Executive Summary:
The F³ (Flexible, Fast and Future) Factory project’s vision was to strengthen the European chemical industry’s global technological leadership through the implementation of faster, more efficient, more environmentally friendly, more flexible and cost efficient production methods. Process intensification is a key challenge for the future industrial competitiveness of the chemical and related process industries in Europe, especially important in view of short product life times, high diversification and shortage of resources. The F³ Factory project focused on the development and implementation of a modular, continuous production technology using novel, intensified equipment and processes in a standardised, container-based manufacturing environment for low to medium scale production. As opposed to the traditional operation of continuous processes at large scale or batchwise operation at low to medium scale, the continuous F³ Factory processes have proven to be not only more economic but also more flexible, simple, robust and more easily adaptable to changing process requirements in the industrial environment. The new technologies and innovative production concepts developed by the interdisciplinary consortium of
26 partners from 9 European Member States are characterised by a « plug-and-produce » philosophy based on three main functional elements: 1) a generic backbone facility constituting an interface, 2) standardised process equipment containers (PEC) and process equipment assemblies (PEA) for high-quality chemicals production and 3) holistic process design methodologies, applying process intensification concepts and innovative decision tools.

F³ Factory combines the efficiency, consistency and scalability of a world scale plant with the versatility of batch plants in terms of the speed of introduction of a new synthetic process at low capital cost (up to -40%) in a data lean environment. It accelerates process and product development and delivers a substantial reduction in footprint of the production systems with respect to energy consumption (up to -30%), waste generation and raw material usage as well as due to increased yields (up to 20%) and plant volumes as a result of process intensification (up to the factor of 500).

In the F³ Factory project, work on seven industrial case studies was carried out and innovative manufacturing approaches for solvent-free polymers, specialty surfactants, pharmaceutical intermediates and polymers produced from renewable resources were demonstrated at industrial scale for commercial applications. The work was organised in nine strongly interlinked work packages and defined novel solutions with potential for leveraging great benefits for the entire chemical industry. The key success factors were the combination of excellent research and a deep understanding of the near molecular process level as well as having clear development targets and establishing joint application-oriented development approaches between equipment suppliers and process owners, thus overcoming boundaries between major industrial competitors. This challenging approach allowed shortening the innovation periods considerably. More than 15 patents and 30 publications in peer reviewed journals as well as 150 conference presentations contribute to dissemination of the project results.

The open backbone facility is provided by the INVITE GmbH, founded in 2009 as a 50/50 joint venture between TU Dortmund University and Bayer Technology Services GmbH. It is an open innovation research facility for developing and demonstrating future manufacturing technologies. Furthermore, it serves as an education centre and thus assures the sustainability of the F³ Factory effort beyond the time constraints of the project.

The F³ Factory project was realised from June 2009 to July 2013. The overall budget amounted to € 30 million, of which €18 million were provided by the European Community’s FP7 programme under grant agreement n° 228867. The construction of the INVITE building for demonstration at the CHEMPARK Leverkusen was supported substantially by the Ministry of Innovation, Science and Research of North Rhine-Westphalia.

Project Context and Objectives:

Rationale and high-level objectives
Widespread, low-cost and high-quality process intensification has been identified as a key challenge for the future industrial competitiveness of the chemical and related process industries in Europe. Especially because of quickly changing markets, shorter product life cycles, diversification of highly specialised products and shortage of raw materials and production capacities, competitive manufacturing must take advantage of holistic, intensified process and plant concepts, to ensure efficiency, improve sustainability, speed up market penetration and enhance the capability to follow the product life-cycle. There is an urgent need for flexibility in production to make it adaptable to product diversity and short product life-cycles as well as a need to improve eco-efficiency by using renewable decentralised feed-stocks. F³ Factory consortium realised its vision to enhance the competitiveness of the chemical industry by providing it with...
Consortium realised its vision to enhance the competitiveness of the chemical industry by providing it with modular continuous processes for low to medium scale production rates. The novel technology is suited to produce a range of diversified products, or to react fast to fluctuating raw materials supply or product demands. The operation of such a plant is more economic and more sustainable than (i) the operation of continuous processes at world scale or (ii) the operation of batch processes at low to medium scale. The two main elements of the concept of the F³ Factory project are:

1. A modular, flexible, adaptable and robust chemical production technology, capable of effective widespread implementation throughout the entire chemical industry, characterised by a "plug-and-produce" philosophy, using a three tier modular plant approach: Generic backbone facilities (tier 1) designed for rapid interfacing with standard process equipment containers (PEC, tier 2), housing process equipment assemblies (PEA, tier 3) composed of intensified process equipment for fast, flexible, efficient, competitive, high-quality chemicals production.

2. A holistic process design methodology based on process intensification to design intensified F³ Factory processes and novel process equipment. This essential feature of the F³ Factory approach accelerates process and product development and delivers a substantial reduction with respect to energy consumption, raw material usage and plant volumes.

Consequently, the F³ Factory project had the following aims:

• Delivery of radically new 'plug and produce' modular chemical production technology
• Development of a 'whole process design' methodology through the application of novel process intensification concepts and innovative decision tools such that raw materials and energy (which represent between 70 to 80 percent of manufacturing costs) employed more economically
• Demonstration of the capabilities of the F³ Factory concept within a broad range of existing and new chemical products
• Delivery of new manufacturing concepts significantly decreasing process development time through standardisation, simplification, modularisation and application of novel process intensification technologies

Thereby, the following main results were aimed at:

• Proof of the technical feasibility of the F³ Factory mode of manufacturing
• Proof of ecological and economic benefits resulting from manufacturing in F³ Factory mode versus conventional modes
• A step change in the technology available for EU companies

The F³ Factory consortium identified three main product classes, i.e. polymers, intermediates, respectively active ingredients and consumer products that more or less represent the full range of organic syntheses in the chemical industry. Case studies of these product types were used to test and validate the F³ Factory concept.

The "plug-and-produce" philosophy was not only intended to provide a flexibility similar to that of conventional batch plants as equipment can be added, reordered or removed by simply rearranging the Process Equipment Assemblies (PEA) inside the Process Equipment Containers (PEC). The new plants should also provide an opportunity to introduce new synthetic processes, to run several processes consecutively in the same PECs without additional capital costs and to adapt operating parameters to changes in process conditions. In addition, the F³ Factory concept aimed at allowing to scale up by "numbering up" (more PEC on the backbone), or by using different PEC capable of production on different
numbering up (more PEC on the backbone), or by using different PEC capable of production on different scales. This would make it possible for the industry to work with decentralised smaller F³ Factory plants, each built at lower investment costs, and to become faster and more flexible as compared to conventional monolithic world scale plants. This would help to respond to market fluctuations both quickly and cost efficiently.

The F³ Factory project also aimed at providing the basis for EU wide standards for modular F³ Factory processes respectively plants and a whole process design methodology incorporating new and existing process intensification principles. In addition, novel process intensified equipment was to be developed as required for reaction and downstream processing. These innovative equipment items would be “wrapped” in Process Equipment Assemblies that will substantially facilitate their effective and widespread implementation in (F³ Factory) commercial processing plants.

The F³ Factory plant was to be designed to be operated either in dedicated manner or as a multipurpose facility, without any changes to the design concept. Four levels of standardised modular elements were involved:

- Novel process intensified reactor technologies and downstream unit operations capable to fulfil the requirements of a F³ Factory. (Examples: PI optimised reactor technology: jet-loop reactor; PI optimised separation technology: organophilic nanofiltration membrane)
- Process Equipment Assembly as the smallest modular element associated with one or several unit operations (Example: a jet loop reactor with integrated membrane separation module)
- Process Equipment Containers which constitute a superstructure holding PEAs in position and providing the services required for operating the PEAs. (Example: The above PEA module with logistics functions, process control elements, etc.)
- Backbone Plants providing general services to the PEC(s). A F³ Factory plant can have one or more backbones

While the Process Equipment Assemblies (PEA) and their internal intensified process equipment are specific to a given unit operation, the process equipment containers (PEC) are highly standardised and available only in a small number of sizes and categories specifically adapted to the needs of the generic backbone interfaces and the constraints of shipping and transport of the PEC between sites.

Operative objectives and implementation

The project work had a twofold structure. Vertically, the work was pursued in seven industrial subprojects, also referred to as “case studies” which were conducted in parallel:

- Case study 1: Demonstration of a new ‘transformation methodology’ for increasing throughput of early phase pharmaceutical materials (Leadership: AstraZeneca)
  This case study was focused on the development of a proof of principle concept for the flexible, continuous production of pharmaceutical development materials for toxicological and clinical studies. A new generic transformation methodology for the formation of pharmaceutical intermediates was to be developed and validated.
- Case study 2: Development and validation of modular, continuous production concept on medium scale plant level (20-30 kilo-tonnes/p.a.) for decentralised production based on renewable resources (Leadership: Arkema)
  The target was to demonstrate the technical and economic viability for the production of high volume...
The target was to demonstrate the technical and economic viability for the production of high volume intermediate chemicals in modular, medium-scale plants on the example of the production process of acrylic acid and its derivatives from biomass-based glycerol. Smaller and more flexible production units were to be developed to be located closer to raw material suppliers or downstream users.

- **Case study 3: Demonstration of F³ Factory concept for process intensification and solvent-free production of high viscous polymers (Leadership: BASF/Bayer)**

  The case study aimed at the demonstration of a concept for multi-product, small-to-medium scale production of high viscous polymers in a solvent-free manufacturing process. A new flexible reactor technology had to be developed and demonstrated within a modular, continuous production unit.

- **Case study 4: Transfer of a multi-step synthetic batch process for pharma intermediates to a fully continuous manufacturing process (Leadership: Bayer)**

  The leader aimed at the development of a modular, flexible continuous production of active pharmaceutical intermediates. 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 was planned to be investigated and demonstrated.

- **Case study 5: Demonstration and economic evaluation of new modular production technologies for highly exothermic reactions (Leadership: EVONIK)**

  The case study focused on the demonstration of the flexible, continuous production of intermediate chemicals. A generic methodology for modularised production plants of medium scale e.g. for fence-to-fence applications in emerging markets had to be developed and validated, exemplified on two different technologies: structured catalyst packing and jet-loop reactor with integrated “cold” membrane separation.

- **Case study 6: Evaluation and demonstration of step-change process intensification in the production of anionic surfactants for local markets (Leadership: PGB)**

  Validating new intensified reaction technology for surfactants production and achieving step-change process intensification in the production of anionic surfactants was in the focus of this case study, concentrating on two key reaction stages (S02 oxidation and sulphonation) using novel reaction technology and modelling of the economic viability of the concepts.

- **Case study 7: Demonstration of the F³ Factory concept to enable transition from batch to continuous multi-product plant for different polymers (Leadership: Rhodia/BASF)**

  This study targeted at a flexible, modular production of water soluble speciality polymers. It was planned to design and build a continuous, multi-product pilot plant to demonstrate the technical and economic viability of the F³ Factory concept for the production of solution polymers. Feasibility studies were to be undertaken on two model polymer systems: acrylic acid-based copolymer and homo-polymerization of acrylic acid and copolymerisation of acrylic acid with second monomer with extremely different copolymerisation parameters.

Horizontally, the following nine interlinking work packages were pursued across all case studies:

- **WP1 Management (Leadership: Bayer Technology Services)**

  The aim of the work package was to control the work in an efficient, economic and flexible way on a day-to-day basis and to make sure that all contractual obligations were met.

- **WP2 Production scenarios (Leadership: TUDO)**

  The aim was to determine the drivers for innovations and the technical and economic barriers of existing production technologies for production in multi-purpose plants and localised production in dedicated plants. A software-based decision-making support tool for process technologists was to be developed and
A software-based decision-making support tool for process technologists was to be developed and applied to each of the industrial case studies. A full performance assessment of F³ Factory concepts against traditional plants was expected. Also a Risk Assessment Methodology (RAM) was needed to understand the value of the F³ Factory approach.

- **WP3 Integrated development and design methodology (Leadership: Britest)**
  WP3 was targeted towards a detailed assessment of existing process methodologies and the development of new methodologies to improve the speed and flexibility of current manufacturing processes. Three main tasks were to be fulfilled:
  - Development of new, generic, whole process design methodologies for the selection of chemical and process routes incorporating work-up and isolation technologies.
  - Application of existing methodologies, modelling and optimisation techniques for equipment selection and the development of new approaches where required within the context of F³ Factory’s Process Equipment Assembly (PEA) requirements.
  - Application of the results on the industrial case studies

- **WP4 Plant operation (Leadership: TUDO)**
  WP4 aimed at the development of engineering tools, methods and standardised solutions for optimal operation of F³ Factory plant and processes. The focus was planned to be placed on:
  - Development of process control concepts for small to medium scale continuous plants
  - Development of automation strategies for flexible small-scale production plants
  - Automation and optimisation of product changeover and adaption to varying raw materials, start-up and shut-down
  - Development of generic modules of a Manufacturing Execution System (MES) for flexible, multi-product, modular, continuous plants.

