Factory
flexible · fast · future

*creating the **future** of production*

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Fast, flexible, modular production technology provides platform for future European growth

Launched in 2009, the €30 million F³ Factory project is a major public/private sector initiative which has sought to define and demonstrate a new paradigm in modular, sustainable production technology for the European chemical industry.

The F³ Factory project vision is to strengthen the European chemical industry's global technological leadership through implementation of faster, more flexible production methods.

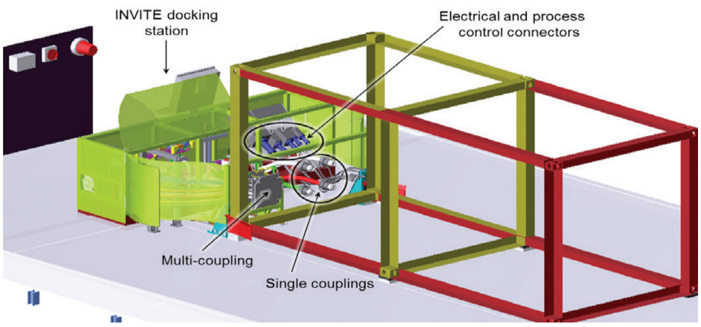
Crossing country and company borders, interdisciplinary teams from 26 partner organisations in 9 EU member states have collaborated successfully to address the key aims of this flagship project:

- to deliver radically new 'plug and play' modular chemical production technology, capable of widespread implementation throughout the chemical industry
- to deliver holistic process design methodologies, applying process intensification concepts and innovative decision tools

Based on seven industrial case studies spanning a broad range of process industry sectors including pharmaceuticals, chemical intermediates, specialty polymers and consumer products, the project has successfully proved the fast, flexible production concept through:

- ✓ demonstration of the F³ Factory modular concept at industrial scale for commercial applications
- ✓ realisation of an open access backbone plant for modular continuous production
- ✓ validation of new intensified and simplified continuous processes
- ✓ design and validation of new/enhanced reactor technologies
- ✓ establishment of design guidelines and standards for modular, container based production units

Realising the F³ Factory concept



Business Impact:

- Increased investment flexibility
- Capex reduction up to 40%
- Opex reduction up to 20%
- Faster time to market

Environmental Impact:

- Reducing energy consumption up to 30%
- Solvent reduction up to 100%
- Footprint reduction up to 50%
- Reduced transportation by local production

Numerical data presented here summarise the successes achieved across the whole F³ Factory project. Outputs from individual processes and industrial case studies may differ from the overview results shown here.

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 228867

SEVENTH FRAMEWORK PROGRAMME

With over 300 scientists, engineers, PhD students, business and academic experts engaged in the project, key successes include:

1. Successful validation of new intensified and simplified continuous processes

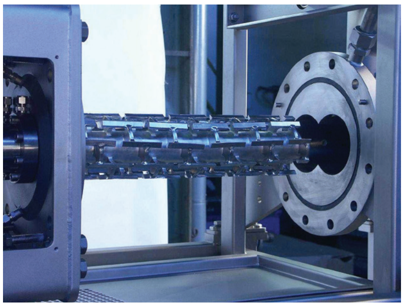
Process intensification up to factor of 500

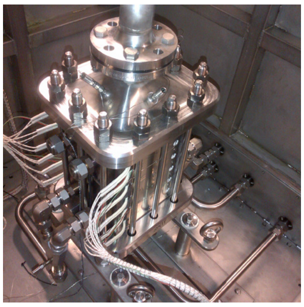
- Increased space-time-yield up to factor >100
- Increased capacity >20%
- Increased production yield >20%
- Solvent reduction up to 100%
- Reduced footprint >50%
- Reduced equipment need >60%
- Reduction of reaction/processing time by factor of 10

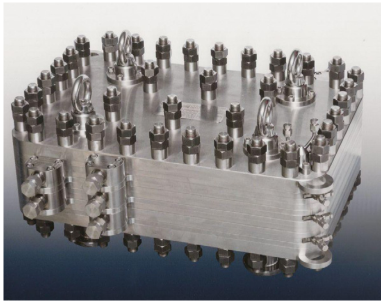
Simplified processes:

- Reduced reaction and processing steps up to 30%

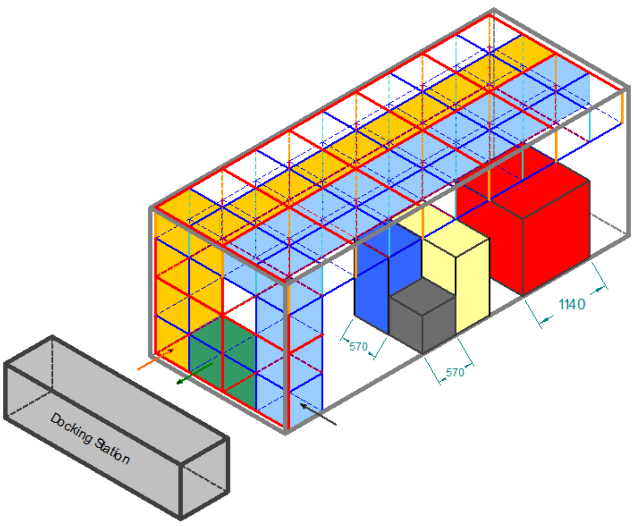
2. Successful design and validation of new/enhanced reactor technologies







3. F³ Factory design guidelines and standards for modular, container based production units defined and implemented in different process equipment containers



4. Realisation of an innovative open access backbone plant (INVITE) for modular continuous production

Tangible Exploitation of Project Results

- New & improved science/knowledge
- New decision tools/methodologies
- New & improved production processes
- New & improved technologies
- New standards/design guidelines
- >15 patents submitted or in progress

Extensive Dissemination of F³ Factory Learning

- >150 conference presentations/papers/posters
- >30 peer reviewed Technical Papers submitted or in preparation
- Open engagement with EU academia and industry through regular Interest Group meetings
- Project website and annual newsletter

Data as at 15 May 2013. Further exploitation and dissemination anticipated.

