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PILLAR 1
Session 1.5

Advances in flexible continuous plants – novel online sensing equipment and closed-loop control of the key product parameters

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Coordinator CONSENS

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This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 767162.
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H2020-Project: “Integrated Control and Sensing for Sustainable Operation of Flexible Intensified Processes”

Duration: Jan 2015 - Dec 2017
EU funding: 6 million €
Coordinator: Bayer AG
Website: www.consens-spire.eu

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N° 636942.
Conventional Plants vs. Modular Intensified Continuous Plants

**Batch plants**
- Discrete flow through plant
- **Flexible** production of **many products** on same equipment
- **Small to medium amounts**
- Pharmaceuticals, specialties, fine chemicals, ...

**Continuous plants**
- Dedicated to specific products
- Continuous flow through plant
- **Very efficient** processes
- Petrochemicals, basic chemicals, ...
  (large scale, low margins)

**Modular Intensified Continuous Plants**

Flexible + Sustainable + Efficient + Short time to market

**Characteristics**
- Miniaturized equipment
- Intensified heat & mass transfer
- Plug-&-play modular setup

**Benefits**
- Product uniformity
- Sustainability
- Fast adaption to market demand
- Innovative products

Containerized modular plant from F³ Factory project

© INVITE GmbH, Leverkusen

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 767162.
Promising Results of F³ Factory Project (2009 – 2013) for Modular Intensified Plants
The research leading to these results has received funding from the European Community’s 7th Framework Programme under grant agreement n° 228867.

<table>
<thead>
<tr>
<th>Category</th>
<th>Up to*</th>
</tr>
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<tbody>
<tr>
<td>Processing steps</td>
<td>-30 %</td>
</tr>
<tr>
<td>Footprint</td>
<td>-50 %</td>
</tr>
<tr>
<td>Solvent reduction</td>
<td>-100%</td>
</tr>
<tr>
<td>Design effort</td>
<td>-25 %</td>
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<tr>
<td>Space-Time-Yield</td>
<td>100-fold</td>
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<th>Category</th>
<th>Up to*</th>
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<tr>
<td>Time-to-market</td>
<td>-50 %</td>
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<tr>
<td>OpEx</td>
<td>-20 %</td>
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<tr>
<td>CapEx</td>
<td>-40%</td>
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<tr>
<td>Logistics</td>
<td>-30 %</td>
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<tr>
<td>Energy consumption</td>
<td>-30 %</td>
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*) Best values out of all case studies
## General Business Opportunities of the new Plant Concept

<table>
<thead>
<tr>
<th>Centralized (on site)</th>
<th>Decentralized</th>
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<tbody>
<tr>
<td><strong>Fixed</strong></td>
<td></td>
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<tr>
<td>Replacement of less efficient batch processes</td>
<td>Production on demand at customer site (e.g. tailored grades, recycling of industrial waste)</td>
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<tr>
<td>Adaptation of capacity by numbering up</td>
<td></td>
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<td>Less engineering by purchasing &amp; duplicating complete modules</td>
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<td><strong>Mobile</strong></td>
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<td>Shared utility on integrated site (e.g., solvent recovery, pretreatment of waste water, ...)</td>
<td>Relocatable production (seasonal business, avoid transportation of hazardous media)</td>
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<tr>
<td></td>
<td>Offshore production (e.g. gas to liquid)</td>
</tr>
</tbody>
</table>
Challenges of the new Plant Concept regarding Process Control – and the State of the Art

General requirements of continuous processes
- Closed-loop quality control
- Online sensors for chemical compositions
- Model-based optimal control for sustainability & efficiency

Specific challenges of Flexible Intensified Plants
 Variety of products
- Flexible sensing & control
- Fast design of integrated control solutions

Frequent new products
- Fast & compact sensors
- Fast model-based control

Short time to market

Small dimensions

Fast process dynamics

Complex phenomena

Online NIR, Raman, or UV/Vis spectroscopy sensors
- High effort for calibration, need for reference analytics
  → Very time consuming, prohibitive effort for many products
- Quickly decomposing substances cannot be calibrated, turbid media are difficult
  → Limited applicability

Conventional control methods
- Optimal control requires very precise rigorous models
  → High modeling effort = very time consuming

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Flexible Automation for Continuous Production of Pharmaceuticals
(manuscript submitted to the journal Science, validation runs performed at INVITE GmbH in Leverkusen)

Online Nuclear Magnetic Resonance (NMR) Spectroscopy
- **Low calibration effort** (spectra of pure components suffice)
- **Compact** sensor for chemical compositions
- **Fully automated** data acquisition and evaluation unit, flow control, as well as data communication
- **Fast measurement** (every 15 s)
- **High accuracy**
- **Can measure intermediates**
- **Modular** design
- Can be used as reference method for other spectroscopic sensors!
- **Explosion-proof** (ATEX 1)

Iterative optimal control using inexact process models
- Model-based control that learns from system response
- **Fast control design** (mechanistic models with less detail)
- **Safety limits** and **quality constraints** are kept
- **Economic optimum (!)** in spite of model-plant mismatch

Unmeasured change of feed composition
Start of the controller

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Achievements regarding Sustainability and Efficiency

**Original Batch Process**
- Highly exothermic reaction at -70°C → very high cooling power required
- High amount of hazardous reaction medium in the reactor (many liters) → potential high safety risk
- Dosing is done very slowly
- Low concentrations are used
- High amount of solvent is used

**Continuous Intensified Process**
- Due to intensification, reaction runs at 15°C - 50°C without deep cooling! → much less cooling power required
- Low amount of hazardous medium in the reactor (few ml) → low hazard potential
- Use of solvent radically reduced → high raw material efficiency

**Optimally Controlled Process**
- Tight quality control in spite of disturbances & process variation → improved quality
  → increased capacity
- Reaction can be run safely near the boiling point of solvent (66°C) → further 36% less solvent
  → 37 kg less CO₂ eq. / kg product
  → 7% cost reduction

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Outlook: How to foster the implementation of this approach in industry?

Examples of current activities
- “Reel”: Lanxess and INVITE built a container-based plant for recycling waste on the site of a leather producer
- “MoBiDiK”: Modular continuous bio production at Bayer
- R&D and standardization: Modular automation devices

Why aren’t there more such plants being built?
- Product development is still focused on batch processes
- It is easier to transfer lab procedures to batch processes
- Continuous processes require additional experimental effort in product and process development
- Time to market is the driving force in many sectors

Full “in silico” design of new products and processes
→ Today still not possible!
- Computer-simulation drives development
- Experiments are only used for model validation
- Systematic exploration of design space using simulation (batch / conti, new process technology, solvent-free, …)
- Best possible process is selected

Quantum mechanics → Molecular dynamics → Thermo-dynamics → Chemical route → Plant scenarios

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Many thanks for your attention!

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CONSENS website  
www.consens-spire.eu

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