- **WP5 Intensified chemical reactors (Leadership: EVONIK)**
  A key challenge was the development and evaluation of new, single and integrated, intensified chemical reactor technologies which would fulfill the requirements of the F³ Factory concept. The following objectives were formulated:
  - Development and evaluation of new PI reaction concepts for chemical transformations
  - Development and evaluation of flexible multi-product reaction concepts based on the holistic optimization of selected reaction types
  - Development and evaluation of new self-cleaning kneading equipment for high viscous polymerization in mass (without solvents) to increase product quality and minimise resources input

- **WP6 Intensified downstream processes (Leadership: Bayer Technology Services)**
  The focus here was on intensified downstream processing. The work package was seeking to develop technical solutions for replacing traditional separation equipment with F³ Factory Process Equipment Assemblies (PEAs) and aimed at:
  - Elaboration of technical solutions to replace traditional separation columns (distillation, absorption etc.) by modules governed by new operation or separation principles
  - Development and construction of downstream processing equipment for F³ Factory modular plant concepts

- **WP7 Validation of F³ Factory technology (Leadership: Rhodia)**
WP7 was about evaluating F³ Factory concepts for process design and modular equipment selection and their applicability across the range of processes operated by the industrial consortium partners. Testing and evaluation of the new F³ Factory technology at different levels of complexity with respect to the desired and foreseen F³ Factory technical and economic advantages assessed in WP2 and WP3 was targeted.

• WP8 Backbone facility demonstration (Leadership: Bayer Technology Services)
  The objective was to demonstrate the effectiveness of the F³ Factory comprehensive concept by operating processes on an open-access F³ Factory Backbone Facility (INVITE). The central facility was to be setup, comprising installation, equipment standardisation, joint demonstration of the PEA and PEC developed within F³ Factory.
  A handbook of standards, guidelines and protocols for the development of F³ Factory processes and the construction of F³ Factory Process Equipment Assemblies and Containers was to be published to facilitate the wider uptake of F³ Factory processes and plant.

• WP9 Dissemination, Exploitation, Training and IP/Knowledge Management (Leadership: Britest)
  WP9 sought to engage with European stakeholders through a comprehensive dissemination programme that would facilitate wider uptake of the F³ Factory concepts. User groups were to be involved to advise on F³ Factory standards, guidelines and protocols, and to help to develop relevant training materials for both industrial and academic audiences. In addition, the eco-efficiency benefits of F³ Factory processes and plants were to be evaluated and disseminated.

Project Results:
Overview of main outcomes
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 proven the flexible, fast, future production concept through:
• Demonstration of the F³ Factory modular concept at industrial scale for commercial applications
• Realisation of an open access backbone plant (i.e. INVITE) 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

Fundamental research was, nevertheless, also instrumental for the success of F³ Factory, especially with respect to:
• Development of new process concepts
• Development of novel equipment
• Fundamental experimental studies
• Modelling and simulation
• Development of tools for optimization and economic analysis.

The most significant results obtained by over 300 scientists, engineers, PhD students, business and academic experts engaged in the project can be enumerated and summarised as follows:
New intensified and simplified continuous processes have been successfully validated.
The industrial processes have been intensified by a significant factor of up to 500. In detail, the project brought about:

- Increased space-time-yield up to a factor of >100
- Increased capacity >20%
- Increased production yield >20%
- Solvent reduction up to 100%
- Footprint reduction >50%
- Reduced equipment need >60%
- Reduction of reaction/processing time by a factor of 10
- Reduction of reaction and processing steps up to 30%

The numbers quoted above represent results achieved across the project. The outputs of individual processes and industrial case studies may be slightly different overall.

New/enhanced reactor technologies have been successfully designed and validated. Five types of reactors have been designed within different case studies of F³ Factory:

- Buss-SMS-Canzler twin shaft, high torque kneader reactor within the BASF/Bayer case study
- Mixer-heat exchange tubular reactor using Fluitec static mixer technology, applied in the Europoly case study of Rhodia-Solvay/BASF as well as in the Bayer case study
- Microstructured reactor for SO2 oxidation and the novel micro sulphonator reactor for the sulphonation reaction in the Procter & Gamble case study
- New continuous micro-structured reactor capable of handling dispersed solid catalyst and a slurry feed developed in the AstraZeneca case study

F³ Factory guidelines and standards for modular, container based production units have been defined and applied in PEA and PEC design and construction. Thus, the consortium not only demonstrated the F³ Factory concept on a range of processes and products, but also enabled and promoted the harmonisation and standardisation of equipment for intensified processing. This has been realised by establishing a strong industrial and academic network both within the consortium and outside, through dissemination activities with other European manufacturers and equipment suppliers. The F³ Factory project defined standards in terms of methods and knowledge, but more importantly for the industry outside the consortium, in terms of equipment and backbone design.

The following main standards have been developed:

- Size of Process Equipment Containers (PEC) based on freight containers for easy transport
- Grid definition within the PEC for easy implementable and interchangeable PEAs. The PEAs have been designed in discretised sizes fitting to the grid in the PEC
- Specific interface location for easy (inter-)connection of PEAs, PECs and backbone facility
- Relevant process control command between the PEAs, the PEC and the backbone

The tangible exploitation of project results applies to new and improved science and knowledge, new decision tools and methodologies, new and improved production processes, new and improved technologies, and new standards and design guidelines. More than 15 patents have been submitted or are planned to be submitted as a result of F³ Factory project.

The results of the dissemination activities comprise more than 150 conference contributions, posters and papers, more than 30 peer reviewed technical papers submitted or in preparation, a series of regular
papers, more than 50 peer reviewed technical papers submitted or in preparation, a series of regular Interest Group meetings organised for interested parties from industry and academia, and a regularly updated website and annual newsletters.

Subprojects/Case studies
Seven industrial case studies have been used to test and validate the developed methods, tools and unit operations. They show the potential of modular fabrication with respect to key parameters including time to market, flexible production volume, plant flexibility, capital expenses, plant location and multi-product plants using new and intensified continuous processes. In all product/process classes, time to market could be significantly reduced, and the production volumes adjusted to the market. In five of seven case studies, the plant could be localized close to the customer, which resulted in faster access to geographically new markets. In almost all cases, the capital costs could be significantly reduced due to the modularisation, which decreased the investment risks.

Subproject 1: Rhodia-Solvay / BASF case study - Europoly: Flexible, modular production of water soluble specialty 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 p.a. and it accounts for over €2.5 billion of annual sales in Europe. The Europoly case study of Rhodia-Solvay and BASF was supported by academic partners CNRS Nancy and TU Dortmund University, where feasibility studies were undertaken on two model polymer systems:

- Homo-polymerization of acrylic acid and co-polymerization of acrylic acid with second monomer with extremely different co-polymerisation parameters (TU Dortmund and BASF)

For the BASF study, co-polymerisation of acrylic acid and maleic anhydride was initially sent to TU Dortmund to develop the best possible intensified process for the production of acrylic acid. They were typical for a semi-batch operation and characterised by two monomers with different reactivity ratios. A study of the co-polymerisation behaviour and kinetic modelling showed, however, that a comparable polymer architecture and high conversion was not possible due to the restriction of three monomer side injections present in the continuous set-up consisting of a tubular reactor with static mixer elements. Therefore, homo-polymerisation of acrylic acid in aqueous solution was chosen for further study instead.

Then, BASF production scenarios were used for the decision-support software, developed together with TU Dortmund, which helped to find the barriers of existing technologies and an optimal production concept which, at the end, consisted in building several identical lines, each one dedicated to one product, with no change-over and with benefit from copying the lines instead this from economies of scales.

- Acrylic acid-based copolymer (CNRS and Rhodia-Solvay)

The Rhodia-Solvay case was an economic study based on different water soluble polymers and a mono-product unit of 10 kT p.a. It was found out that there was a high potential of reduced investments (by 30-50%) thanks to space-time-yield but only if the technology and equipment for continuous operation was drastically simplified, especially because a more expensive type of stainless steel needed to be used for chloride species. An important barrier to the use of simplified/smaller equipment was found out to be the unstable and drastic specifications for residual monomers. This case study was based on already existing results for milli-fluidic scale equipment for different polymer systems at TUDO and was validated at Rhodia and CNRS.

A key challenge in polymer production is to manage the high heat production rate during radical polymerisation reactions. This is particularly difficult to manage it in conventional large-volume stirred vessels.
polymerisation 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 Europol project 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 the 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 or lower investment cost
• Reduced fixed costs through lean simplified processes and productivity enhancements
• Improved process robustness by replacing batch reactors used to manufacture multiple products with continuous, product-optimized process equipment
• Improved product uniformity resulting from continuous process control instead of batch production with batch-to-batch deviations

A key success of the Europol project was the development of a scalable mixer-heat exchanger tubular reactor concept using Fluitec static mixer technology. The reactor is equipped with a novel internal cooling system element controlling the heat production during the process.

Intensive use of kinetic data in milli-fluidic devices and rheokinetic data from lab-scale batch reactors, built at TUDO and CNRS, tested during the validation stage, was crucial for the design of the intensified continuous reactor used later in the demonstration at INVITE. The continuous polymerization process was monitored by:

• In-line spectroscopy with Mid-IR at TU Dortmund University
• Raman spectroscopy at CNRS, Nancy

Lab-scale evaluation at TU Dortmund University and CRNS 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 leading to products in specification with respect to residual monomer content and molecular weight.

The fast, flexible production of polymers according to the F³ Factory concept has been achieved. The successful transfer of the co-polymerisation 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 meant for demonstration was transported to INVITE Research Center in Leverkusen, Germany, and installed there in 2013. With focus on the three aspects of F³ Factory, i.e. fast, flexible and future, the above processes were demonstrated successfully:

• Fast: The continuous and highly efficient production of polymers by radical polymerisation, with a reasonable intensification factor, exemplified the feasibility of the F³ Factory “plug & produce” approach with a “from truck to backbone” time of only a few hours.
• Flexible: The consecutive use of the same PEC and PEAs for two different polymers, one from Rhodia-Solvay, one from BASF, showed that after a short period of transient behaviour product of in-spec quality was received.
• Future: The applicability of modular technology for polymer production in a multi-product environment i.e. in a “standard” PEC consisting of several “standard” PEAs was verified.

Within the Europoly subproject, the transferability of semi-batch and batch polymerization processes to a continuous plug-flow reactor plant has been successfully demonstrated. For the semi-batch process, the continuous addition process could not be directly transferred to the continuous process because of the...
Continuous addition process could not be directly transferred to the continuous process because of the limited possibility of adding materials to the reactor. Therefore, a completely new approach was developed to optimise the degrees of freedom in the continuous plant and to reach the same product quality as in the semi-batch process. For the batch process, an experimental methodology as an aid for transposition from batch to continuous process was developed, which was particularly relevant for viscous media for polymerisation reactions, with an innovative set-up based on a small calibrated stirred tank reactor equipped with coupled in-situ Raman spectroscopy and rheology measurements. This system allowed the estimation of kinetics of the reaction as well as of the evolution of viscosity and pressure drop expected in continuous tubular reactor.

As acrylic acid is sensitive to the quality of raw materials, adaptation to variations and optimising control is crucial for the polymerisation. Therefore, a model-based control scheme for the reactor was proposed, able to detect and compensate the effects of raw material quality variations and able to maximise the reactor throughput while fulfilling the product specifications.

Regarding the medium-term production planning, the operational costs of the modularisation of equipment in terms of cost for product changeovers including physical equipment reconfiguration were estimated and analysed. The changeover costs compared to a similar batch production increase, but they can be justified for longer planning horizons.

Case study 2: AstraZeneca case study - Fast and flexible continuous processing for pharmaceutical molecules

Fine chemicals and pharmaceuticals are typically manufactured in batch-operated multi product plants for products with small to medium sales volume (range of 1 t/a-20,000 t/a). Such arrangements equipped with standard stirred tanks enable production of more diversified products and higher flexibility to fulfil specific customer demands, especially with regard to quantities and time to delivery.

Typically, the manufacturing process is fitted into an existing plant, which creates inefficiencies. Due to the given plant specification a transfer from lab scale to existing production is resource intensive and for a range of transformations can be the cause of a significant variation in yield, productivity and/or product quality, thus resulting in reduced performance in comparison to lab scale.

AstraZeneca developed a transformation methodology for nitroreductions that will enable faster process development and manufacture. The application of the methodology to several substrates was demonstrated. Technology and infrastructure allowing continuous manufacture in AstraZeneca facilities was developed and its use was demonstrated.

AstraZeneca 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.

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

- Reducing the costs of process development
- Increasing throughput and improving robustness
- Increasing manufacturing flexibility

A key barrier to overcome was 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
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. Therefore, the development and validation of a new Transformation Methodology is
one of the key achievements within this case study. 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. Several case studies have been completed (2-nitro-4-
chlorodiphenylamine, 3-nitrobenzoic acid) described in several presentations in conferences.
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. It has been demonstrated comparing the continuous and batch process. For AstraZeneca,
the RAM provided a structured approach and useful visualisation of risk assessment processes
undertaken as a matter of routine.

From equipment (“hardware”) point-of-view, the 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
• The development of a new continuous, micro-structured reactor (in cooperation with KIT) capable of
  handling dispersed solid catalyst and a slurry feed, thus removing the need for fixed bed technology
The micro-structured PI reactor equipment was validated for performing the transfer hydrogenation under
pressure in KIT. Compared to previous results (max. conversion ~ 45%), the conversion has risen,
complete conversion can be observed for a residence time of only 38 s at 60 °C. A clear dependence of
the conversion on the residence time can be observed, while the influence of the pressure is not essential
once it is high enough to keep the produced gas in solution. A new mixer and plate for the laboratory
reactor, that gave a longer residence time were designed and built by KIT, and further demonstrated on a
larger scale at AstraZeneca.

A semi modular production unit with the ability to install different PEAs depending on the chemistry
required has been designed, constructed and installed successfully at AstraZeneca’s large-scale
laboratory in the UK. Tests of this PEC-like facility accommodating the slurry flow reactions have fully
validated this new transformation methodology including the transfer nitroreductions. This effort further
included the scale-up of solid supported evaporation in collaboration with KTH and the derivation of scale-
up rules for this unit operation.

