applying flexibility concepts significantly. This was proven in the Capstone project, where Tebodin built a plant for Huntsman offsite[12]. In many cases reduction of project times will result in lower project costs.

Increased responsiveness to customer demand
Flexibility will result in a greater ability to react to changes in customer wishes. Product flexibility offers opportunities to adapt a product to specific customer needs in a short time. Innovation flexibility will result in more advanced products. When tailored to the needs of customers, this will contribute to increased customer loyalty, less churn, and a higher willingness to pay. The image of being an innovative supplier will be reinforced.

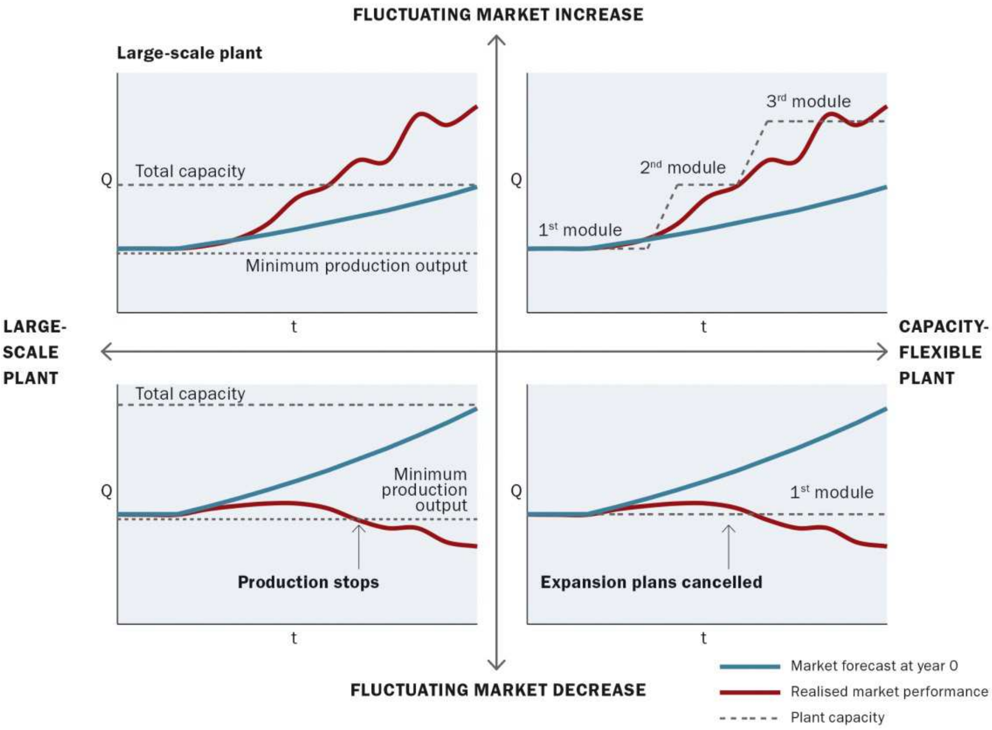
Besides product flexibility, also capacity flexibility can increase responsiveness. When market demand fluctuates, a company can easily react to it by adapting production capacity.

Market entry in emerging economies
Many companies want to create a foothold in emerging economies like Asia and Latin America to profit from growing market demand and increase revenues. However market conditions are uncertain and room for investment is often limited. Starting with smaller-scale production facilities that can be easily scaled up will help to create a foothold in these new markets with reduced investment risk. If the product introduction is successful, the production capacity can be scaled up in a step-wise manner according to the market developments. In such cases, capacity flexibility (ability to meet the changing demand by adjusting capacity levels) can prove advantageous.