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SEVENTH FRAMEWORK PROGRAMME

Flexible, modular production of water soluble specialty polymers

Rhodia-Solvay and BASF have collaborated in the 'Europoly' project to design and build a continuous, multi-product pilot plant to demonstrate the technical and economic viability of the F³ Factory concept for solution polymers.

Water soluble synthetic polymers are used in a wide range of markets and industrial / consumer applications. European production of water soluble polymers is estimated to be in excess of 750 kT per annum and accounts for over €2.5 billion of annual sales in Europe.

The Europoly case study was supported by academic partners CNRS Nancy and TU Dortmund, where feasibility studies were undertaken on two model polymer systems:

1. acrylic acid-based copolymer (CNRS & Rhodia-Solvay)
2. homo-polymerization of acrylic acid and copolymerization of acrylic acid with second monomer with extremely different copolymerization parameters (TU Dortmund and BASF)

Production challenges addressed by the Europoly project

A key challenge in polymer production is to manage the high heat production rate during radical polymerization reactions. This is particularly difficult to manage in conventional large-volume stirred batch reactors due to heat transfer limitations related to the low surface area-to-volume ratio. These batch processes are usually run in fed batch mode with a long cycle time and semi-continuous addition of reactants, such as monomers and initiators, to control the exothermic reaction.

The Europoly project has evaluated the advantages of a new continuous, intensified process technology that could deliver product characteristics with a heat transfer capability more appropriate for the reaction, by adapting the process to the product and not the product to the process!

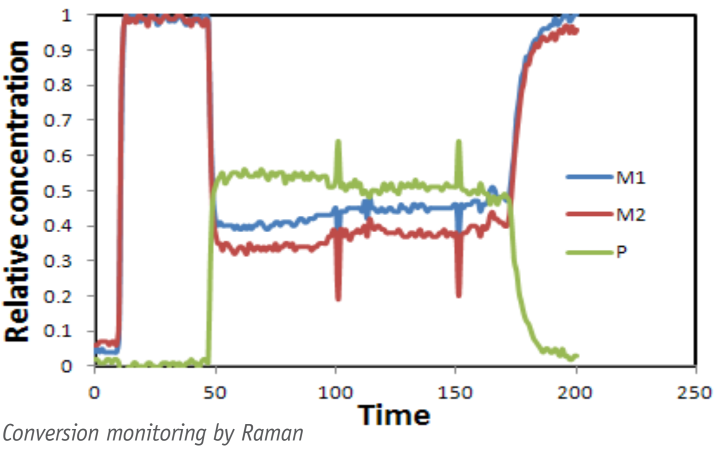
In transferring production from batch-to-continuous, based on process intensification and standardized modules, the project team targeted improved sustainability and competitiveness via:

- increased productivity for the same investment cost
- reduced fixed costs through lean processes and productivity enhancements
- improved process robustness by replacing batch reactors used to manufacture multiple products with continuous, product-optimized processes
- improved product uniformity resulting from continuous process control in place of batch production with batch-to-batch deviations

Intensification of a radical polymerization process

A key success of the Europoly project has been the development of a scalable mixer-heat exchange tubular reactor concept using Fluitec static mixer technology. This is equipped with a novel internal cooling system element that controls heat production during the process.

Fluitec Tubular Reactor



Conversion monitoring by Raman

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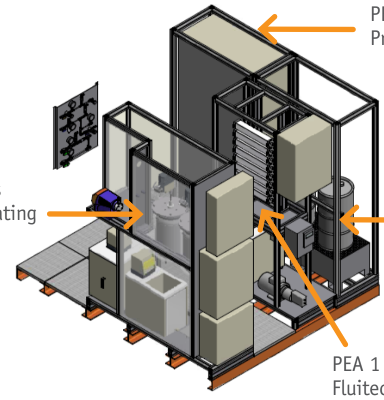
Intensive use of kinetic data in millifluidic devices and rheokinetic data from lab-scale batch reactors - tested during the validation stage - was key to the successful design of the intensified continuous reactor used in the demonstration. The continuous polymerization process was monitored by:

- in-line spectroscopy with Mid-IR at TU Dortmund
- Raman spectroscopy at CNRS, Nancy



Design layout for the Europoly PEC

Lab-scale evaluation at TU Dortmund and CRNS, Nancy has successfully validated the transfer of (co)polymerization reactions from batch to continuous operation for both products. Process intensification factors from 10 – >100 have been achieved with products in specification in relation to:

- residual monomer content.
- molecular weight.

PEC in transit from Rhodia to INVITE

Inside the Europoly PEC during demonstration at INVITE

Fast, flexible production of polymers achieved

The successful transfer of the copolymerization reactions was designed to fit in a half-sized standard process equipment container (PEC). Built initially at Rhodia-Solvay's site in France, the PEC was transported, installed and the process was successfully demonstrated at the INVITE Research Center in Leverkusen, Germany during Q2, 2013.

In the Europoly case study, the F3 Factory concept of fast, flexible and future has largely been achieved:

Fast: Through the continuous operation of an intensified process.

Flexible: Through use of the same PEC and PEAs for two different polymers.

Future: Through use of modular technology in a multi-product environment i.e. use of the same PEC and PEAs.

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Fast and flexible continuous processing for pharmaceutical molecules

AstraZeneca has focused on the development of a proof of principle concept for the flexible, continuous production of pharmaceutical development materials for toxicological and clinical studies. Working with academic partners - KTH Institute of Technology, Denmark Technical University (DTU), Newcastle University and Karlsruhe Institute of Technology (KIT) – as well as industrial partner Britest - the project has developed and validated a new generic transformation methodology for the formation of pharmaceutical intermediates.

Production challenges addressed

One of the biggest challenges facing the international pharmaceutical industry is the ability to offer a flexible response to the production of new materials for toxicological studies (in vivo, in vitro).