AstraZeneca is now evaluating this new production unit for drug projects and obtaining better yields
(above 70% in continuous operation vs. 50% in batch).

Case study 3: EVONIK case study - Flexible, continuous production of chemical intermediates

Evonik Industries AG focused on the demonstration of the flexible, continuous production concept for
intermediate chemicals which are the basis for products on the final markets. The work aimed at the
investigation and economic evaluation of radical changes in production technology of highly exothermic
reactions, the performance of which suffers from the tremendous amount of heat released by the reaction,
e.g. resulting in steep temperature gradients in the reactors. This nowadays leads to complicated technical
reactor constructions as multi-tubular reactors with up to 30,000 reactor tubes or equipment with complex
and fragile internal cooling devices. Such reactors are unique in construction and are usually newly
designed every time a new application or capacity is necessary. Numerous oxidation products such as
acids, aldehydes etc., are nowadays economically produced only in large scale plants with capacities
around 100,000 t/a.
The problems in heat and mass transfer in contemporary reactors also limit the performance of the reaction, i.e. space-time-yield, product selectivities, or catalyst lifetimes. Therefore, F³ Factory sought to optimise mass and heat transfer in the reaction units, simplify the reactor designs and parallelise the plant operation. Preliminary data show that if innovative Process Intensification technologies are implemented, the following substantial improvements in scale-up effort and performance of plant during operation can be reached:

- Space-time-yield +50 %
- Reactor manufacturing costs -50 %
- Energy input for reaction -10 to -20 %

Furthermore, not yet quantified improvements have been reached, such as more safety in plant operation or CO2 savings.

The academic partners – TU Dortmund University, TU Eindhoven and Newcastle University – were involved into the EVONIK case study and worked on 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. Two different technologies focusing on the intensification of mass and heat transfer were investigated:

- Structured catalyst pickings - Three-dimensional open foams were applied as carrier materials for catalytic material applied in highly exothermic reactions. The structured packings can intensify mass and heat transfer in the reactor, i.e. significantly lowering the temperature gradients within the reactor at similar other reaction conditions and performances. In consequence, space-time-yield and selectivity can be enhanced, and the reactor construction can become simpler.

- Jet-loop reactor with integrated “cold” membrane separation – Jet-loop reactors have narrow gas bubble distribution with smaller size compared to conventional bubble columns. Their use in combination with integrated, innovative cold separation technology via membranes for catalyst retention, however, offers an intelligent approach for significant reduction of manufacturing cost and energy input.

The first reactor technology required new catalyst structures which can 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 reduces investment and enables greater standardization of reactor technology. Parallelisation of this technique also offers high potential for more flexibility in production capacity to support future market growth.

The second reactor technology was designed for highly exothermic liquid-gas reactions. Innovation in catalyst development (e.g. coating of the foam catalyst in order to increase the active catalyst mass) makes an improved reactor design/concept in terms of heat management and mixing necessary. 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 scalable reactor equipment
- Reduced operating costs due to maximized space-time yield and integrated heat management
- Improved selectivity due to low heat gradients and ideal mixing
- Improved catalyst lifespan due to separation under process conditions

Partial oxidation, epoxidation and hydroformylation were selected as example reaction classes for the case studies. In cooperation with TU Dortmund, a software tool called ProMoT was developed to evaluate the economic and technological aspects of applying the F³ Factory approach. The results showed economic benefits for the F³ Factory concept under the applied boundary conditions. Especially for an
economic benefits for the F Factory concept under the applied boundary conditions. Especially for an expansion strategy, the modular concept of a jetloop reactor with membrane separation offered valuable benefits. Also overall methodology was developed in cooperation with UNEW and the Excel based multi-decision suite called ChemPrompt. As a result, a systematic workflow was obtained for screening process options based on available equipment / PEAs.

With the help of the universities, models including detailed representation of the processes and equipment have been set-up to optimize operation conditions and operation control aspects and applied with inclusion of EVONIK.

Together with TUDO, a control strategy for the jet-loop set-up was simulated. The obtained results were based on a dynamic model of the pilot plant developed by the DYN group at TUDO based on the reaction kinetics data and the parameters of the membrane separation model provided by TUE and the FVT group at TUDO. The model includes the heat balance with both a cooling jacket that is used to control the temperature of the reactor and a heat exchanger that is used to cool down the stream out of the reactor. Using this model, the best control structure from the point of view of a profitable operation of the plant was selected in a systematic manner, by comparing the profit the results for different possible structures. The experimental work confirmed nearly all of the targets except for the application of catalytic foams in the liquid phase operation. It was performed for both the structured catalytic packings and for the jetloop reactor. The focus of the structured foam catalyst was on the development of a coating procedure to further increase the active catalyst mass. This was successfully done by modifying the slurry parameters resulting in an increase in active material loads varying between 0.3x to 0.5x compared to material load of the fixed bed reference. Unfortunately the promising results from gas phase applications could not be transferred to liquid phase epoxidation reaction. Therefore, the application of structured foam catalysts was abandoned for liquid phase applications.

The jet-loop reactor with integral membrane separation in 5 l scale was set-up. The continuous experiments of the two parallel jet loops were successfully performed at the pilot plant of the EVONIK site in Marl. Expected yields and selectivities were achieved. Different membrane types were further tested in a separate set-up. Improvements in retention could be gained in a way that an economic application is feasible. Modeling the kinetics of three substrates at TU Eindhoven supported the operations by identifying optimum substrates and operating conditions. Two of the substrates were used to demonstrate continuous operations in the jet-loop reactor with membrane separation. 1-pentene shows great potential to achieve unprecedented high TTONs.

The design and engineering of a PEC for the hydroformylation process placed special focus on the safety and toxicity concept. Considering the circumstances of INVITE Center (parallel running of different PECs, ventilation system) the EVONIK PEC consists of a glove box system. The construction work of the PEC was finished in time at EVONIK, transported to INVITE and connected to the backbone facility.

The newly developed process was operated continuously for more than 100 hours for the first time at INVITE. The goals in terms of membrane performance, yield, selectivity and safe operation were reached. However, more experimental time is needed to evaluate the long-term behaviour of the membrane section as well as possible by-product formation. This will be followed further internally after the project at EVONIK. It is worth noting that the PEC was operated on the same back bone facility in parallel to another PEC of Bayer Technology Services.

Case study 4: Arkema case study - Demonstrating modular production technology for high volume intermediate chemicals

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. This high volume
year) are traditionally manufactured in large, dedicated, continuous world-scale plants. This 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 improved technologies.

Arkema sought to demonstrate both the technical and economic viability for producing high volume intermediate chemicals in decentralized, modular, continuous, medium scale plants, focusing on the development of smaller and more flexible production units located closer to raw material suppliers or downstream users. Several identical plants, which have been thoroughly optimized with whole process design and process intensification, were designed based on the principle of row housing.

Working in collaboration with Process Design Center, Ehrfeld, Coatex and three academic partners, CNRS Nancy, TU Dortmund and the Institute of Catalysis & Surface Chemistry of the Polish Academy of Sciences, this case study is exemplified by the production process of acrylic acid and its derivatives from biomass-based glycerol – a widely available green byproduct of oleochemistry and biodiesel production. Whole process design evaluation by PDC, 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. 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 crystallisation apparatus for melt crystallisation using milli/microstructured devices in a falling film setup increasing the productivity by 70% has also been developed and patented by CNRS and Arkema. The reduction of necessary equipments also allowed for lowering operation costs, i.e. raw material and energy use.

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

Another important achievement is the integration of reaction and separation step, here distillation, for the production of butyl acrylate. TU Dortmund University developed in cooperation a reactive distillation column which simplifies the process and for which all specifications of the products have been achieved. The main challenge was to inhibit the potential polymerisation within the column which has been realised by the development of a generalised polymerisation inhibition method for columns. Furthermore, besides energy saving, the production price per ton of product using a reactive distillation could be lowered. Coatex developed a novel process of continuous polymerisation of acrylic acid in tubular reactor. Limitation of gel formation during polymerization was successfully obtained with Controlled Radical Polymerisation. An intensification factor of 60 was obtained with this new process in comparison with state of the art semi-batch polymerisation.

All developed equipment parts have been validated at Arkema and TU Dortmund University within two pilot plants of the F³ Factory concepts at a scale of several kg/h, whereas bio-based acrylic acid has been successfully polymerized at Coatex. It has been found out that the concept of F³ Factory intensification at changing scale with decentralized medium-scale plants is economically competitive as compared to world-scale plants. Even if specific capital and labour costs increase, they can be compensated by decreasing transport costs and by higher degree of utilization due to the ability to follow market step by step investment. A net profit value increase
Degree of utilization due to the ability to follow market step-by-step investment. A net profit value increase by 30% has been obtained with three plants as compared to one world scale plant. It has also been found out that the production costs of acrylic acid produced in two to four plants from glycerol are competitive to the production in one big plant. As all sister plants are similar in design, the reduction of engineering efforts and purchase bring another significant saving of investments.

Arkema also demonstrated flexibility concept of F³ Factory. The idea is that a PEC that has been designed for one chemistry can be used for another chemistry with only minor adjustments. A continuous polycondensation reaction to manufacture polyamides was successfully piloted in the PEC that was used for BASF/Bayer demonstration of high viscous polymer. The versatility of such equipments will allow to reduce their unitary cost and increase profitability of the equipment supplier.

Case study 5: Bayer case study - 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, INVITE, Ehrfeld, Britest, TU Dortmund University, 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. In spin-off benefits, it will also progressively enable the F³ Factory partners to secure faster development, design and engineering of future processes.

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, the key stages of the project included:

• Chemical redesign against the paradigm shift of continuous processing
• Simultaneous chemical and continuous process development
• Integration of reaction and separation steps in the container
• Demonstration in the modular F³ Factory design

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 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. The key benefits identified 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 the 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 the transformations involved)
• Reduction in apparatus cost (ca. 30% depending on the intensification of the relevant module)
Being the first industrial case study that was demonstrated at INVITE backbone facility, the Bayer project paved the way to establishing the standards for Process Equipment Assemblies (PEAs), the Process Equipment Container (PEC) and its integration into the backbone infrastructure services 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. Bayer demonstrated synthesis steps 1 and 2 in the Process Equipment Container at the INVITE backbone facility.

Case study 6: Procter & Gamble case study - 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 PGB project has focused on the intensification of two key reactions stages (SO2 oxidation and sulphonation) using novel reaction technology and modelling of the economic viability of the concepts in the latter stage of the project.

With no major progress in surfactants production technology for decades, potential gains from the F³ Factory approach could be significant. The current business model is to produce bulk surfactants at large-scale, centralised locations and then to ship them to finishing sites.

Process Intensification is seen as the main lever available to progress the supply chain to a more sustainable and lower cost model. The concentration on two unit operations is essential to attain an overall step change; therefore, the project focused on SO2 oxidation and sulphonation.

The size and inertia of current SO2 oxidation towers negatively impact the whole plant agility. Additionally, due to the limited use of intensification, sulphonation forces the dilution of SO3 with large amounts of air. This markedly increases the plant’s capital, volumetric and environmental footprint. New processes providing flexibility, agility and sustainability may lead to more flexible, modular and intensified plants to produce the surfactants including the supply chains which are needed by the consumers.

The project team investigated the concept of a micro-structured 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 micro-structured reactors has been developed. Through detailed modelling of this new reactor at the TU Dortmund University, the performance has been optimised to achieve a conversion rate of more than 98%. Based on this, a sophisticated control was developed able to reduce the time between the start-up phase and the established steady-state (production) by a factor of 3.

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 were determined and an adequate correlation developed.

The sulphonation process on the lab-scale reactor prototypes, designed and manufactured at ICPF, was tested during the demonstration phase of the project in PGB’s pilot plant facility in Brussels.

For the PGB case study, intensification of two key reactions stages (SO2 oxidation and sulphonation) in the production of anionic surfactants - using novel reaction technology - has largely been proven at the lab scale with a potential space-time-yield improvement by a factor of 5. The work focused mainly on designing the equipment for the oxidation of SO2/SO3 convertor (KIT), developing and designing a micro sulphonator reactor (ICPF) to carry out the sulphonation reaction and lastly upgrading and integrating the
A novel reactor concept for sulphonation reactions was developed by ICPF and received with high attention by the industrial partner because it is assumed to have a high potential to change some of the paradigms existing in the industry concerning the contemporary operation mode of reactors. A lot of fundamental work is still required in this area, thus, PGB and ICPF intend to cooperate on this topic also in the future, beyond the boundaries of F³ Factory project.

The economic viability of the new technology was re-evaluated using the ProMoT tool. At the current state of the art of the new technology it is challenging to meet the formulated objectives of a dispersed supply chain concept. However, the evaluation revealed what requirements had to be fulfilled for the objectives to be fully met. These requirements can be regarded as boundary conditions serving as guidelines for the future development in this area.

Generally speaking, a proof of concept was achieved. The new technologies developed under the F³ Factory can deliver the desired transformation. Concerning the SO2/SO3 conversion, the lab-scale reactor demonstrated a successful reactor concept able to achieve at least the same conversion rate. Thermal management with the integration of heater cartridges inside the reactor body and proper insulation of the equipment also proved to work very efficiently. The new technology developed by ICPF to track SO2/SO3 conversion in a highly corrosive environment was implemented successfully. This is a first-of-the-kind development, and PGB will continue developing this technology for possible re-application at full scale to enable an improved process control over the entire process.

Although the development was very young, it was demonstrated that alternative approaches were economically competitive with the incumbent technology. PGB and ICPF have already agreed to continue the collaboration in developing further fundamental knowledge around the hydrodynamics.