Risk reduction
When a company introduces a new product, demand usually increases slowly at first, then grows at higher pace and eventually becomes stable as the market for this product matures. When a new product is introduced, production output is planned based on market projections which carry a certain level of uncertainty. The picture below shows how capacity flexibility can reduce CAPEX risks in uncertain market circumstances. On the left the situation for a large-scale plant is depicted: total capacity of the plant is determined for a long term based on the market forecast at the investment moment. When market demand increases more than projected, capacity may get too small. When market demand appears to be

[12] petrochem-projects.creatavist.com/petrochem-projects-2014

disappointing, capacity is too high which leads to capital destruction, especially when production has to be stopped. In case of capacity flexibility, the plant can be expanded when market demand increases. Investments are limited when market demand decreases.



CAPEX risk reduction by applying capacity flexibility: installed capacity follows market demand, both when market demand increases and decreases.

In 5.3 implications of capacity flexibility for cash flow will be elaborated in an example.

Risk reduction by applying capacity flexibility is very interesting in emerging economies. Uncertainty is high in these markets, but meanwhile they are very attractive and many companies want te create a foothold in e.g. Asia.

Security of supply is another aspect where capacity flexibility can help. Especially in pharmaceuticals this is a main issue.

Feedstock flexibility can help reduce dependence on traditional energy and feedstock sources. This will result in a lower sensitivity for price increases of traditional feedstock.

5.3 Example: risk reduction by applying capacity flexibility

Generally, a plant can adjust production output levels within its operational envelop (minimum and maximum output). With that in mind, it is easy to adjust the supply of a product based on the way demand fluctuates. There, we can distinguish two cases:

- Demand > Installed capacity: in this case, a company needs to make strategic decisions about expanding its capacity; for this, reliable market information and access to capital are essential
- Demand < Installed capacity: one option[13] is to adjust production output to the demand level, meaning that the installed capacity is not fully utilized; in this case variable costs fluctuate with production output, however fixed costs remain constant. In this case, the larger the gap between installed capacity and output, the higher the risk of reducing profit margins

When a new product is introduced, market projections are used to predict the required volumes and plan the production output. In the hypothetical example below, we are looking at two different companies (Company A and Company B) that have decided to produce an innovative bio-based material (product X). The initial market projections for this product had indicated that demand would increase by 20% on an annual basis. Company A has decided to invest in new production facilities for product X in a step-wise manner due to the increased risk related to its innovativeness, as well as lack of available funds for a larger plant. Company B, on the other hand, has decided to invest in a large-scale plant that will meet the projected demand for the first decade of its operation. Two scenarios related to the way the market develops are investigated:

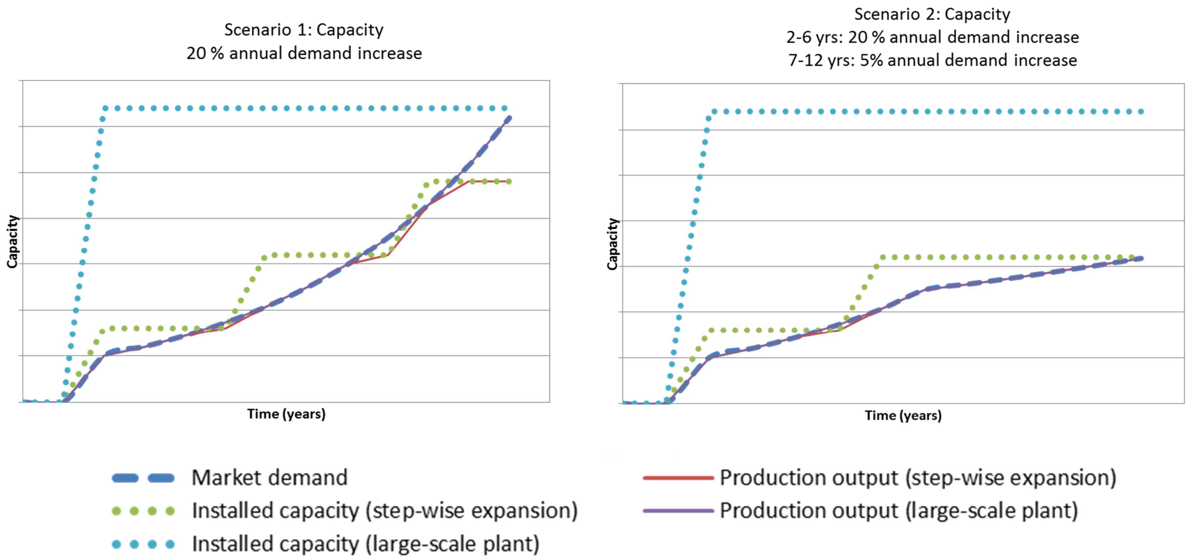
- Scenario 1: market growth follows the initial market projections (20% increase in demand on an annual basis)
- Scenario 2: market grows by 20% for the first 5 years of the plants' operation and, then, drops to 5%