The F³ Factory approach to providing a "one size fits most" process synthesis for the production of intermediates for campaign 2 material, offers an opportunity to build a faster and more flexible response to this need by:

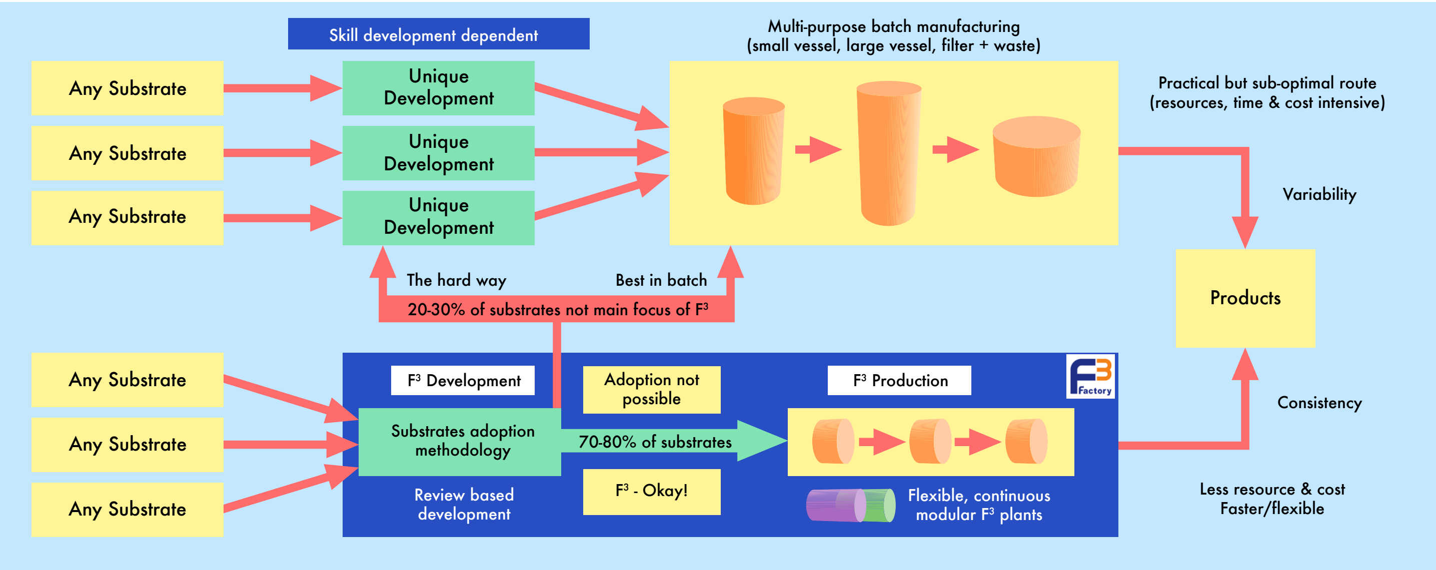
- reducing cost of process development
- increasing throughput and improving robustness
- increasing manufacturing flexibility

Continuous manufacturing technologies for work-up in final stage active pharmaceutical ingredient synthesis are also of major interest to AstraZeneca.

Barriers to overcome in implementing the new F³ Factory concept

A key barrier to overcome is a mindset issue of "we've always done things this way, so why change" and/or "if it isn't broke why fix it?" In recent years there has been some progress in this respect across the pharmaceutical industry but there is more progress to be made. There are also Quality Assurance issues to overcome with regard to continuous processing Vs batch manufacture e.g. how to define 'in spec' and 'out of spec' material.

The Transformation Methodology



Development and validation of a new Transformation Methodology

Nitro reductions were selected to test the F³ Factory concept with transfer / catalytic hydrogenation identified as key options. A generic process and Substrate Adoption Methodology (SAM) were developed with DTU and Britest to enable more effective screening of molecules before they are put into the reactor.

A Risk Assessment Methodology (RAM) was also developed by the University of Newcastle to understand the value of the F³ Factory approach, not only in economic terms, but also in terms of reducing business risk in general. For AstraZeneca, the (RAM) provided a structured approach and useful visualisation of risk assessment processes undertaken as a matter of routine.

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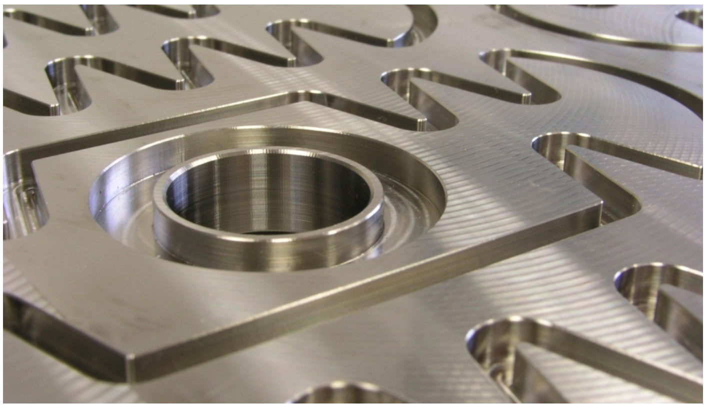
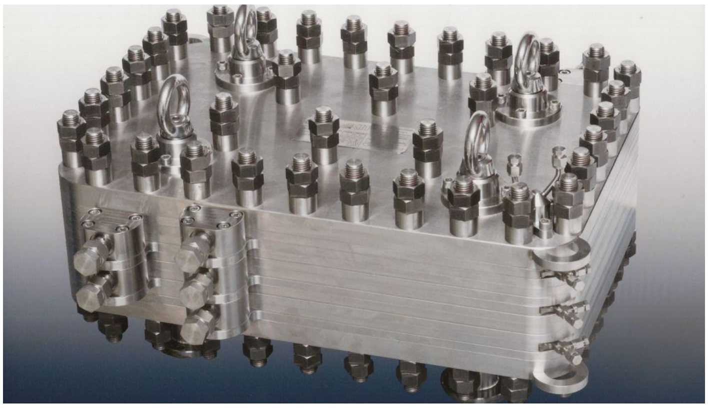
Key technical features of the project included the:

- development of a novel isolation technology (in conjunction with KTH Institute of Technology) to isolate solid material, evaporate solvent and achieve uniform solid beads.
- development of a new continuous, micro-structured reactor (in conjunction with KIT) capable of handling dispersed solid catalyst and a slurry feed, thus removing the need for fixed bed technology.