Case study 7: BASF / Bayer case study - Process intensification for high viscous polymer production

BASF and Bayer Technology Services (BTS) 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 the 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 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” such as solvent-free polymerisation cannot be carried out in standard mixers. Therefore, this F³ Factory case study 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.

A new twin-shaft, high-torque kneader reactor was demonstrated 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 a flexible adaptation to different products and processes, with the ability to switch rapidly between different mixing rotor assemblies. The following performance indicators show that the R&D effort has been successful:
following performance indicators show that the R&D-effort has been successful:

• Good mixing through the whole range of viscosities
• Narrow residence time distribution
• Instant removal of volatile components
• Self-cleaning behaviour
• Construction to withstand high dynamic loads

The University of Paderborn (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-Canzler (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 the validation of the new reactor technology at a lab scale and successful polymerisation experiments, the modular plant concept was designed by BTS and demonstrated successfully at the INVITE facility in Leverkusen over an extended processing time, confirming both the strength and integrity of the kneader reactor.

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. By eliminating the use of solvents, the process has been intensified significantly. It has reduced complexity and energy consumption, and it facilitated the successful transfer from batch to continuous polymerization. In addition to the technological advancement achieved in this project, the transfer from batch to continuous of a new solvent-free polymerization process demonstrated both the cost (30% decrease in energy demand) and environmental (100% solvent reduction) benefits for the continuous production of high viscous polymers. The demonstration result is a polymer within the specification regarding molecular mass and polydispersity. The new concept allows significant savings in both the capital and operational expenses. Detailed CFD modelling will allow for further optimisation of the reaction technology.

Work packages

The following nine work packages had an important task to provide crosslinking between the case studies and to support synergies wherever they could play an important role.

WP1 Management (Leader: Bayer Technology Services)

F³ Factory was managed according to well defined procedures built up based on the extensive experience of the coordinator. The role of the management team was to control the project work flow and observe the delivery of all results in an appropriate quality, in an appropriate time and within the budget, and thus to make sure that all contract obligations are met. The management fulfilled the following tasks:

• To identify and confirm deliverables, milestones, staff levels, materials, external costs, travel, depreciation of capital items
• To coordinate and conduct the project according to the work plan and adapt the work plan, if necessary
• To ensure efficient and high quality communication between the partners
To ensure efficient and high-quality communication between the partners

- To ensure a smooth transfer of information (e.g. reports) to and from the Commission
- To administer and distribute the financial contribution paid by the Commission among the partners

The objectives were successfully implemented on a day-to-day basis.

WP2 Production scenarios (Leader: TUDO)

Work package 2 aimed at the following two main aspects:

- The development of the production scenarios for modular, continuous production concepts and
- The development of a decision making tool for the selection of the right production mode for each of the case studies.

TU Dortmund University worked closely together with the seven industrial companies on their case studies (Arkema, AstraZeneca, BASF, Bayer Technology Services, EVONIK, Procter & Gamble, Rhodia) as well as with CNRS, Process Design Center and the University of Newcastle.

The WP started by the determination of the drivers for F³ Factory innovation and the technical and economic barriers of existing production technologies across the various industrial case study projects and work packages for both the production in multi-purpose plants and localised production in dedicated plants. This work also result in economic, technical and development time targets for other work packages in the project.

The next step was the development of a new software-based decision-making support tool - Production Mode selection Tool (ProMoT) - to help process technologists to effectively apply F³ Factory concepts by finding the right production scenario for each of the industrial subprojects. It has been specifically developed using the F³ Factory industrial base cases as examples, each having its own specific production characteristics. Thus, a high variety of factors was taken into account and influenced the production mode decision. The processes under investigation ranged from small-scale batch production of pharmaceutical intermediates (AstraZeneca, Bayer Technology Services) via medium-scale production of specialty polymers (BASF, Rhodia) to the production of large-scale intermediates (Arkema, EVONIK, Procter & Gamble).

For the ProMoT development, F³ Factory processes for each production scenario were used to develop black-box models, for both batch and continuous operation. To facilitate the economic evaluation of scenario alternatives, a generic cost model applicable for conventional and F³ Factory processes was developed, taking into account the new features of the F³ Factory concept. Equipment models were used to develop drag-and-drop items for fast process implementation. This feature accounts for additional economic drivers such as shorter time-to-market by applying a modular process design based on F³ Factory equipment, less development and implementation effort or advantages due to a breathing production. The changes in the cost structure due to the modular design were also determined.

The novel ProMoT tool assists the user in the decision-making process by helping him to find out when and under which conditions a new F³ Factory production concept is more efficient than the existing state-of-the-art production technology and to evaluate the economic and ecological efficiency of the whole production supply chain including:

- Raw material and energy supply (incl. transport)
- Process needs
- Energy use and waste production
- Time to market constraints
- Product transportation
- Site constraints
The output from the ProMoT tool provides a full performance assessment of F³ Factory concepts against traditional plant concepts. As opposed to the conventional simulation software, ProMoT is designed to be able to simulate both batch and continuous production scenarios. ProMoT combines the determined requirements for non-conventional process modelling, cost models and equipment models and makes a generic evaluation of the whole supply chain and life cycle of a production possible. As the decision for the right production mode has to be taken in early phases of process development, ProMoT allows for a simple calculation of mass and energy balances with a direct subsequent cost calculation – a feature also making it a pioneer. Exploiting this unique combination of features, the ProMoT prototype was used within the project to perform a benchmarking of F³ Factory processes against traditional processes based on the production scenarios, which lead to a definition of economic and technical development targets. As an additional outcome of the ProMoT development, a draft work flow was designed to make ProMoT assist the decision maker leading to find a fast and well-founded decision about the right production mode.

The work on the development of the ProMoT tool for assessing both Net Present Value (NPV) based economic evaluations and process simulation has been successfully completed. The tool was developed, validated and optimised in respect to time-dependent production capacities. Also here, strategies concerning the risk and account for uncertainty and variability in the business / production scenarios and product line portfolio were developed by UNEW and tested by AZ.

WP3 Integrated development and design methodology (Leader: Britest)
Under the leadership of Britest, BTS, Arkema, AstraZeneca, BASF, SMS, CNRS, DTU, EMB, EVO, ICPF, KTH, PDC, PGB, Rhodia, TUDO, TUE, UNEW, UPB and INVITE contributed to this work. Work package 3 developed tools and methodologies for the design of innovative flexible intensified production processes for operation in F³ Factory plants. These tools and methods consider:

- Selecting, integrating and ordering of unit operations to deliver the most efficient process
- Appropriate use of scale-up and scale-out approaches for capacity increase
- Mapping processing tasks onto F³ Factory Process Equipment Assemblies taking into account business, technical, regulatory, SHE and energy requirements.

Innovative methodologies, mathematical and graphical descriptions and optimisation methods and tools were developed to address:

- The decision about when and how to integrate, separate or re-order unit operations and pieces of equipment and to develop the most efficient whole process to make a defined product
- Appropriate selection of scale up and/or scale out
- Selection and design of process equipment from priority areas identified by industrial partners. This includes process intensified units like integrated reaction and separation units and hybrid separation processes
- Mapping of processing tasks onto Process Equipment Assemblies (PEA)
- Modelling, screening and optimising design options, using numerical modelling techniques
- Selection of a preferred process option, accounting for business, technical, regulatory, HSE and energy requirements

The methodologies and tools were developed from, and applied to, specific industrial processes in the frame of the case studies to deliver and validate the overall F³ Factory objectives for the fast design of flexible and future plants.
WP3 comprised three tasks. The first one, led by Britest, generated conceptual process design methodologies for developing multipurpose, modular plant, involving multistage reactions and work ups, in a data lean environment, in a short time scale. It also incorporates methodologies to reduce a large number of options to a small number of possible lead options.

The most significant achievements in this task were:

- Collation of the existing methodologies to set the baseline for methodology development
- Collation of information from each of the partners and used to define what Fast, Flexible and Future means in the context of their varying business strategies. This was crucial to set the overall generic conceptual process design methodology into context for each of the industrial partners.
- Based on the above work, and the methodological development work also done, a preliminary methodology for the conceptual design of F³ Factory processes was proposed. This comprises such key activities as the development of process understanding, the conceptual reaction design, the conceptual separation design and the conceptual flowsheet design. Conceptual process models provide a basis for identifying key experimental work to support fast process development, design and scale-up.
- Validation of the draft methodology with each of the teams working on the industrial case studies

- A revised approach, involving two related methodologies was developed: a “fast” methodology for the rapid design of processes where an existing suite of PEAs is available, and a “full” methodology where engineering of new PEAs is required.
- The Britest team synthesised information provided by Bayer Technology Services concerning conversion of a process flowsheet into PEAs into a set of points to be addressed when designing PEAs. This list was included in the “full” conceptual process design methodology.

The second task in this work package, led by partner University of Newcastle, applied the existing methodologies, modelling and optimisation techniques, to select the equipment for plants, and developing new approaches only where required within the context of F³ Factory PEA requirements.

Significant cross-project achievements in these tasks were:

- The development and demonstration of the ChemPrompt multi-decision suite software tool for the selection of equipment incorporating risk and uncertainty. A module was developed to select and design appropriate process equipment based on mathematical programming, which makes faster equipment selection possible.
- A preliminary methodology for conceptual equipment selection, design and optimisation was proposed and validated. This identified the following decision scenarios:
  - PEA meeting process technical requirements is available
  - Sub-optimal PEA not meeting technical requirements but enabling process to satisfy business needs is available
  - No appropriate PEA is available but business drivers support new PEA design
  - No appropriate PEA is available and business drivers do not support new PEA design
- The results of feedback received during the validation meetings were also used for the same software tool as the equipment selection tool in WP2.

The third task in this work package integrated the conceptual process and optimised equipment design through the application to specific example product types, for the development of F³ Factory processes by the industrial partners. The collation and generation of fundamental data required, for different product types, for the use in the methodologies and models, was also carried out.
The activities in Work Package 4 were focused on the development of engineering tools, methods and standardised solutions for the optimal operation of F³ Factory plant and processes. Also this work package worked across the seven industrial case studies. Under the leadership of TUDO, RWTH, Bayer Technology Services, BASF, Arkema, Rhodia and KIT contributed to the work done.

The most important actions and results consisted in:

• Development of process control concepts for small to medium scale continuous plants
• Development of automation strategies for flexible small scale production plants
• Automation and optimisation of product changeover and adaption to varying raw materials, start-up and shut-down
• Development of generic modules of a Manufacturing Execution System (MES) for flexible, multi-product, modular, continuous plants

The focus of the process control concepts was on the analysis of the controllability and selection of control structures for modules of intensified plants and for plants that are composed of several modules. Control structures have been investigated across four of the industrial case studies and second-phase studies on these projects were done as follows:

• Modular tubular reactor for producing water soluble polymers (Rhodia/BASF)
• Sequence of reactors for intermediate production (Bayer Technology Services)
• Jet loop reactor with membrane separation (EVONIK)
• Reactive distillation column for butyl-acrylate production (Arkema)

Additional project activity concentrated around:

• An estimation scheme for the state of a high-viscous kneader reactor (BASF/Bayer)
• Dynamic spatially distributed 3D modelling and simulation of an intensified SO2-oxidation process and control design for the pilot plant (PGB)

Concerning the task on automation strategy, under the lead of Bayer Technology Services, the requirements for the automation of future, flexible, modular production units have been defined and are now available as a key outcome of this work package. Bayer Technology Services also investigated and realised automation concepts for the first Process Equipment Container (PEC).

For the automation and optimisation of product changeover and compensation of varying raw materials, two test cases for the plant-wide optimisation and control of modularised F³ Factory plants were defined:

• Flexible variant of the Bayer API production PEC
• Pilot plant for production of water soluble polymers

For both these examples, product changeover, start-up and compensation of disturbances by advanced control were studied.

For the flexible API production plant, an integrated dynamic model has been built and the optimisation of product changeovers, including structural changes of the plant (bypassing units), has been demonstrated by RWTH Aachen.

Concerning the water soluble polymer plant, the goal is to maximise the throughput for given specifications of the final polymer at the outlet of a series of tubular reactors. Degrees of freedom are the side injections of monomer and initiator, and the temperatures of the modules.

The requirements for a Manufacturing Execution System (MES) for future, flexible modular plants were elaborated by Bayer and discussed with project partners and a specification document was drawn up covering:

• Introduction to MES
• Modularity of MES
In the final year of the project, some of the functionalities of a MES System were demonstrated using examples derived from process developments by the industrial partners e.g. the flexible API production process and production of water soluble polymers. Such functionalities include:

- An F³ Factory configuration monitor
- A module for campaign planning in flexible continuous plants including reconfiguration of the modules of the plant according to the needs of specific products

WP5 Intensified chemical reactors (Leader: EVONIK)

EVONIK led a team of the following partners through this work package: Bayer Technology Services, Arkema, AstraZeneca, BASF, SMS, CNRS, EVO, KIT, ICPF, PGB, Rhodia, TUDO, TUE and UPB.

A key challenge for WP5 is the development and evaluation of new, single and integrated, intensified chemical reactor technologies which fulfill the requirements of the F³ Factory concept.

Two strategies were followed:

- New PI reaction concepts for chemical transformations with respect to optimised heat and mass transfer to achieve maximum selectivity or space-time-yield towards the desired products, to minimise the energy input to the reaction system, to increase the product quality and to minimise the input of resources, e.g. solvents, and with respect to the applicability to varying feed quality, e.g. renewable resources.
- Flexible multi-product reaction concepts based on the holistic optimization of selected reaction types by combining several reaction operations (integrating in new monolithic devices) or by assembling modular reaction equipment.