The table below describes two different scenarios about the way the market develops and how the two companies (A and B) respond to the introduction of the product X

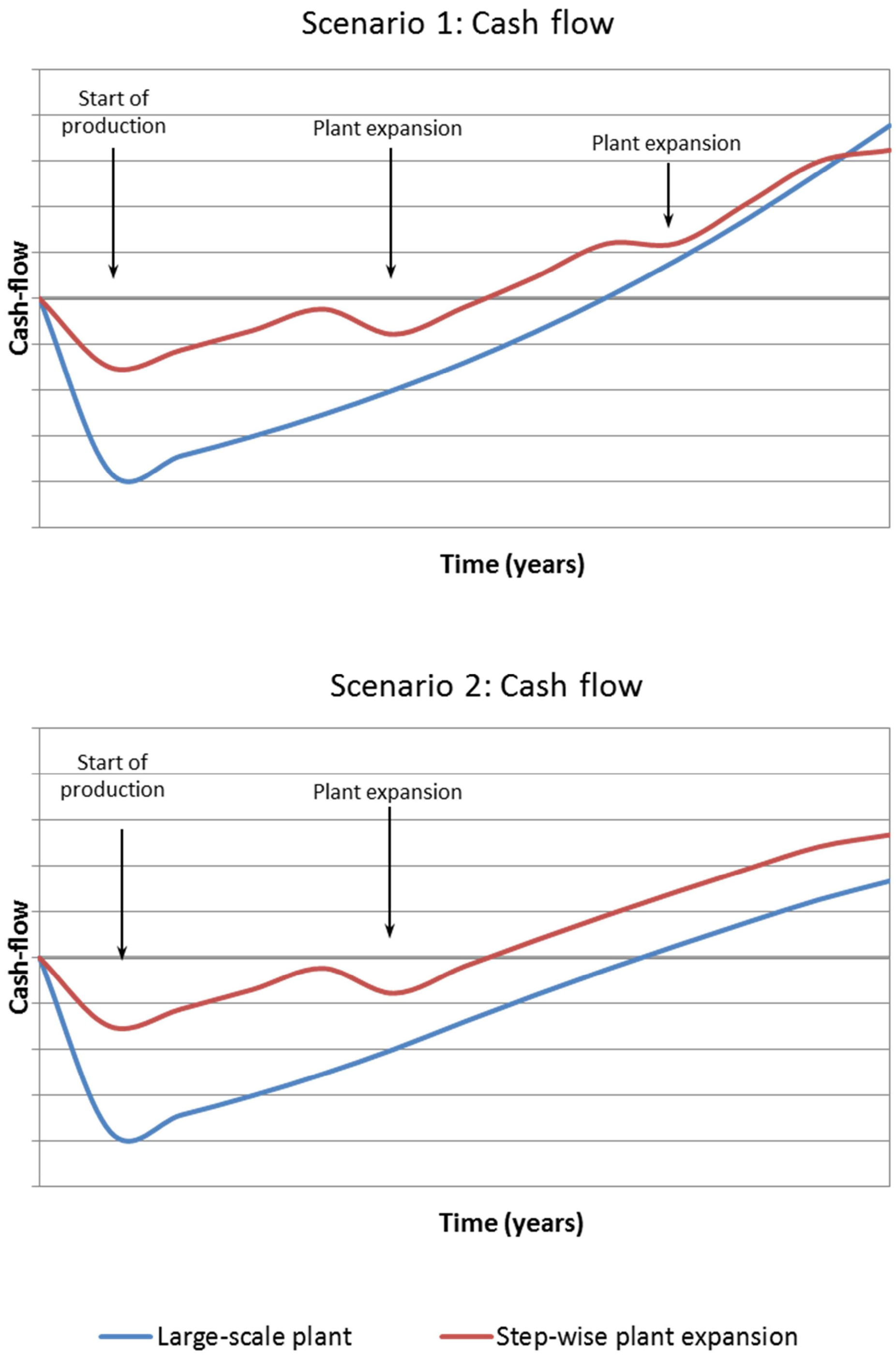
[13] Another option for the company is to continue utilizing the installed capacity, which in turn can create oversupply of the product and create disruption in the market; this option is not investigated in this report).