Micro-structured reactor plate



The new micro-structured reactor

Reactions undertaken in AstraZeneca's Large Scale Laboratory in the UK, have fully validated this new transformation methodology. A semi modular production unit, with the ability to install different PEAs depending on the chemistry required, has been installed successfully. AstraZeneca is now evaluating this new production unit for drug projects and obtaining better yields (mid 70% vs 50% batch).

AstraZeneca recognises the value of collaborating in EU Framework projects as an important and practical means of supporting and enhancing its own internal R&D activities. It recognised at an early stage, that the aims and objectives of the F³ Factory project aligned closely with its own research objectives and that the collaborative aspects of this large demonstrator project could lead to step-change process innovation in the development of new pharmaceutical compounds.

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Flexible, continuous production of chemical intermediates

Evonik Industries AG has focused on demonstration of the flexible, continuous production concept for intermediate chemicals. Working with academic partners – TU Dortmund, TU Eindhoven and Newcastle University - the project has looked at the development and validation of a generic methodology for modularised production plants of medium scale e.g. for fence-to-fence applications in emerging markets.

Production challenges addressed

Evonik Industries AG is a global leader in specialty chemicals production. Its products are used in a wide variety of high end application areas including pharmaceuticals, agrochemicals, paints & coatings, paper, plastics, personal care & hygiene, adhesives and sealants. Innovative production strategies in these fields are, therefore, a key focus of Evonik's research and development projects.

Typical intermediates include those produced in highly exothermic reactions which suffer from limited heat and mass transfer capabilities. Present reactor technologies are, therefore, complex and unique for each product and plant and mainly economic only in world scale capacities i.e. > 100.000 t/a.

The F³ Factory approach will help Evonik become more flexible in production capacities, the use of different feed qualities and faster scale-up procedures to reduce time-to-market. Depending on the respective reactions investigated, step changes in production are expected e.g. increased production effectiveness, energy savings and lower investment costs (amongst others).

Developing flexible, continuous, modular production technology

The challenging goals of the F³ Factory project can only be reached through innovative process intensification technologies. For the Evonik project, two different technologies were investigated:

1. structured catalyst packing
2. jet-loop reactor with integrated "cold" membrane separation.

Both technologies focused on the intensification of mass and heat transfer as well as simplification of the respective chemical reactor design.

The first reactor technology required new catalyst structures which could be implemented as "plug-in" technology in existing plants. In the near future these could also be used in modularized new reactor concepts.

Simpler reactor construction will reduce investment and enable greater standardization of reactor technology. Parallelization of this technique also offers high potential for more flexibility in production capacity to support future market growth.

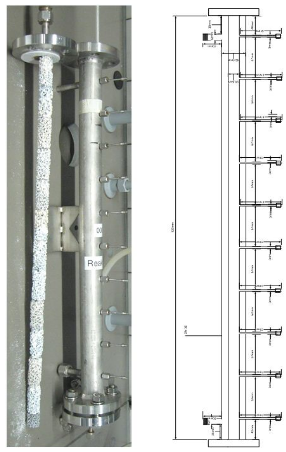

Fig. 1: Structured catalytic packing for tubular reactors

The second reactor technology is designed for highly exothermic liquid-gas reactions. Innovation in catalyst development makes an improved reactor design/concept in terms of heat management and mixing necessary.

For the F³ Factory modular approach, a parallelized jet-loop setup was envisioned, which combines high mass transfer performance and efficient heat management through the jet-loop principle with an integrated membrane separation for catalyst retention. The basic setup is shown in Figure 2.

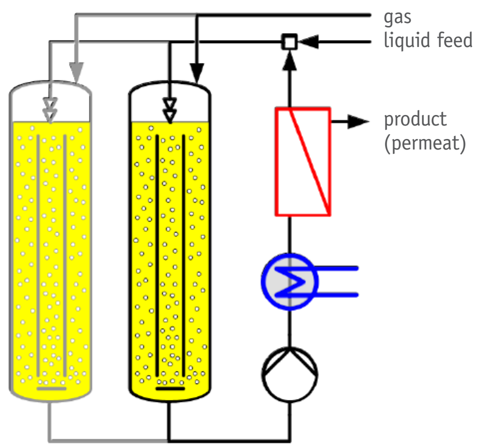

Fig. 2: Basic set-up of used jet-loop reactor with integrated membrane separation

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This modular approach can easily be adapted to varying production scenarios by adding additional reactors or membrane PEAs. The benefits of this approach are:

- reduced investment costs through standardized and easily scaleable reactor equipment,
- reduced operating costs due to maximized space-time yield and integrated heat management,
- high selectivities due to low heat gradients and ideal mixing
- improved catalyst lifespan due to separation under process conditions

Following process development the production unit was transferred to the modular, container-based concept developed within the F³ Factory project (see figure 3).

This hydroformylation process in a jet-loop, with an integrated membrane separation, has now been successfully demonstrated in the F³ Factory backbone facility at the INVITE Research Center in Leverkusen, Germany.

With successful demonstration of the intensified technologies in a modular production environment, the basics of a possible future new production concept have been realised. The concept now has now to be applied and further optimised in the coming years.