The reactor concepts of the work package were realised on lab-scale level and were experimentally investigated and validated with respect to their applicability to the F³ factory methodology. Performance tests were conducted and debugging and optimisation was performed substituted by basic knowledge gathered and optimisation strategies developed in WP3. Finally, the delivered reactor technologies were designed in detail to fit to the proposed Process Equipment Container Technology for F³ Factory modular plant concepts of the three different F³ Factory product lines (a) polymers, (b) specialty chemicals and intermediates and (c) fine chemicals for consumer goods. These were - if applicable - installed in the PEC’s and PEA’s and were applied in the F³ Factory facility. This broad spectrum of different applications should show the widespread aspect of the new F³ Factory technology within the different areas of chemical production.

Due to the complex structure of the F³ Factory project and the chosen development strategy of the different partners involved in WP 5, the palette of work performed was widespread. The following tasks have been successfully completed:

- Definition of products and their constraints with respect to the reactor-set-ups
- Definition of operating conditions for single and multiple product reactor operation
- Design and set-up of reliable lab-scale equipment
- Estimated economic and technical benefit of the new PI reactor technology
- Performance of PI equipment and scale up concepts for PEA

The reactor technologies were investigated for all industrial case studies with respect to:

- Performance optimization by modifying operation conditions
Performance optimization by modifying operation conditions
- Mass and heat transfer performance
- Model set-up and simulation of PI reactor technology to show the potential against the conventional operation
- Applicability to F³ Factory approach

In the following, a short summary of the main results within each of the case studies is given.

In the Arkema case study, it was demonstrated that a fast deactivating catalyst can be implemented in a 2-reactor system or even one single multi-section reactor leading to an important decrease of the equipment as well as installation costs. New operating conditions in reaction and in regeneration with fewer energy consumption lead to a reduction of 20% of total variable costs (raw material + energy) of acrylic acid, and an improvement by about 25% of the space-time yield of the dehydration reaction. Scale-up concept was proven in WP7.

In the second one of the Arkema case studies, two integrated PI reaction technologies were studied for the acrylic ester production. The feasibility of a reactive distillation for butyl acrylate production from acrylic acid and butanol was shown leading to a calculated reduction of 12% total production costs compared to state of the art process. In a second modular approach a membrane separation coupled with reaction in acrylate ester production showed a decrease in energy demand of 10 – 20%.

EVONIK case study investigated the use of structured foam catalyst for application in highly exothermic reactions (gas and liquid phase) in order to reduce the commonly observed hot spot formation. For gas-phase applications, promising results could be achieved: Lower observed peak temperatures lead to higher product selectivity which come along with a decrease in CO2 formation and higher space-time-yield. Also a jet-loop reactor was operated successfully with an integrated membrane separation of the homogeneous catalyst for the first time. This allows an easy and gentle catalyst recycle resulting in enhanced catalyst lifetime as well as an improved reaction performance (increase in selectivity). Proof of principle in terms of the F³ Factory concept was achieved demonstrating a parallel jet-loop setup.

In the Rhodia case study, the transfer from batch to a continuous process was successfully developed for water soluble polymer reactions. Therefore, a continuous Static Mixer Reactor concept has been developed which is highly versatile, flexible, scalable and modular. A key point of this study was to produce three different polymers (Rhodia and BASF) with various issues in the same equipment to illustrate the multi-product concept.

For the example of BASF, a reactor technology for high viscous polymerisation was introduced. For that technology a methodology was developed that allows the scale up of those reactors even for large-volume applications. Thus, a new production technology for a solvent-free (non-toxic and eco efficient) polymers was established.

For AstraZeneca case study, a batch process for a model reaction step was transferred to continuous mode. The newly designed reactor system was evaluated to carry out the nitroreduction (by transfer hydrogenation) of two model compounds. The system was shown to be of advantage by increasing the space-time-yield and flexible applicability to different reactions and process conditions.

The PGB case focused on two key unit operations in anionic surfactant making plants. In that course two intensified reactors (micro-converter and micro-sulphonator) were developed leading to improvements in terms of reactor size (reduced capital costs) and utility streams (e.g. air).

In summary, almost all technologies developed within the work package showed the proposed benefits and could successfully be transferred to a PEA. Four of them were installed in a PEC and were demonstrated at INVITE.
WP6 Intensified downstream processes (Leader: Bayer Technology Services)
The team lead by Bayer Technology Services (BTS) in this work package consisted of Arkema,
AstraZeneca, BASF, SMS, CNRS, EMB, EVO, KTH, Rhodia, TUDO, TUE, UPB and RUB.
This work package was seeking to develop technical solutions for replacing traditional separation
equipment with F³ Factory Process Equipment Assemblies (PEAs) and focused on:
• Micro-distillation and absorption
• Membrane separations
• Evaporation and condensation
• Crystallisation
• Polymer processing

Micro-distillation and absorption concepts
Distillation and absorption tasks have focused on the comparison of innovative and conventional
(modularised packed columns) concepts in unit operations handling gas or vapour flows counter-currently
to a liquid. They comprise micro-falling-film devices, micro-membrane contactors and HiGee contacting
devices as intensified technologies as well as conventional modularised packed columns as technology
with high maturity. A comparison of mass transfer characteristics in the respective operation windows of
the different devices has been carried out.
Irrespective of the separation process, the number of transfer units decreases with increasing throughput.
It has been demonstrated by the modelling studies that in most cases the separation efficiency within the
intensified equipment can be increased by one order of magnitude, based on the free active volume within
the respective equipment. This finding was confirmed for the concept of sorptive gas/liquid contacting in a
micro-membrane device, which was developed by BTS in collaboration with EMB. The device was
successfully operated using the process of stripping of toluene from water as a test system.
As far as the process design for downstream processing of the Bayer subproject is concerned, the
feasibility of solvent exchange after reaction stage, additional necessary liquid/liquid separation steps, the
removal of a light boiling component with a stripping column, an extraction process for the final product as
well as its treatment in a washing process were examined experimentally. The combined process
consisting of all reaction and separation steps was demonstrated in a continuously operated laboratory
setup. Concerning the production of acrylic acid based on renewable feedstock in the ARK subproject, two
schemes for the purification of bio-based acrylic acid by a set of distillations to produce high quality acrylic
acid from reactor outlet flow have been validated in laboratory scale experiments. The second one of the
schemes is much simpler, due to a lower number of distillation columns. One impurity, however, could not
be removed by distillation. A CNRS study revealed that melt crystallisation was efficient for the separation
of this impurity, and thus the number of required crystallisation steps was evaluated.

Membrane separations
TUDO investigated a separation process consisting of a hydroformylation reactor and membrane
separation, which was especially relevant for the EVONIK case study. The goal was to use validated
models of the prediction of membrane separation performance to optimise process efficiency.
In contrast to distillation processes, cold separation processes carried out within membrane devices offer
the benefit of saving in the field of energy consumption, catalyst separation or to overcome thermodynamic
limitations of gas/liquid equilibria.
The main objective of TUDO’s contribution was to investigate the process consisting of a hydroformylation...
The main objective of TUDO’s contribution was to investigate the process consisting of a hydroformylation reactor and membrane separation. The goal was to use validated models for the prediction of membrane separation performance, which could be used for the optimisation of the separation process with respect to economic efficiency. The optimum separation strategy was determined by means of a mathematical optimisation routine that takes into account different types of membrane modules.

An existing model for permeation through polymeric membranes was extended to ceramic membranes. Moreover, a comparison to experimental data reported in literature was performed. The result is a structured approach to the modelling of membrane permeation. Due to a multitude of different transport mechanisms and important parameters reported in literature, the model was set-up in a flexible way allowing the user to switch between different modelling depths. While the transport mechanism for polymeric membranes is based on a sorption-diffusion-desorption behaviour, transport through ceramic membranes is mainly due to convection through narrow pores. For both types, model parameters were estimated based on experimental data from EVONIK and literature.

For the purification of acrylate ester/alcohol azeotropic mixtures, CNRS evaluated membrane separation that had scarcely been considered in the field of acrylic derivatives. Efficient membranes were selected and surprisingly no ageing of the membrane was observed in long term test trials under fouling conditions.

Simulation studies showed that hybrid separation (distillation and membrane) is very efficient for the type of separation and much more efficient than classical processes.

Evaporation and condensation in micro-channels
New equipment was developed and characterised for evaporation and condensation. The technology was suggested by EMB and BTS and is based on the concept of rectangular channels in the Miprowa technology. By month 18 of the project the first prototype was ready. It was suggested to implement further developments mainly on the side of the service medium. However, before implementing any of the new concepts, thorough characterization of the equipment was imperative. This work has been partially carried out with project partner RUB.

The prototype was characterized and optimized later in the project by EMB. In conclusion it can be stated that evaporation has been investigated in two different Miprowa® channels both with and without mixing inserts. The range of total evaporation can be extended by the inserts by about 50%. The more interesting questions and tasks for this design lie in heat transfer and its use as a reactor instead of using it as evaporator.

Evaporation is an inherent process for distillative applications, but is also applied in applications such as evaporation to dryness and solvent swaps. In particular, evaporation to dryness can lead to thermal stability issues and the solid can become difficult to handle because of electrostatic charging, sticking to walls, and dust formation. The team at KTH together with researchers from AZ developed a solid supported evaporation method where a support in form of porous polymer beads is used to facilitate the solidification of the compound upon solvent removal (crystallisation).

The compound loaded on to the beads is less prone to dust formation and sticking, and it is easier to handle because the solid is in the form of a flowable granular material. Moreover, as the beads provide an additional heat sink, the risk for thermal decomposition during solvent removal is lowered. The method has been tested for various compounds that vary widely in their physical and chemical properties. Preservation of flowability of the loaded beads has been selected as a criterion for determining the maximum loading under a given evaporation protocol. Experiments at higher loading or at faster evaporation lead to beads sticking to the walls of rotavap flask or to neat material depositing on the flask used for evaporation.

Using either operating mode, all compounds could be loaded onto the beads. However, in batch mode,
Using either operating mode, all compounds could be loaded onto the beads. However, in batch mode experiments it was found that the loading capacity, i.e. the amount of compound that can be loaded onto the beads before extensive sticking of beads and deposition of neat compound onto the glass walls of the flask occurs, depends on the substrate. This can be explained by considering the solubility of the substrate in the given solvent and by mass transfer into the inside of the porous beads. Experiments in the continuous mode where the beads form an agitated granular bed can handle higher loadings and the process is less sensitive to the nature of the substrate. However, high evaporation rates with respect to the feed rate need to be maintained in order to operate the process.

Novel crystallisation concepts

In this task, KTH and AZ developed a solid supported evaporation method where porous polymer bead supports are used to facilitate solidification of the compound upon solvent removal. In some applications, the focus is not on a simple isolation of solid material but on purification of solid material. As mentioned before, the acrylic acid produced from glycerol feedstock and purified by distillation in the Arkema subproject still contains propionic acid, which has to be separated by other processes since classical purification techniques like distillations cannot efficiently separate these two components. Nevertheless, due to a favorable phase diagram, melt crystallization is a promising purification technique. Separation of PA from AA was first studied with filled glass and stainless steel calender tubes. A falling film device was then built. Several operating parameters were studied in order to obtain an optimal yield, a high purity and reduced crystallization times for purification.

Nevertheless, due to high similarities between the two molecules, strong hydrogen bonds and particularly the purification is still difficult. Improvements seem, however, achievable if the efficiency factor can be improved. A promising way identified is to use microdevices, since increasing the ratio between cooling surface and reactor volume is an interesting way to improve heat transfer and to reduce super-cooling. Thus, micro-grooved surface or fish-bones structures allowed an increase of productivity of a full crystallization step by up to 550% compared to the first set of experiments, for the same crystallisation yield and efficiency of separation of the undesired impurity. According to the experimental results, a sequence of crystallisation steps was simulated.

Polymer processing

In another application, where the solid is not formed by crystallization but rather in a reactive way as in polymerization processes, major difficulties in handling the highly viscous phase during the polymerization have prevented in many cases the implementation of solvent free processes. To overcome these difficulties intensified equipment is necessary, which guarantees material integrity and enables supplementary effective mixing as well as devolatilisation and solidification especially at long residence times in continuous mode. For these purposes a new intensified continuous kneader is investigated as well as validated by experiments under varying conditions within WP 6.7 (Polymer processing – devolatilisation & solidification).

By applying the concept of effective viscosity an integral model for the torque of the kneader was developed by Bayer Technology Services which allows the prediction of power input. Concerning material integrity, the strain at defined parts of the rotor has been measured at UPB and was compared to results of numerical simulations performed at TUE by using CFD. Both are in good qualitative agreement.

WP7 Validation of F³ Factory technology (Leader: Rhodia)

F³ Factory project aims to promote “smart-scale” production which will improve the ability to serve market
The Factory project aims to promote “smart scale” production which will improve the ability to serve market needs by being able to respond quickly to market demands and will allow larger financial benefits: in place of large world-scale plants, numbering up of “smart scale” plants are targeted, with the advantage of being more flexible and readily implementable. Benefits provided by a fast market response must be secured by developing a new concept of plant design, involving a “plug and produce” approach based on intensification, modularisation and standardisation of equipment to ensure the fast implementation of a new chemical plant at affordable capital expenses.

The partners involved into this work package led by Rhodia were: BTS, Arkema, AstraZeneca, BASF, CNRS, COA, DTU, EVO, KIT, ICSC, PGB, Rhodia, TUDO and INVITE.