	Company A Capacity expansion in step-wise manner due to increased risk (new product) & lack of available funds for a larger plant	**Company B** Investment in large-scale plant planned to meet projected demand within the first decade of operation
Scenario 1: market growth follows the initial market projections (20% increase in demand on an annual basis)	• Initial capacity: Q/4 • Capacity expansion at 4th and 8th year of operation (expansion step Q/4) • 100% capacity utilisation within a decade of operation, 22% of demand is not met	• Initial capacity: Q • No additional investments in capacity expansion • 97% capacity utilisation within a decade of operation
Scenario 2: market growth by 20% for the first 5 years of the plants' operation and, then, it drops to 5%	• Initial capacity: Q/4 • Capacity expansion at 4th and 8th year of operation (expansion step Q/4) • >99% capacity utilisation within a decade of operation	• Initial capacity: Q • No additional investments in capacity expansion • 50% capacity utilisation within a decade of operation

The figures below demonstrate how company A (step-wise expansion) and company B (large-scale plant) respond to the market changes in terms of installed capacity and production output for both scenarios.



We calculated the cash flows within the first decade of operation with a cost model that was developed within TNO. The result is as follows for both companies and scenarios:



Looking at the cash flows for both scenarios, we see that company A reduces its investment risk during the stage of the first investment. The smaller-scale plant provides risk reduction. The investment is kept to lower levels compared to company B, while it still manages to meet market demand. In addition, company A recovers its first two investments (initial and first plant expansion) faster than company B.

In scenario 1, the market develops at a higher pace, and even though company A invests in an additional increase in capacity, we can foresee that company B has higher profitability potential in the long-run.

Looking at scenario 2, however, we can see that the significant drop in market growth has a significant impact on the profitability performance of company B. This can probably be attributed to the low utilisation rate of the plant due to low demand levels from the market in combination with high fixed costs related to the large capacity of the plant. On the other hand, company A makes the decision not to invest in a second capacity expansion, having little effect on its profitability as well as resulting in an overall better performance compared to company B.

Key take-aways

- Smaller-scale plant expansions can enable faster time-to-market in case of low capital availability.
- Large-scale plants are generally more profitable in the longer term, but require access to reliable market projection information.
- In uncertain market conditions smaller-scale stepwise plant expansions allow for faster response to changes in demand. This is especially relevant to new market entries as well launch of innovative products to cover for uncertainties regarding market adoption.
- Based on the figures above, profitability not only depends on the installed capacity and the related costs, but also on timing. The projected lifetime of a product can be a determining factor in choosing the most attractive strategy in planning production.

6 To accelerate innovation, a collaborative effort of the EU industry is needed

The EU chemical industry is looking for ways to make its business and production more flexible. The concept of small-scale flexible plants presented in this report offers possibilities to implement the envisaged flexibility.