Validation and demonstration of the F³ Factory concept

- Partial oxidation, epoxidation and hydroformylation were selected as example reaction classes for the case studies.
- In cooperation with the University of Newcastle and TU Dortmund, software tools have been developed to evaluate the economic and technological aspects of applying the F³ Factory approach.
- With the help of the universities, models have been set-up to optimize operation conditions and operation control aspects.
- The applied process intensification technologies have been proven to operate successfully at both lab and pilot scale levels.
- Design and engineering of modularized process equipment assemblies (PEA) and process equipment containers (PEC) for the hydroformylation reaction was completed successfully.
- The modularized hydroformylation process was successfully demonstrated at INVITE.

Fig. 3: Evonik´s Process Equipment Container for hydroformylation at the F³ Factory

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EVONIK INDUSTRIES   technische universität dortmund   TU/e Technische Universiteit Eindhoven University of Technology Where innovation starts   Newcastle University   invite

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SEVENTH FRAMEWORK PROGRAMME

creating the future of production

Demonstrating modular production technology for high volume intermediate chemicals

Arkema has sought to demonstrate both the technical and economic viability for producing high volume intermediate chemicals in modular, medium scale plants. Working in collaboration with the Process Design Centre, Ehrfeld, Coatex and three academic partners, CNRS Nancy, TU Dortmund and the Institute of Catalysis & Surface Chemistry PA, Poland, this case study is exemplified by the production process of acrylic acid and its derivatives from biomass-based glycerol.

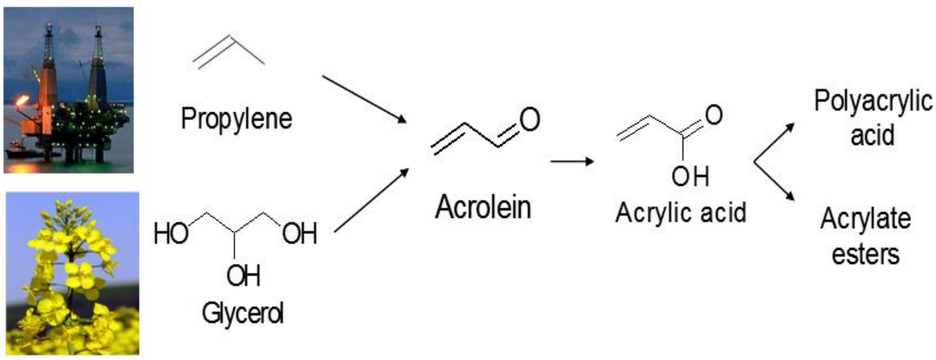
The F³ Factory concept

Chemical intermediates produced in high volumes (hundreds of thousands to several million tonnes per year) are traditionally manufactured in large, dedicated, continuous world-scale plants. These high volume, highly optimised plants benefit from economy of scale, e.g. capital expenditure per unit of product, efficient use of raw materials and energy integration. However, they require large upfront investment and significant development time and effort to build. They also lack flexibility in terms of quick adaptation to changing market conditions and the introduction of new or more efficient technologies.

The F³ Factory concept for **decentralised, modular, continuous, medium scale plants** is therefore focused on the development of smaller and more flexible production units that can be located closer to raw material suppliers or downstream users.

The state-of-the-art process for acrylic acid and its derivatives production starts with fossil-based propylene. The Arkema case study sought to develop a new **greener** and more **cost effective** production process that starts from **bio-sourced** glycerol - a widely available green by-product of oleochemistry and biodiesel production.

State of the art world-scale plant



F³ Factory decentralized medium-scale plant

F³ Factory methodology for medium scale plants

To compete with state-of-the-art world-scale processes, the new F³ Factory process needed a refined optimisation to discover the most economic alternatives. PDC (Process Design Center) developed a methodology for the design of optimised, complex, medium scale plants by adapting conceptual process designs to fit with the new F³ Factory concept. This systematic approach is an iterative 'whole process design' which comprises:

1. black-box modelling to establish an initial idea of the process steps
2. selection of possible function or tasks
3. selection of unit operations capable of providing the required performances (within the F³ Factory approach, unit operations that are more compact or easy to number up, are preferred)
4. integration in a detailed flow-sheet and mass balance

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From production challenges to innovative solutions

Replacing fossil fuel feedstocks with bio-sourced feedstocks leads to several challenges:

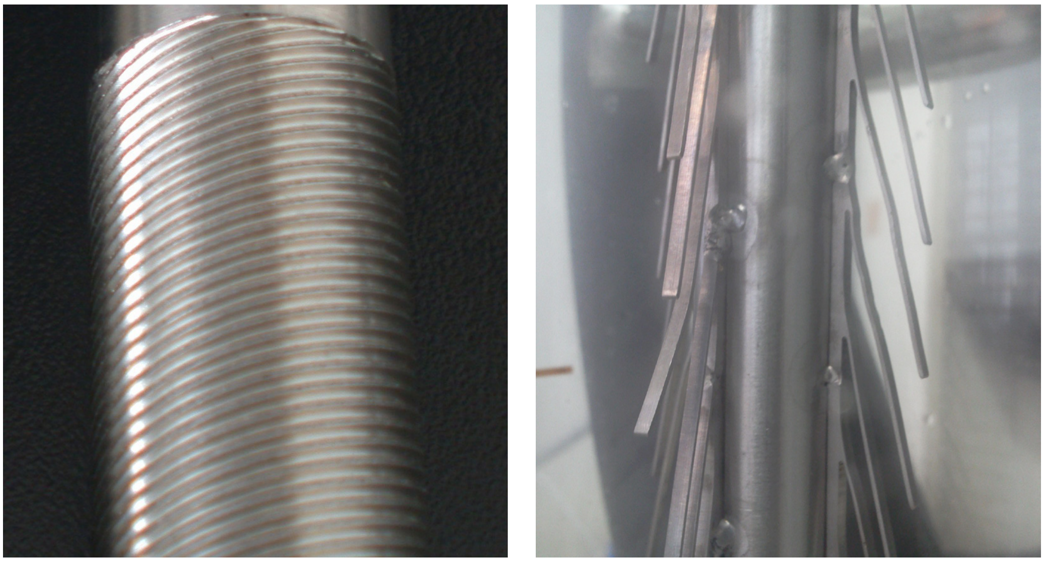
- the new impurity profile needs to be managed
- varying quality of the raw material
- in some cases, faster de-activation of catalyst can occur and must be addressed, while maintaining high production yields.
- a bio-based process is competitive from an economical and environmental point of view but only if the process is not too energy intensive.