Through many workshops involving the engineering departments of the different industrial partners, the standard guidelines for the modules design have been established and applied to fully operational processes. These guidelines aim to standardize the F³ Factory modules based on PEA (Process Equipment Assembly: these “wrap” process equipment items associated with one or several process tasks are the smallest modular element, they are specific to a given production application) and PEC (Process Equipment Containers: a superstructure that holds the PEAs in position and provides the services required by the PEA, which can be skid-mounted and equipped with racks and may have their own process control system) concepts. These guidelines for PEA and PEC have been defined in coherence with the INVITE backbone developed for demonstration purpose in the frame of F³ Factory project, and according to most of the needs of each industrial sub-projects. Most of the industrial sub-projects have developed their modular process according to F³ Factory guidelines, showing the relevance and robustness of the standards which were proposed.

The processes developed in the seven industrial sub-projects have been validated at lab scale or pilot-scale based on a modular F³ Factory approach, before most of them were implemented in the INVITE backbone facility for demonstration, to validate that smart scale plants are economically viable thanks to the combination of the different advantages developed by F³ Factory methodology, and according to the drivers of the seven industrial sub-projects, as identified in WP2.

Regarding F³ Factory process validation, it must be highlighted that all the 7 sub-projects successfully passed the technical validation of the different intensification-based PEAs which were developed (mainly reactors), showing the maturity of the intensification approach in Europe. Four projects out of seven, which is already a remarkable result, have validated the F³ Factory modular approach with F³ Factory guidelines, with a demonstration at INVITE and promising perspectives at the industrialisation scale. This result underlines some limitations which were encountered regarding modular plant development, the boundary of which having been challenged F³ Factory projects:

- The footprint impact: one of the constraints encountered by some processes is the PEC size imposed by the standardization approach, which may be not compatible with some unit operations due to their size: to implement equipment or modules in the limited size of a container, size and footprint decrease thanks to intensification is crucial: however, some unit operations like distillation, due to poor mass transfer, remains difficult to miniaturize.

- For very large volume of production (with an order of magnitude of several hundreds of kT p.a.) to compete with fully optimized and centralised world scale plants will remain challenging

- On the other hand, for small volumes, regarding current batchwise multi-product plants with complex recipes, a key point remains to justify the switch from a multi-functional single equipment to a series of several continuous equipment, through a drastic simplification of the process and a significant intensification factor.
Besides these limitations, fast, flexible and future production concept has been validated during the last project period with key results and learnings:

- **Fast**, with the quick transformation of lab results in modular PEA/PEC based process and the efficient F³ Factory “plug & produce” approach validated in INVITE, and with a time from truck to operation of less than one hour;
- **Flexible**, with the almost “one fits all” approach, since four different processes have been containerized under the same standards, and with different products made in the same PEAs;
- **Future**, with strong interest and support from the engineering departments of the industrial companies involved in the F³ Factory project, yielding current production range from 5 to 200 T/a at INVITE, and industrial projection of a few kT/a easily reachable from a technical perspective.

In conclusion, it can be stated that, based on the results achieved with F³ Factory project, a large room for modular processes exists, consisting in an additional route for “smart-scale” unit, and F³ Factory has been a multifaceted project which must be considered a major advance in modular plant learning curve, thanks to the validation of key objectives:

- The validation of new processes and elements, by developing new processes based on intensification, and by being able to design the modular process according to the product chemistry and not to adapt the product recipe to the equipment limitations
- The validation of operational and efficient standards for modular processes, as exemplified by the modularization of almost all processes according to F³ Factory standards and with a positive financial impact.
- The validation of containers and backbone exploitable at the industrial scale, as demonstrated for four different modular processes at pilot scale in INVITE container plant, showing the robustness of the concept with promising potentials at the industrial scale.

Regarding the perspectives, F³ Factory, which is to be considered as the beginning and the corner stone of modular processes, has also pointed out how to move forward on our learning curve, with regards to both standardized equipment and industrial modular scale

- **For standardised equipment**, mature standardized equipment based on intensification is still not available, and this issue must be addressed by the reduction of equipment footprint and size, especially for downstream operations, by encouraging continuous process development at micro, milli and centi-fluidic scale in academic and industrial worlds, by improving equipment robustness and flexibility (residence time range, solid handling, etc.)
- **For industrial modular scale**, the concept of modularity of manufacturing plant and supply chain needs to go further: cost decrease of standardized equipment remains a wager on the future, and this wager on the future must be won by challenging and improving F³ Factory standards with the input of engineering companies, by disseminating the standards regarding modules and interfaces with the enrolment of equipment manufacturers and process control supplier in the modularisation, and by developing advanced business model including integrated product supply chain for modular plants.

**WP8 Backbone facility demonstration (Leader: Bayer Technology Services)**

This work package demonstrated the effectiveness of the F³ Factory concept by operating demonstration processes on an open access F³ Factory Backbone Facility (INVITE) at CHEMPARK Leverkusen.
processes on an open access F Factory Backbone Facility (INVITE) at CHEMPARK Leverkusen. A handbook of standards, guidelines and protocols for the development of F³ Factory processes and the construction of F³ Factory Process Equipment Assemblies and Containers have been made available to facilitate the wider uptake of F³ Factory processes and plant.

The partners involved into this work package under the leadership of Bayer Technology Services (BTS) were: Arkema, AstraZeneca, BASF, KIT, ICPF, EVO, PGB, Rhodia, CNRS, TUDO and INVITE.

The work in this work package started with the design and construction of the backbone facility both for PEA and PEC, the design of the interface between PECs and the respective backbone facility as well as the development of a logistics concept for reactant and product handling, in the second project year, conceptual as well as construction work on the backbone facility was completed.

The backbone facility INVITE Research Center, which was co-funded by the Ministry on Innovation, Science and Research of North Rhine Westphalia, was opened in September 2011. For F³ Factory Factory, it serves as the backbone facility for the demonstration of chemical and pharmaceutical processes designed in a modular, flexible and sustainable way, providing infrastructure and site services.

Following an Open Innovation approach, INVITE Research Center is open to the public. After the completion of the construction work, the focus shifted towards the evaluation of plant concepts and the work necessary for setting PECs and PEAs into operation in INVITE.

In order to achieve the main objective of the F³ Factory project, i.e. to develop and demonstrate Fast, Flexible and Future oriented processes, radically new 'plug and produce' modular production technology was developed. Important cornerstones of this approach comprise of Process Equipment Containers (PEC) which hold several Process Equipment Assemblies (PEA) that were designed according to guidelines for design and standardization developed within the F³ Factory consortium.

In this context, modularity and interchangeability of PEAs was an important aspect in both PEA and PEC design. The development of the PEC grid, the discretisation of PEA sizes, the work carried out in the standardisation of interfaces and the analyses carried out to identify the optimum PEA arrangement inside a PEC all aim at obtaining flexible, modular and easily exchangeable PEAs. Eventually, the developed modular and container-based plants were predominantly tested and operated in INVITE.

To fulfil the criterion of demonstrating the continuous operation of both multi-product and dedicated plants as well as all key technological aspects of F³ Factory, 3 lines were built in parallel. They were devoted to the production of polymers, of intermediates and of consumer goods, respectively. The following five out of seven industrial case studies were successfully demonstrated at INVITE in the container-based, modular F³ Factory approach:

- Bayer started the demonstration series by the proof of PI concept regarding active pharmaceutical intermediates
- BASF/Bayer investigated the suitability of the F³ Factory approach for the solvent free production of high viscous polymers.
- EVONIK demonstrated a jet-loop reactor for the production of chemical intermediates
- Rhodia/BASF illustrated the multi-product concept by demonstrating the production of different water soluble polymers in the same equipment
- Arkema/Bayer demonstrated a continuous polycondensation reaction to manufacture polyamides successfully in the Bayer-PEC that was used for BASF/Bayer demonstration

It can be concluded that through the demonstration of the different subprojects, case studies results for all dimensions of modular manufacturing were generated. It was e.g. demonstrated that the F³ Factory modular concept is feasible at industrial scale for commercial applications. From an environmental and resource efficiency point of view the project demonstrated that drugs, polymers or surfactants can be
resource efficiency point of view the project demonstrated that drugs, polymers or surfactants can be produced with a reduced energy consumption up to 30%, a solvent reduction up to 100%, a footprint reduction up to 50% and the potential to reduce or eliminate transportation by enabling local or point of use production by installing the production plants in ISO containers.

An open access backbone plant for modular continuous production, i.e. INVITE Research Center was realised, and new intensified and simplified continuous processes were designed and validated. Design guidelines and standards for modular, container based production units including design and control have not only been established but also validated. And finally, through the strong intra-company network formed over the duration of the F³ Factory project, a platform for future projects, young scientists and a link to education has been created. It is thus foreseen, that besides conventional production plants, these modular plants will play an increasingly important role in future industrial production.

WP9 Dissemination, Exploitation, Training, IP/Knowledge Management and Eco-Efficiency Assessment (Leader: Britest)
The goal of this work package was to proactively engage with European industry (particularly SMEs), academia and other stakeholders to enable wide dissemination of the F³ Factory concept. In this way the potential of the backbone facility as an accessible platform for dissemination, exploitation and training purposes should be maximised. Apart from Britest also Bayer Technology Services (BTS), BASF, DTU; INPL and TUDO were involved. Other aims of WP9 were to continually facilitate the rapid exploitation of project results by the consortium partners, refine and update the exploitation plan and provide industrially focused training, education and awareness materials for the tools and methodologies developed in the RTD work packages aimed at a variety of target audiences within and external to the consortium. The projects outcomes also needed facilitation in order to be transferred into academic curricula. Doing all this, an effective and efficient mechanism for knowledge management including IP protection and approval processes for publications was developed and observed. Also the evaluation of the eco-efficiency of F³ Factory processes and dissemination of its outcome to the wider European processing community was a task in this work package.

In the frame of dissemination activities, the project website www.f3factory.com was created in WP1 at the start of the project. It has been updated periodically throughout the duration of the project with information and progress on the individual work packages and industrial case studies. This activity concluded with the publication of the outputs from the industrial case studies and overall project achievements. The content for all website material has been generated based on the input from Consortium partners against a schedule agreed with the IPR/Exploitation board. In addition, a suite of industrially focused training, education and awareness materials has been developed which can be accessed and downloaded from the project website. Britest has worked closely with BTS in the general administration of the website and IT interface with the website hosts in Bayer.

To establish and maintain a good communication with potential interest groups, three successful joint Industrial and Academic Interest Group meetings were held during the project period. The first, in March 2010, set out to communicate the F³ Factory aims and objectives and engage with industrial and academic groups outside the Consortium on key project challenges. The second, in November 2011 at the then newly opened INVITE facility, sought to communicate key scientific/technical developments in the project. It also provided an opportunity for the interest group attendees to view the Process Equipment Containers and Equipment Assemblies. The third, in April 2013, also at the INVITE facility, sought to disseminate key achievements in relation to design standards and methodologies for new modular, flexible production technology and showcase some of the industrial case studies that were being demonstrated at
production technology and showcase some of the industrial case studies that were being demonstrated at the INVITE facility. The Interest Group meetings were all well attended with 50-60 delegates at each event and proved to be a valuable part of the project dissemination plan. Additional interest registered via the website has been responded to as appropriate.

Dissemination activities addressing external target groups also took place throughout the duration of the project at several key industrial conferences and events including ECCE, CHISA 2010 & 2012 and ACHEMA 2012. In most cases, Britest and BTS led the coordination of a broader EU Framework 7 project session at these key industrial conferences incorporating input from the F³ Factory, COPIRIDE, PILLS, SYNFLOW and POLYCAT projects. The sessions were attended by the EU Project Officer and/or EU Technical Advisor and were well received. At the conclusion of the project there had been 153 conference papers, posters and/or press articles delivered as part of the project dissemination activities.

A great variety of communication materials (slide decks, invitations, fliers, poster templates etc.) were created to introduce the F³ Factory project and encourage attendance at workshops in support of key work package programmes including activity on F³ Factory engineering standards. Project newsletters were published in M14, M27 and M38 in both electronic and hard copy format. In addition, a suite of literature summarising the key achievements of the project and outputs from each of the seven industrial case studies were published and distributed at the SusChem Stakeholder Event and final project dissemination event in M47. All publication material was distributed to Consortium partners for onward dissemination to their key industry / academia contacts, uploaded to the project website and distributed at key industry events.

Since the start of the project a number of media enquiries have been responded to that have resulted in several published feature articles as well as several smaller editorial pieces. A Q&A set was developed to facilitate consistent messaging about the project and these were made openly available to the media (and other interested parties) via the website. A final project Press Statement highlighting the key project achievements was prepared by BRIT for use by the Consortium partners and for release to external audiences via the project coordinator. A project exploitation plan has been developed. This has been updated on a regular basis through annual teleconference discussions / meetings with the Consortium partners and via discussion at work package, subproject and General Assembly meetings. A formal Exploitation Strategy Seminar (ESS) was attempted in June 2012 but the process and external facilitation was deemed to be unsatisfactory. Since then, all exploitable results emerging from the project were identified and documented in a structured way by the Consortium. At the end of the project lifetime in M50, there were 38 exploitable results documented. These have since been uploaded to the EC Cordis website. The assessment of barriers to innovation and the approach to strategic decision-making in relation to modular, flexible production technology versus conventional production routes has been integrated into the training and educational resource materials.

The business model for a flexible, backbone production facility has been defined by BTS and successfully demonstrated through the construction and ongoing development of the INVITE Research Center in Leverkusen. This is now being taken forward by the INVITE Management Team as part of the legacy for exploitation of this facility beyond the F³ Factory project.