Currently the concept of flexible production is mainly applied in R&D and pilot setting. In the meantime the first pilot projects have found their way into implementation in an operational, commercial setting. Like with most innovations that are in an early stage, early adopters can be found mainly in areas where the innovation has the highest added value, that must compensate for relatively high investments in early stage innovation. That makes it not surprising that most commercial implementations can be found in higher value segments, i.e. pharma, fine chemicals and specialties. However also in bulk the concept of small-scale flexible production is already applied, but driven by another need: safety. Early adopters will drive development, make the technology proven and eliminate childhood diseases. In this way they will pave the way towards broader market adoption.

The table below shows the term on which we expect the different types of flexibility to become implemented in each market segment. Location and innovation flexibility are already being applied in some cases. They are currently mainly relevant for pharma and fine chemicals, and will also become for specialties. They are not relevant for commodities, except in the case where location flexibility is applied for safety reasons (offsite plant building or production of hazardous materials on customer location). Product flexibility is relevant for the same segments, but it will take more time before it will get adopted by the industry. Capacity and feedstock flexibility are more relevant for higher volume production and thus apply most in specialties and commodities. Since costs play an important role here the costs for implementing flexibility will have to drop significantly before the innovations will be applied. The arrow in the picture indicates the expansion of flexibility from higher value products to specialties (mid-term) and commodities (long-term).

	Pharma	Fine chemicals	Specialties	Commodities
Location flexibility	Short-term	Short-term	Mid-term	Short-term*
Innovation flexibility	Short-term	Short-term	Mid-term	Less relevant
Product flexibility	Mid-term	Mid-term	Long-term	Less relevant
Capacity flexibility	Less relevant	Less relevant	Mid-term	Long-term
Feedstock flexibility	Less relevant	Less relevant	Mid-term	Long-term

** only for safety reasons e.g. offsite plant construction or production of hazardous materials*

During the interviews industry representatives have indicated that the concept replies to a number of important business drivers:

- Shorten time to market
- Gain greater responsiveness to customer demand
- Create a position in emerging markets
- Risk reduction:
  - Financial: reduce CAPEX risks in a highly volatile market
  - Other: security of supply (especially in pharma), reduce feedstock and energy dependence
- Cost reduction (in special cases)
- Deal with decentralisation of feedstock and energy
- Production of hazardous materials on location
- Easy integration of technologies

However, to keep Europe's competitive position with respect to the rest of the world, implementation and innovation should be accelerated. Businesses and ecosystems that do not innovate will be too late when competition has taken over their position. However, as is usually the case in innovation, the route from concept and first application towards broad adoption is long and bumpy. Even when technologies and novel business approaches have proven themselves, many barriers have to be overcome.

During the interviews, a number of barriers were named that should be overcome to let broad adoption take off. They are summed up below, together with suggestions how to overcome the specific barrier:

- *Economic feasibility is many times not proven*: More businesses should disseminate their showcases. Knowledge and technology providers should focus more on specific business cases and not only on technology push.
- *Installed base will not be easily amortized*: New approaches should be developed on how to fit novel technologies into existing infrastructure. Novel business models and players should be employed that are not burdened by existing assets.
- *Conservative character of the industry*: People from all parts of the organisation should be involved in the innovation process. Risk management and innovation decision support tools should be developed for management and plant workers should be involved in an early stage to create a landing place for novel approaches and technologies.
- *Cultural change is needed*: By employing tools from other industries and using showcases from different sectors like ICT and high-tech, people from within the chemical industry could be shown that not every problem is unique and that solutions might exist of more generic building blocks.
- *Lack of standardisation for modularisation*: In standardisation platforms, involving multiple chemical businesses and engineering firms in setting some form of standard, it will be easier to exchange ideas and technologies across businesses, accelerating implementation.
- *Equipment and engineering firms do not have a business case without widespread adoption*: Both chemical players and their suppliers should be involved in the innovation process and both should be willing to take risks and share benefits. This could be facilitated by an independent innovation platform

that does not have a stake in the outcome of the development itself and would best be helped with government support.