Whole process design evaluation, focusing on the systematic examination of alternatives allowed Arkema to select processes with low emissions and high energy integration. Parallel laboratory and process work has successfully optimised the process, taking into account specific conditions for reaction and purification requirements.

As part of the development work on intensified chemical reactors, Arkema has developed and patented innovative solutions to handle faster de-activating catalysts with a very low number of reactors. Process intensification was also implemented by combining reaction and distillation in a single piece of equipment for acrylate ester production.

Looking at downstream processes, this case study focused on optimised purification sequences that combine a set of distillation and crystallisation steps. As part of this activity, a new process with a reduced number of distillation columns has been patented. Intensified crystallization apparatus for melt crystallization using milli/microstructured devices has also been developed and patented. Breaking azeotrope with membrane was also introduced to reduce the number of equipment and energy consumption.

Milli/microstructured surfaces for intensified melt crystallization



Validation of F³ Factory solutions

In conducting the validation studies for this case study, Arkema has discovered and patented a new process for the selective chemical elimination of propanal in acrolein which simplifies the purification scheme of acrylic acid.

Two pilot plants for validation of the F³ Factory concepts, at a scale of several kg/h, have been established at Arkema and TU Dortmund and bio-based acrylic acid has been successfully polymerized at Coatex.

Whole process design (optimising the whole process as opposed to individual unit operations) and process intensification have been key success factors in establishing a new process for the production of an intermediate chemical from a new bio-based feedstock.

Learning from this case study suggests that the development of modular, medium scale production - through identical decentralised plants (row housing) - can deliver production flexibility and reduce financial risk when considering production needs for a new or growing market.

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Modular, flexible continuous production of active pharmaceutical intermediates

Bayer Technology Services (BTS) has investigated the transfer of a multi-step synthetic batch process for pharmaceutical intermediates to a fully continuous manufacturing process in a modular, flexible infrastructure - including downstream processing. Working with industrial/academic partners, Ehrfeld, Britest, TU Dortmund, University of Paderborn, Ruhr-University Bochum and RWTH Aachen, this case study has successfully validated and demonstrated a major paradigm shift towards modular, continuous processing of active pharmaceutical intermediates.

Bayer's Process Equipment Container Unit installed at INVITE

Production challenges addressed

The Bayer project sought to assess the potential to replicate the cost, quality and efficiency benefits of large scale continuous production (already realised in the chemical industry) in modular, flexible, small-scale container-based production units.

In demonstrating a sequence of synthesis stages in a container environment, Bayer has also integrated a range of innovative, highly efficient process equipment solutions.

Starting from a five stage reaction step with intermediate isolation, key stages of the project included:

1. Chemical redesign against the paradigm shift of continuous processing
2. Simultaneous chemical and continous process development
3. Integration of reaction and separation steps in the container
4. Demonstration in the modular F³ Factory design

Cost & efficiency gains through process intensification

Research and development activity in the first phase of the project demonstrated significant savings and efficiency gains - with cross-project benefits for the wider F³ Factory programme.

Transfer of the chemical synthesis to an intensified fully continuous process led to a significant reduction in processing steps, reaction time and solvents involved.

Bayer has operated the process sequence successfully for several days at bench scale, confirming the assumed benefits of the F³ Factory approach in terms of impact on footprint, resource consumption, continuous monitoring and process operability.

Key benefits identified to date include:

- reduction in starting material costs (average 15% depending on transformations involved)
- increase in space time yield (up to factors >100)
- significant reduction in both reaction and processing time
- simplified work up processes due to elimination of intermediate isolation and purification stages
- unification of solvents and reduction in consumables
- reduction in equipment size
- reduction in design and installation costs (up to 30% depending on transformations involved)
- reduction in apparatus cost (ca. 30% depending on intensification of respective module)

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Demonstration in a modular, flexible production environment

As the first industrial case study to be demonstrated in the INVITE backbone facility, the Bayer project has led the way in establishing standards for process equipment assemblies (PEAs), the Process Equipment Container (PEC) and its integration with the backbone infrastructure services at INVITE.

Bayer's Process Equipment Container Unit installed at INVITE

In order to achieve maximum flexibility, the standardised and scalable equipment used for the development and production phases, has enabled a fast and robust transfer from research to production - according to the development timeline - with minimal effort.

Modular PECs will provide the respective production capacity along the full product life-cylce. In addition, standardised chemical and physical processing PEA units will allow for faster implementation of these new manufacturing strategies in the highly regulated environment of pharmaceutical production.

In the latter stages of the project, Bayer has successfully demonstrated synthesis steps 1 and 2 in the Process Equipment Container at the INVITE backbone facility.

The technological and economic benefits demonstrated through this case study, provide a platform for the introduction of new technologies, production concepts and process equipment solutions for the European pharmaceutical manufacturing sector. And, in spin-off benefits, it will also progressively enable the F^3 Factory partners to secure faster development, design and engineering of future processes.

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Validating new intensified reaction technology for surfactants production

Achieving step-change process intensification in the production of anionic surfactants was the primary goal of the Procter & Gamble industrial case study. Working with project partners – the Institute of Chemical Process Fundamentals (ICPF), Britest and Karlsruhe Institute of Technology (KIT), the P&G project has focused on the intensification of two key reactions stages (SO_2 oxidation and sulphonation) using novel reaction technology and modelling of the economic viability of the concepts in the latter stage of the project.

Production challenges addressed

As one of the world's leading consumer products businesses, Procter & Gamble (P&G) is one of the largest global manufacturers of surfactants.