Concerning the training, Britest facilitated planning meetings and co-ordination of the development of education and training materials for use by the partners and more broadly by EU industry and academia. INPL led the development of these materials with input from Consortium partners based on defined topic areas agreed at WPL/SPL meetings. These materials cover five subject areas:

- F³ Factory project overview
• Factory project overview
• Modular and flexible continuous chemical production concept
• Business drivers for implementation of modular production technologies
• Eco-efficiency evaluation of flexible, modular continuous production
• Conceptual process design methodologies

The training and education materials have been developed as voiced over PowerPoint presentations with scripts that can be accessed and downloaded directly from the project website.

BASF, who was the task leader on the eco-efficiency analysis of the F³ Factory concept, and INPL completed their task using the BASF case study and eco-efficiency model. It was hoped initially that this would also be conducted on two other case study projects but this was not possible due to confidentiality issues.

Key outputs from WP9 have been:
• A comprehensive range of dissemination activities including: website, newsletters, fliers conference presentations/papers/poster, workshops, access to the F³ Factory backbone facility in Leverkusen etc., to foster engagement and communication to a broad range of industrial and academic audiences in the European processing community
• Co-ordination and publication of a project Exploitation Plan and Industrial Case Studies
• Publication of a suite of industrially relevant training and education materials
• Contribution to building innovation skills capacity in Europe via the SusChem-led Educate to Innovate initiative.
• Co-ordination of IP and Knowledge Management activities emanating from the project and facilitation of generic knowledge sharing via publication of a Generic Knowledge report.
• Report on the eco-efficiency evaluation of F³ Factory processes

These activities sought to enable a wider uptake of the sustainable benefits of F³ Factory processing by European industry.

Potential Impact:
In the F³ Factory project, the European chemical industry came together to develop advanced technologies and to enable early validation of novel and knowledge-based tools and demonstration of the next generation’s production systems.

Macroeconomic impact on European level
The F³ Factory will have a high leverage on the chemical industry. Owing to the results of the project, possible annual cost savings of up to € 300 million to € 3,750 million have been calculated, for the time of about ten years after the project ends. At least € 100 million additional turnover will also be generated from the sales of new products for which the production will become economically viable as a result of the F³ Factory concept. Whilst it is difficult to accurately project the impact of F³ Factory on the growth of new business, it can be expected to have a significant effect also there.

European socio-economic impact
The remarkable savings which can be realised by the implementation of the F³ Factory concept will by no means result in a reduction in jobs. Rather the opposite is expected because of a) additional new business that will be started up and b) a reinforcement of SMEs, manufacturers of new process equipment and producers of chemicals. They will afford the development of new equipment and processes due to the
producers of chemicals. They will afford the development of new equipment and processes due to the access to F³ Factory backbone facilities and through the utilisation of standards. They can more easily keep their high level of specialized process and manufacturing know-how and stay competitive. Moreover, the working conditions and safety will improve due to 40% less hazardous materials and inventory.

Environmental impact
Eliminating “waste operations”, estimated 5 fold reduction in process heat/cool utility requirements, 100% principal solvent saving, >50% reduction in process area are an impressive outcome of the F³ Factory. The calculations by the F³ Factory partners reveal significant potential impacts on:

• The carbon footprint: 150,000 tons of CO2 can be avoided if bio-produced glycerol is used as feedstock for the production of 10% of the demand for acrylic acid
• Energy: distillation currently consumes ~7% of the overall energy used by the chemical industry (more than the total consumption of NASA & the aviation manufacturing industry). With the F³ Factory approach, it can be reduced by up to 30%.

While the F³ Factory engineering and early validation concept clearly address very specific challenges (and expectations) of companies and their processes, the transfer and demonstration of the F³ Factory concept in the three product lines deliver business cases which already have impact on the European chemical industry as a whole. The F³ Factory’s holistic approach clearly extends to all levels of technical and economic development of the European chemical industry and provides a sustainable change to more sustainable ecologic production.

Strategic impact
The outcome of F³ Factory leads to the following impacts:

• Increased product diversification: Existing products can be manufactured in a more economic and efficient way in multi-product plants owing to faster changeover and clean out (e.g. low hold up volumes). The turnover of bio-based acrylic acid alone is higher than €100 million. Also in case of new and improved products, the portfolio can be broadened significantly due to the availability of small, economically efficient production plants, which will lead to an increase in sales volumes. Novel technologies can be implemented into small and medium scale products with high added value, where prices are higher than € 100/kg. The sales by manufacturers of equipment can rise by 50%. The production of customised products will only be economic in regional F³ Factory plants.
• Shorter time-to-market: The development time for intermediates can be decreased by 30%. The relevant savings are assessed to amount to about € 150 million p.a.
• Flexible production in accordance with market demands: only for the representative polymers (SAP, POM), savings of about € 65 million are expected. The costs for plant engineering will be reduced by 25%. The logistics costs (warehousing and transport) will decrease by about 30%. Small scale production adaptable to market demand through economic viable numbering up (e.g. realising same specific capital investments in small-scale compared to world-scale plants).
• Substantial drop in capital expenditure for new plant and/or retrofit: 40% reduction in capital investment during product life time through standardized, modular toolkit is expected, whereas retrofit through modular/standardized equipment will go faster by 50%.

Impact along the product types “Polymers”, “Intermediates” and “Consumer products” and associated Three segments of the European chemical industry cover €180 billion sales per year, which represents 38% of the whole sales volume (CEFIC). Along these product types and even beyond towards the
38% of the whole sales volume (CEFIC). Along these product types and even beyond towards the complete chemical industry and associated industries such as manufacturers of equipment, the examples demonstrated in the F³ Factory project function as nuclei for the tremendous impact of the F³ Factory technology.

F³ Factory Example 1: Paradigm change by introducing solvent free processing
For the range of low to medium viscous materials, the high cost of individual plant engineering can be reduced by more than 20% due to improved heat transfer capability by one order of magnitude. This allows for concentrated recipes and thus reduced solvent use and energy savings. Furthermore, the project outcome allows a simple design and transfer from batch to continuous processes, thus gaining flexibility in lot size, process stability, and safety. The modular approach can easily follow changing market demands by adding or removing process lines. This is advantageous for big companies and also opens an opportunity for start-ups and SMEs to enter new markets and to grow out of market niches.

For high viscous materials, such as high-temperature thermoplastics, here polyoxymethylene (POM) and super-absorbing polymers (SAP) e.g. for diapers, it is expected, that intensified devices like high-viscous processing modules will reduce the production costs by 10%. POM and SAP alone have a worldwide turnover of more than € 4 billion p.a. Hence, a potential impact of € 400 million p.a. is expected in this area. For the European producers with a market share of about 30%, this means savings of at least € 130 million p.a. more if the market share increases due to reinforced competitiveness. We expect that within 10 years this potential will be exploited to 50%.

A real step change is solvent-free production enabled by F³ Factory. For amorphous high-temperature thermoplastics, 0.3-0.5 €/kg production costs are accounted for solvents due to wasted solvents, distillation and related energy costs, as well as higher investments for devices and lower space-time-yield. The savings potential of this segment of industry (considering approx. 50 kT p.a. and € 10 – 30 \( \text{p.kg} \) market price) sums up to € 15 million p.a. (PERP 03/04S12).

F³ Factory Example 2: New products
For the production of novel high performance products, a knowledge-intensive production is necessary. As an example, processing and compounding of and in high-viscosity products made from renewable raw materials and polycondensates, rapidly increasing viscosity of the polymer can cause problems while mixing both to a homogenous level. These can be overcome within limits by increasing the mixing energy introduced into the system. Limiting effects are e.g. depolymerisation of the polymer or mechanical limits. New ways of mixing using optimized kneader geometries are necessary to overcome these limits.

F³ Factory Example 3: Production of intermediates using standardized process equipment
The use of this equipment shall enable faster, yet inherently safe production of kg amounts of products made by standard transformations such as Grignard reactions and Suzuki couplings. These intermediates are conventionally prepared at “kilogramme-laboratories”. The production processes for these transformation products will be less time and expense consuming. It is expected that the development time for intermediates is reduced by 30%, which has a direct impact on the resources needed. This reduces the costs of product and process development leading to a saving of € 20 million p.a. for AstraZeneca: The reduction of waste and of costly reactants increases the expected savings. This is merely 0.4% of the R&D volume of AZ in 2011, but for a common specialty chemicals company with lower expenses for R&D it can be assumed to be 4%. Extrapolated to the R&D volumes of the European producers of fine chemicals (~5% of sales; ~20% market share for specialty chemicals (CEFIC); total sales of European chemical industry in 2011: € 539 billion), this sums up to savings of € 215 billion p.a. to be used to 70%.

The transformation of products will also increase the throughput of potential products, improve process...
The transformation of products will also increase the throughput of potential products, improve process robustness and maintain product quality by generation of processes using standard transformation methodologies. It will increase manufacturing flexibility and reduce the change-over time between manufacturing campaigns (standardized equipment). And also it will help to avoid cross-contamination by standardised cleaning protocols and equipment ease substantially the scale-up to production campaigns.

F³ Factory Example 4: Novel production of fine chemicals and intermediates

Pharmaceutical intermediates and drug product are a growing worldwide market. Process-intensified production enables process novel and sustainable routes for these meeting the regulatory requirements and high quality specifications. High rates of heat transfer to avoid “hot spots” and therewith formation of by-products, reduction of waste and consumables, narrow residence time distributions are only provided by PI production. High yield, high selectivity, production adapted (responsive) to market demand are enabled and made economically viable by F³ Factory technology.

F³ Factory Example 5: Production of intermediates of life science products

For life science and crop science products, a sub-segment of specialty chemicals in terms of CEFIC, the production costs will be significantly reduced by approximately € 3-4 million p.a. per product. This reduction is based on savings of € 0.3 to 0.4 million p.a. and per process step for typical intermediates due to the use of process intensified F³ Factory equipment leading to reduced energy consumption, less waste etc. Even if this is applied to only 20 products, savings of € 60-80 million can be achieved. Crop protection products cover only ~1.3% of the sales of the chemical industry (CEFIC). If the impact can be extended to only 10% of the production of the European chemical industry, savings of € 460 to 610 million p.a. are expected 10 years after project end.

F³ Factory Example 6: small and medium sized production of epoxides

Epoxides are used in a variety of applications. Present production routes exhibit deficiencies with respect to undesired side products. Furthermore, the products are required by customers in varying amounts. Alternative reaction routes, e.g. direct epoxidation in innovative F³ Factory reactors and downstream technologies will suppress “hot spots” and therewith production of the side-products. A selectivity increase of 10 % as compared to the conventional process is envisioned as well as yields close to the stoichiometric value. “Cold” separation technologies will enable to significantly reduce energy consumption and loss of product due to decomposition. Applying F³ Factory technology, variable costs will be reduced by 20 % and the modular, size-independent concept of F³ Factory will enable to build plants in different sizes with no additional development costs dedicated to the customers’ needs at the sites of the customers. This development will initiate new markets for the environmental benign oxidant H2O2 in the field of chemical production of small to medium size products.

F³ Factory Example 7: production of anionic surfactants

PGB’s network of world size, highly optimized continuous plants, with a volume of ~1.5million tons/a, represent the state of the art in the field of anionic surfactants, a primary ingredient in consumer goods. By using F³ Factory process intensification and modularization it is intended to shift the balance in favour of regional production sites, leading to at least 10% reduction in total manufacturing cost and increased supply chain response time, which basically will pave the way to cost effective distributed production sites. Today, in principle these smaller regional sites have a natural advantage in responsiveness and transport cost, but to date they are not attractive because of the increased CAPEX and OPEX at lower throughput, as well as the process being too complex to allow spreading operations to many more locations. F³ Factory allows for several significant advantages:

• €5 million p.a. savings in logistics (warehousing, transportation)
- €5 million p.a. savings in logistics (warehousing, transportation).
- Reduction of business risk: If a specialized product happened to fail at the market, the plant is readily re-dedicated to other products.
- Enabling the production of specialized, higher value surfactants
- Enabling customized products, not feasible in dedicated large scale architectures
- Increase of the safety factor (-> increased acceptance of chemical sites)

**Macroeconomic impact**

Besides the extrapolations derived from the impact of the demonstrators of F³ Factory, a more generalized calculation of the macroeconomic impact reveals a greater potential for reduced costs of goods manufactured (COGMs):

Britest members cover the manufacture of a significant range of chemicals including precious metals, catalysts, agrochemicals, printing inks, speciality chemicals and pharmaceuticals, as well as innovative engineering design. The processes in these companies are traditionally operated in multipurpose batch plant. Previous studies have shown that at least 50% of processes that are currently batch could be done in a continuous manner. Other studies have shown that in batch processing 50-80% of production cost and time is associated with work-up and isolation and that 35% of business costs are associated with development, manufacture and formulation. Work published by Foster Wheeler reveals that significant savings can be achieved. By jointly developing the F³ Factory modular approach we expect savings:

Taking a turnover of € 56 billion p.a. (Britest members), assuming a 25% margin leaves € 42 billion of which 35% = € 15 billion is associated with manufacturing.

Assuming 50% of processes can benefit and make a 50% saving (i.e. 25% saving)

25% of € 15 billion p.a. = € 3.75 billion p.a!

If this number holds for the Britest membership, which has been calculated in a top-down approach, and it compares by its order of magnitude to the number calculated bottom-up from the sum of F³ Factory industrial partners, it gives some strength to the assertion that these levels of savings are achievable by the chemical industry following the F³ Factory approach.