- *Regulation is experienced as a burden for innovation*: Governments should be convinced to be more flexible when novel innovative approaches are employed so that there is not an extra barrier due to, sometimes unnecessary, regulation.
- *Some crucial technical components are still missing*: Flexible separation and formulation technology should be further developed, as well as systems engineering approaches and the integration of manufacturing approaches and ICT.

The basis to overcome these barriers is the common interest of the EU chemical industry to utilize the advantages offered by flexible production that are named above.

There are already a number of public-private initiatives in the field that drive flexible production: EUROPIC, Britest (UK), FISCH (Belgium), Provide (TNO in the Netherlands) and INVITE (BTS in Germany). Apart from that there are multiple private collaborations and platforms. By joining forces in North Western Europe development in flexible production can get even stronger. Therefore, it is key that companies, knowledge suppliers and governments follow the same direction together, each organisation in its own role and with its own strength. In this way the industry can overcome the barriers. A collaborative business and technology roadmap, combining the knowledge, information and capabilities of the main players will greatly facilitate the innovation process. Then the way to broad adoption is open and the concept of flexible production can be implemented on a wide scale, contributing to a stronger competitive position of the EU chemical industry.

7 List of interviewees

We would like to thank all industry representatives that provided valuable insights during the interviews:

Hans-Jurgen Federsel, Senior Principal Scientist, PhD, Assoc Professor, Astrazeneca

Mark Talford, Innovation Director, Britest

Frank Groenen, Vice President SACHEM, General Manager SACHEMEurope

Martin Riegels, Site Manager Rubber Chemicals, Lanxess

Olaf Wachsen, Head of Group Process Technology, Technology & Innovation, Clariant

Peter Jansens, corporate scientist process technology, director ChemTec R&D, DSM

Ralf Karch, Director Research & Development, Precious Metals Chemistry, Umicore

Alan Gow, is Global Technology Director Polyurethanes, Huntsman

Jean-Luc Dubois, Scientific Director, Catalysis and Processes, Arkema

Jos Keurentjes, CSO TNO, professor Chemical Engineering at TU Eindhoven, formerly director technology and open innovation at AkzoNobel

Cees Biesheuvel, Technology Innovation Manager, Dow Benelux

8 References

[1] Cefic, The European chemical industry, Facts & Figures 2013
[2] Cefic, The European chemical industry, Facts & Figures 2014
[3] Rabobank, Een voorwaardelijke toekomst. De chemie in Nederland, 2014
[4] AT Kearny, Chemical Industry Vision 2030: A European Perspective, 2012
[5] McKinsey on Chemicals, Nr 3, Winter 2011
[6] Ronald Berger, A different world – Chemicals 2030, Nov 2011
[7] KPMG, The future of the European chemical industry, 2010
[8] KPMG, Reaction Magazine, 11. Edition, Strategic Realignment in the global chemical industry, 2013
[9] Alex Osterwalder, “Business Model Generation”, 2010
[10] Chemical Industry Vision 2030: A European Perspective. AT Kearny, 2012
[11] Plant Design and Economics for Chemical Engineers, M.S. Peters, K.D. Timmerhaus & R.E. West (2004)
[12] http://cen.acs.org/articles/93/i2/Chemical-Outlook-2015-Region.html#3
[13] https://www.akzonobel.com/ic/products/remote_controlled_chlorine_production/
[14] http://www.uhdenora.com/skid_mounted_plants.asp
[15] https://petrochem-projects.creatavist.com/petrochem-projects-2014
[16] http://www.petrochem.nl/zetten-huntsman-en-btg-btl-trend-met-modulaire.150329.lynkx
[17] http://www.nestle.com/media/newsandfeatures/modular-factories
[18] http://www.f3factory.com
[19] ASTM International (2012). ASTM F2792-10
[20] Duisterwinkel and J.-M. Bassett, Chimica Oggi, 29, 4, 2011
[21] http://www.efce.info/EUROPIN.html
[22] http://www.smartindustry.nl/eng/
[23] http://www.effra.eu/
[24] http://www.spire2030.eu/
[25] http://www.ispt.eu/economy-chain-factories-containers/