With no major progress in surfactants production technology for decades, potential gains from the F^3 Factory approach could be significant.

The current business model is to produce bulk surfactants at large scale, centralised locations and then ship to finishing sites. A step change in the base technology could lead to different supply chains – including more distributed, less transport-intensive scenarios and reduced business risk.

In changing the operating strategy for anionic surfactants, P&G is seeking to unlock the benefits of flexibility, agility and long term sustainability.

Technological developments in surfactants manufacturing

Process intensification is seen as the main lever available to progress the supply chain to a more sustainable and lower cost model.

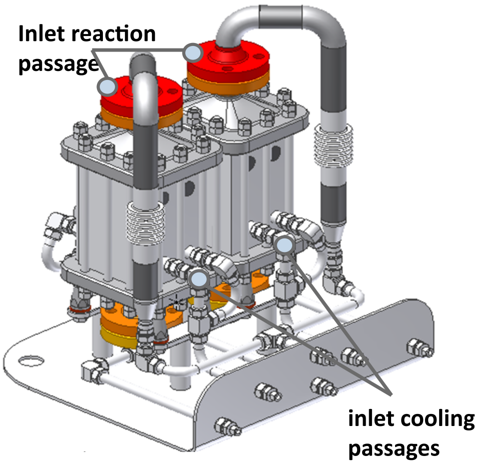
Concentrating on the two unit operations is essential to an overall step change, therefore, the project has focused on SO_2 oxidation and sulphonation.

The size and inertia of current SO_2 oxidation towers negatively impacts on the whole plant agility. Additionally, due to limited use of intensification, sulphonation forces the dilution of SO_3 with large amounts of air. This markedly increases the plant's capital, volumetric and environmental footprint.

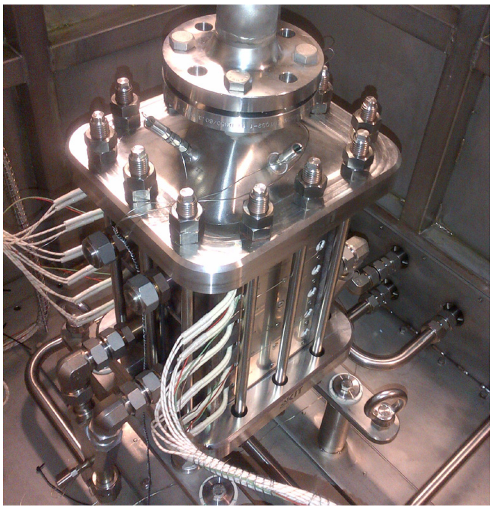
Proof-of-concept work has focused on:

- Obtaining targeted lab scale information on oxidation of SO_2 in micro-channel settings.
- Identifying technical intensification strategies for sulphonation.
- Development of two new reactor designs.

The project team investigated the concept of a microstructured reactor with adiabatic section at the reactor beginning and one cooling section at the reactor rear. Based on experimental measurements of kinetics, simulations on the reaction kinetics and heat transfer, a new reactor design with two parallel microstructured reactors has been developed.



SO_2 reactor system consisting of 2 micro-reactors for the oxidation of SO_2 for 1 kg/h at a total flow of up to 16 kg/h



The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 228867

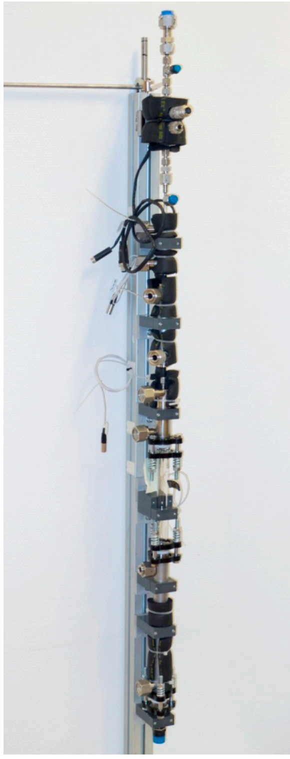
The project team also investigated the concept of a new intensified device for sulphonation. The experimental study focused on hydrodynamic behaviour of lab scale equipment in a wide range of operating conditions. The pressure drop and heat transfer coefficient has been determined and adequate correlation developed.

The sulphonation process on the lab scale reactor prototypes, designed and manufactured at ICPF in Prague, has been tested during the demonstration phase of the project in P&G's pilot plant facility, Brussels.

This intensified sulphonation process has developed new learning – moving away from conventional beliefs - which may help in further intensifying current reaction systems.

The F³ Factory programme has been a unique collaborative endeavour that could stimulate the transition to a new business model for the whole chemical sector. In this new model – flexible, modular, continuous and intensified technologies are used to meet the challenge of producing "what's needed, when needed, where needed" - minimising the environmental and economical footprint and reducing business risk.

For the P&G case study, intensification of two key reactions stages (SO_2 oxidation and sulphonation) in the production of anionic surfactants - using novel reaction technology – has largely been proven at the lab scale. The challenge going forward will be to prove the economic viability of modular production technologies on highly optimised, large scale surfactants manufacture.



Microsulfonator assembly

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creating the future of production

Process intensification for high viscous polymer production

BASF and Bayer Technology Services (BTS) have collaborated to demonstrate the F³ Factory concept for multi-product, small-to-medium scale production of high viscous polymers in a solvent-free manufacturing process. Supported by academic input from the Technical University of Eindhoven and the University of Paderborn, this case study features the development and demonstration of a new flexible, reactor technology within a modular, continuous production unit.

The new kneader reactor technology – developed by Buss-SMS-Canzler - has been validated successfully in plant trials at BASF and a flexible, modular production unit has run successfully at the INVITE facility in Leverkusen, Germany, realising both cost and environmental benefits.