**Sales volume and impact on SMEs**

Especially SMEs in the field of chemical production (SMEs are an important part of the European Chemical Industry as they have a market share of 30% in sales and provide 37% of the jobs in the chemical industry) will profit from the standardization and modularization efforts of F³ Factory, as that will enable them to set-up flexible and cost-efficient small- to medium-scale production plants. An example:

**F³ Factory Example 8:**

BASF spent € 5.4 billion for property, plant and equipment in 2012. At the same time BASF had a business volume of about 23% for polymer and 20% specialty polymer related productions. Assuming only 50% of investment in polymerization plants on the basis of 2012 (€ 756 million) will use this technology, an investment volume of more than € 350 million would contribute to the growth of that modular design concept, helping the European producers to grow and further develop and optimize the technology. Stimulating new developments along the supply chain of chemical production

**F³ Factory Example 9:**

By developing integrated and multifunctional prototypes for industrial production of chemicals F³ Factory stimulates for example also at partnering industries like equipment manufacturing. As a viable example
stimulates foreground also at partnering industries like equipment manufacturing. As a viable example EMB will serve to show the relevance of interdisciplinary synergies in the area of process intensification. The business of EMB as an example for modular plant equipment supplier has increased in the last four years by 140%. The main part of this development bases on the assortment of equipment for lab scale. The intensified commercialization for the production scale due to F³ Factory will result in an increase of 50 % of sales.
Moreover, the development of F³ Factory technology will not only broaden the assortment of EMB, but will also open the door for BTS for new markets on the fields of process development and plant design and construction. In this context the F³ Factory demonstration facility opens up the possibilities for BTS to be the preferred partner on the market of engineering companies for Process Intensification and future manufacturing concepts.

Impact on European Research Area: Benefit of a European approach
European chemical and pharmaceutical industries become more global and competitive, and pressures are applied by the USA and Asian competitors. In “Technology Vision 2020” a strategic plan has been developed to maintain the competitiveness of U.S. chemical companies in the global business environment. Here, a key area of R&D, is the development of efficient approaches for intensified processes. The F³ Factory project competed with this vision in order to strengthen the European competitiveness in this future-oriented area, helped to respond to the growing demand for affordable chemicals and thus contribute to European Research Area. Because of the collaboration of the global players and leading academic centres the fragmentation was and will be reduced by improved cooperation and set the basis for long-lasting cooperation and the promotion of a common European Research Area. The project construction required the close partner collaboration not only during the project but also far beyond the project lifetime and therefore forces the main players to exploit the project results in a concerted way allowing for strategic exploitation alliances in the global economy. The overall objective was to provide the sector with the necessary framework conditions for assuring a sustainable development and contributing to the accomplishment of the Lisbon objective and contribute to EU Framework Programme for Competitiveness and Innovation (CIP). The F³ Factory project generated standards for intensified and uniformed production of chemicals contributing to the REACH initiative and support the High Level Group on the Competitiveness of the Chemicals Industry in the European Union.

The European approach within F³ Factory was imperative to the successful exploitation of PI, as the main players and experts in this field are distributed over Europe and additionally essential for the developing of industry standards. Several national and international projects have been started which fostered either academic developments or favoured technical interoperability of a heterogeneous architecture. It was time to get down to an economic view on process intensification that stimulates further development of technologies instead of integrating new technologies. F³ Factory turned the view on process development by focusing on industrial relevant processes, economically attractive product groups, practically relevant methods across the entire value chain of chemical production and SHE aspects on several levels – thus requiring a true interdisciplinary and European approach.

Steps to achieve the impact
In parallel to the project, the consortium partners Bayer Technology Services and TU Dortmund established the open backbone facility INVITE for any demonstration purposes in European chemical industry. Demonstration here does not only mean that processes of the partners are implemented and tested in this plant. This F³ Factory backbone facility is open to any companies of the European chemical
tested in this plant. This factory backbone facility is open to any companies of the European chemical and chemical engineering industry and academia to test and apply the F³ Factory concept.

Further steps will be taken outside this project in order to deepen the impact stimulated by the proposed project. Follow-up projects in partner companies will be pursued in order to transfer the results of this project to other product segments and process types.

In addition, the guidelines developed in F³ Factory have to be advanced and broadened and have to be brought into a standardisation process leading to common standards.

A final key aspect will be to apply international training modules developed to spread the holistic PI approach to specific target groups, such as plant designers, hardware suppliers, engineering companies and into the education of chemists and engineers to develop a most sustaining impact on European brains.

Relevance to national or international research activities
A most stimulating result of F³ Factory which also affects the global view on Chemistry in Europe will be the successful implementation of the F³ Factory concept for three quite different, yet representative segments of the European chemical industry. The implementation in these three segments will be initiated by the exploitation of the project’s outcome by the consortium. Simultaneously, all information necessary to take part in the exploitation of F³ Factory is disseminated in a controlled, directed manner by means of open platforms such as SusChem as well as European industrial interest groups. By doing so, F³ Factory also harvested expertise from a previous European Project (FP6-IMPULSE), of which several partners are members of the F³ Factory consortium. Further partners represent several national activities, such as the German DEMIS project, the µChemTech project, the µProChem project and others.

Assumptions and external factors – boundary conditions to the impact
For a number of parameters, a usual development was taken into account for the assessment of the impact of F³ Factory. Unexpected changes of these parameters towards values, most of which are normally considered as being disadvantageous, improve the impact of F³ Factory:

Market prices
- Increased costs for oil based feedstock
- Increased costs for primary energies

Regulatory constraints by authorities
- Decreased exposition levels for hazardous, irritant or toxic substances
- Decreased emission levels for hazardous substances
- Raised taxes on primary energies
- Diminishing inventory of hazardous materials
- More restrictive rules for CO2 emissions / increased costs for CO2 certificates

Public opinion
- Increasing demand for biodegradable chemicals
- Increasing demand for customized / individualized products

All of the above mentioned tendencies amplify the impact of F³ Factory, because industrialisation and production become more economic under these circumstances.

Individual impact on the level of case studies:

Evonik case study
Evonik case study
The impact of jet loop reactors and membranes on overall investment costs is very high (nearly 80%). Thus, numbering up of distillation columns does not increase the overall investment costs significantly (+10%). In addition the effect of economy of scale is weakened. Therefore, the stepwise expansion leads to an increase of 16% in NPV compared to a PI plant without stepwise expansion.
Concerning the membrane separation step, a comparison was drawn to the conventionally used distillation step. Assuming a total capacity of 100kta an investment cost reduction of around 30% can be estimated. Even more attractive is the reduction in energy costs. Here more than 70 % can be saved which sums up to more than €0.3 million p.a. Most of the benefits are gained from the improved life time of the catalyst. Depending on the current catalyst, price savings of more than €2.7 million p.a. can be achieved assuming the long-term behaviour of the membranes is similar to the performance during demonstration phase. Finally the improvements in yield and selectivity in the reaction step due to a better heat and mass transfer sum up to savings in the range of €0.5 million p.a. Thus for a 100 kta plant savings of more than €3.5 million p.a. can be realised with the new technology developed.
Summing up, the following attempt was made to characterise the impact:
The STY increase was assessed to amount to 50%, the CAPEX reduction 30%, savings through increased selectivity up to € 450 T p.a. the decrease of variable costs (solvent, energy, utilities etc) amounted to €2.7 million p.a. From the technological point of view on process robustness, improved temperature control and increased selectivity could be reached.

AstraZeneca case study
The use of the transformation methodology shall enable faster, yet inherently safe production of kg-amounts of products made by standard transformations such as Grignard reactions and Suzuki-couplings. These intermediates are conventionally prepared at “kilogram-laboratories”. The new production processes for these transformation products will
- increase the throughput of potential products, improve process robustness and maintain product quality by generation of processes using standard transformation methodologies.
- increase manufacturing flexibility and reduce the change-over time between manufacturing campaigns (standardized equipment)
- avoid cross-contamination by standardised cleaning protocols and equipment
- ease substantially the scale-up to production campaigns
- reduce development time for intermediates

Rhodia/BASF case study
Regarding Rhodia case, based on the different water soluble polymers which were considered, the economic study based on a mono-product unit gave the following key learnings:
- A decrease in the investment of 30% to 50% for a mono product process of 10 kT p.a. could be achieved by an important increase of the space-time-yield
- If the continuous is not simplified and need more equipment and a too sophisticated technology, the impact on the Capex will be negative.
- Process simplification is key to justify the switch from single multifunctional batch equipment to a series of several continuous monofunctional equipment
- Moving specifications and more and more drastic specifications on residual monomers prevent the access to small equipment with negative impact on CAPEX
The intensification factor was assessed in this case study to be between 20 and 150. For the value of
The intensification factor was assessed in this case study to be between 20 and 150. For the value of intensification of more than 50, 30% CAPEX was achieved. From the process robustness point of view, better control of operating conditions was achieved.

Bayer case study
A development platform for modular chemical production was established at Bayer Technology Services and INVITE. The prototype demonstration of a modular, continuous API production aims at initiating a paradigm shift. The base was laid for further integration into pharmaceutical production. The chemical redesign and implementation of process intensification led to a significant reduction of lead time from the starting material to the readily available active substance (estimated reduction up to 60 %), a significant increase in space-time-yield (up to factors > 100) and thus a reduction of equipment size, a unification of solvents and a reduction of consumables. Also, the overall number of unit operations decreased as isolation steps could be eliminated. A reduction of process steps by 40 % can be therefore estimated. The influence on starting material costs depends on the respective transformations, as for approx. 70% of transformations in the respective field the yield in the classical process exceeded 90 % already before optimization. Reduction in starting material costs of 15 % in average can be foreseen.

Over all it was concluded for APIs, that by process intensification, elimination of process steps and modularization, CAPEX can be reduced by 20%, OPEX can be reduced by up to 25% and footprint by 50%.

The exchange with work packages and sub projects on process development and design requirements/methodologies contributes to a standardized approach which will enable the F³ Factory partners to significantly reduce the effort for development, design and engineering of future processes.

Arkema case study
The intensification factor through process miniaturisation was not yet satisfactory as the distillation columns were still a limitation factor. Nevertheless, 40% of CAPEX reduction was possible in the reaction step. OPEX savings are assessed to be 10%, which is also the factor for the savings in raw materials and energy. From the technological perspective, bio-based chemistry was applied.

BASF case study
The intensification factor for polymerisation equalled 12, the global FI being between 40 and 50. CAPEX decrease was reached through the total elimination of solvents.

PGB case study
The intensification factor for SO2 oxidation was between 10 and 20 and for sulfonation between 5-10. CAPEX decrease could not be assessed because the process in question was not yet competitive with current processes. Further development is necessary and planned for the time after the end of the project. For the oxidation an improved SO2 yield could be determined, and for the sulfonation, shorter residence time. The intensified reactor optimisation is still in progress and will remain beyond the project lifetime. This will have impact on the decrease in variable costs and in better product quality in the future. The final impact of an intensified, delocalized, modular surfactant making (SM) plant, will be to reduce energy cost, drastically reduce shipping cost, without increasing capital cost, and likely increase manpower cost (i.e double). Additionally, inventory size could be decreased. Having the same depreciation with more and smaller plants is equivalent to a significant absolute capital cost decrease (in the range of 25%). The new intensified, modular technology is needed not only to improve the economics
The new intensified, modular technology is needed not only to improve the economics for smaller plants, but also to increase the confidence to increase the number of SM sites (more sites, more complexity). In this sense, the size reduction and modularity is essential in order to move to fully skid mounted plants that can be erected more easily, faster and cheaper than today.

A very conservative estimation of the potential impact of a success of an intensified, modular SM technology, is a reduction of 10% of MOE. PGB management will need approximately a clear path for a 100 million NPV benefit to provide funds/manpower to install the demo skid.

Real options. This technology case is a classic example of the importance of “technology options”. Typical corporate approach calls for individual evaluation of NPV benefit for each project (i.e. how to provide surfactants for a new product or geography). In the case of surfactant making, since the investment to improve the technology is considerable both in cost and lead time, only marginal improvements in technology are possible in conventional delivery projects and therefore technology improvement is not staffed, thus the new technology is never available. Incumbent technology providers might not have the resources or the will to improve technology. Projects like F³ FACTORY allow to study in parallel the development of a breakthrough technology and to demonstrate it in a semi-industrial setting. At that point the “real option” (as opposed to a “virtual option”) for a new technology is available for the normal delivery projects that can implement them within their stricter timelines.

Beyond the limits of the F³ Factory project, the impact was increased by the open research center INVITE for development and demonstration of future manufacturing technologies, which not only served as an open backbone facility for F³ Factory but also beyond. Being a non-profit organization committed to at least 15 years of cooperation, it provides and will continue providing a platform for collaboration of industrial and academic partners.

The main means to reach the potential impact are the dissemination and exploitation activities, as they were realised in WP9 (please cf. chapter on WP9 in this final report as well as tables on dissemination and exploitation activities). All target interest groups were identified and addressed by appropriate communication channels. The exploitable results were protected by a confidentiality agreement and by patents filed. Over 150 conference presentations, papers and / or publications were issued and several events were organised to inform about the F³ Factory results and involve interest groups into a discussion. A suite of training and educational resources was prepared based on the outcome of F³ Factory. This material is used by both the industrial and academic partners and is also being used as part of a pilot initiative - Educate to Innovate - a SusChem programme for building innovation skills capacity and forming new generations of professionals in the field. The programme is linking innovation themes to academic teaching at undergraduate / Masters level.

List of Websites:
www.f3factory.eu

Name of the scientific representative of the project's coordinator:
Dr. Sigurd Buchholz
BAYER TECHNOLOGY SERVICES GMBH
51368 Leverkusen
Germany
Tel. +492173383032
E-mail: sigurd.buchholz(at)bayer.com
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