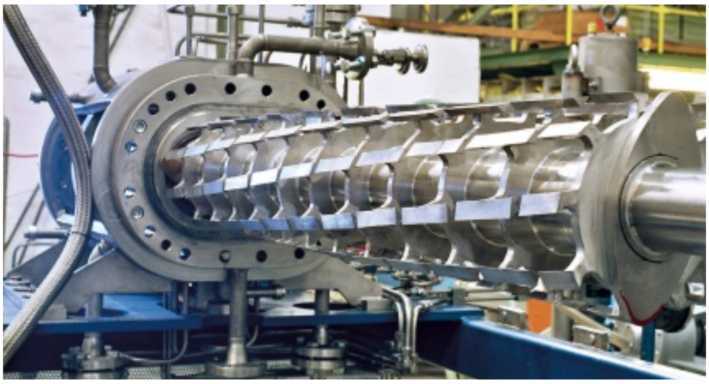
Production challenges

The transfer of multi-product batch polymerisation of high temperature thermoplastics in organic solvent to a solvent-free process is notably challenging and has so far prevented producers from developing solvent-free processes.

Without reducing viscosity by applying huge amounts of solvents, "difficult processes" like solvent-free polymerisation cannot be carried out in standard mixers. The focus of this F³ Factory case study therefore concentrated on the development of intensified, high-strength mixing equipment. This must be shown to guarantee material integrity and enable effective supplementary mixing – as well as devolatilisation and solidification. Performance at long residence times in continuous mode must also be assured.

New reactor technology developed

A new twin-shaft, high-torque kneader reactor was shown to meet the key requirements of strength and operational flexibility and has led to a step-change improvement in viscosity handling up to 10,000 Pa·s. Modular construction and many standardised parts also allow for flexible adaptation to different products and processes, with the ability to switch rapidly between different mixing rotor assemblies.



Buss-SMS-Canzler twin shaft, high torque kneader reactor

Collaboration key to success

To realize the full potential of this intensified kneader reactor, its complex geometry has required focus on several key durability issues. Their examination has been a classic model of F³ Factory project partnerships.

The Univeristy of Padeborn (UPB) investigated the mechanical integrity, modelling of unit processes, radial and axial mixing, micro/macro mixing and axial dispersion. Investigations confirmed the ecological and economic advantages of the kneader from its fast radial mixing and minor back mixing – plus well-developed devolatilisation based on reactor partial-fill operation.

Numerical simulations using CFD analysis were performed by Technical University Eindhoven to calculate the velocity and pressure fields within the kneaded material, leading to rotor strength and fatigue computations by Buss-SMS-Cransler (SMS). Online measurement techniques for the high-torque kneaders were then developed by BASF, with technology transfer to UPB and SMS.

Bayer Technology Services (BTS) derived a mass-balance for the intensified kneader reactor design, providing the liquid filling level as a function of viscosity, throughput and rotational speed. Following validation of the new reactor technology at lab-scale and successful polymerisation trials, the modular plant concept was designed by BTS and demonstrated successfully at the INVITE facility.

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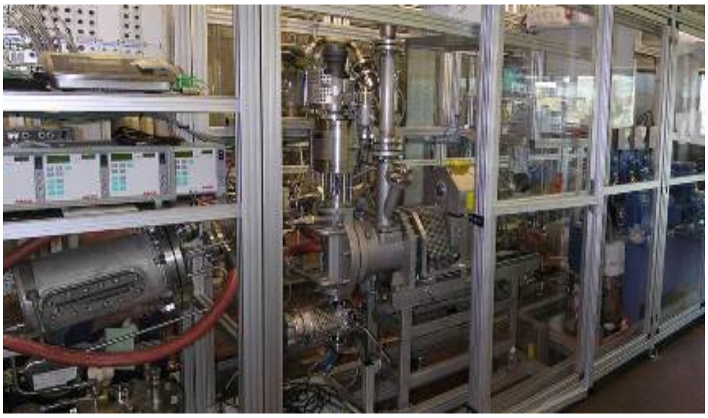
Validated benefits for solvent-free, high viscous polymers

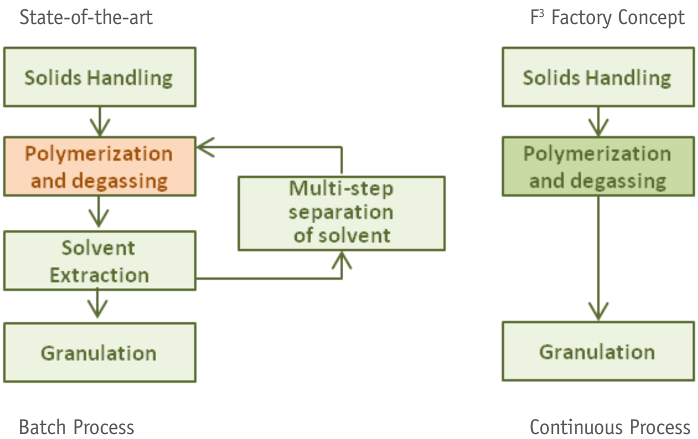
Excellent progress on the integration of process and equipment design enabled illustration of the plant concept and contributed to the design and construction of a pilot facility at BASF's site in Ludwigshafen. The new solvent-free process was subsequently validated with a continuous lab-scale kneader reactor.

The intensified process was then transferred to the F³ Factory modular, continuous plant concept with design of a demonstrator Process Equipment Container (PEC) and respective Process Equipment Assemblies (PEAs).

By eliminating the use of solvents, the process has been intensified significantly. It has reduced complexity, energy consumption and facilitated the successful transfer from batch to continuous polymerization.



BASF's lab-scale facility used to validate the new high torque, kneader reactor technology



BASF PEC in demonstration at INVITE

The case study was demonstrated successfully at the INVITE facility in Leverkusen, over an extended processing time, confirming both the strength and integrity of the kneader rector.

In addition to the technological advancement achieved in this project, the transfer from batch to continuous of a new solvent-free polymerization process has demonstrated both cost (30% reduction in energy demand) and environmental benefits (100% solvent reduction) for the continuous production of high viscous polymers.

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