



# WP2: Turbomachinery Final Report

*Imperial College London*

*BASF*

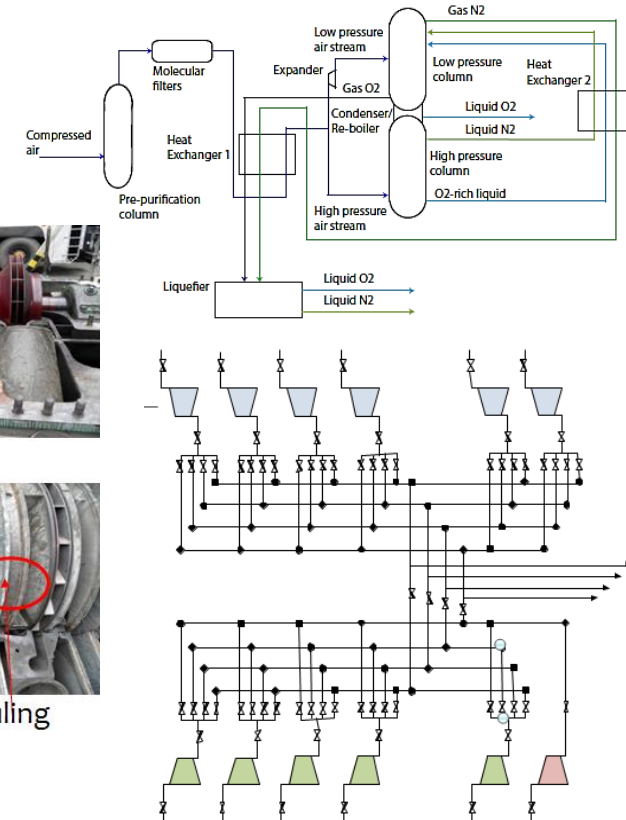
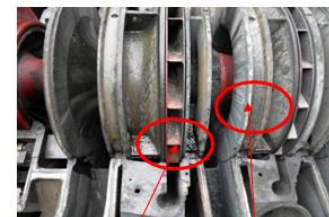
31/03/2015

## Energy savings in compressor operation

- Develop scalable and complete equipment monitoring systems
- Devise new algorithms for overall performance monitoring and control
- Study ways that energy savings can be achieved

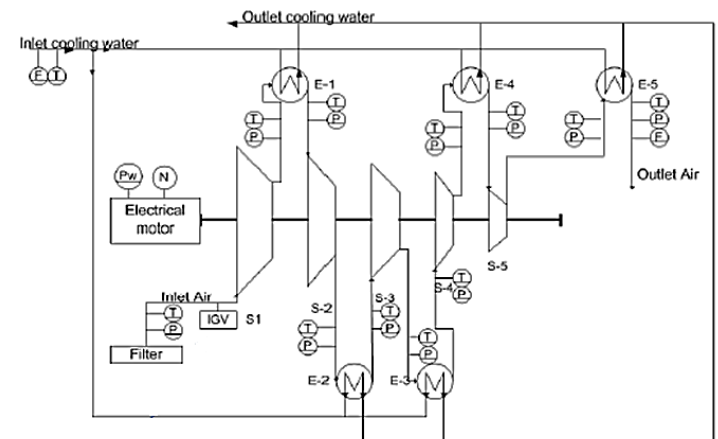
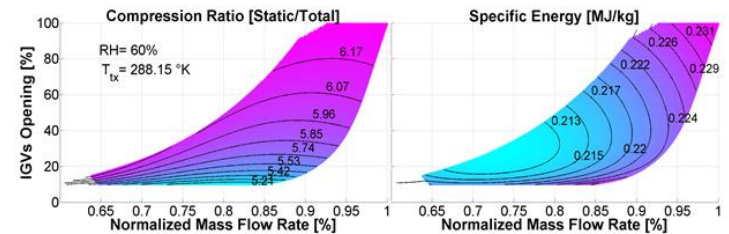
## Tasks in WP2

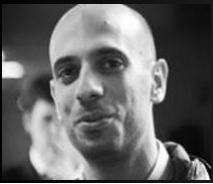
- Adaptive monitoring of condition and performance of centrifugal compressors
- Optimization of centrifugal compressor operation and maintenance
- Aerodynamic impact of fouling in centrifugal compressors
- Control systems for centrifugal CO<sub>2</sub> compressors



- Task: Adaptive monitoring of condition and performance of centrifugal compressors
  - Lead: BASF Ciccioni (ESR-E ), Bouaswaig, Geist and Kahrs
  - Others: IMPERIAL Martinez-Botas (PhD supervisor), Xenos (ESR-F), Thornhill
- Outcomes :
  - Modelling of compressor performance by physical aerodynamic relationships.
  - Model-based condition monitoring and prognostics for effects of fouling, erosion and corrosion investigated on-site on an industrial compressor
  - Successful validation and an industrial prototype developed
- Secondment and PhD studies
  - Imperial College London

Automatic generation and update of performance maps from industrial process data





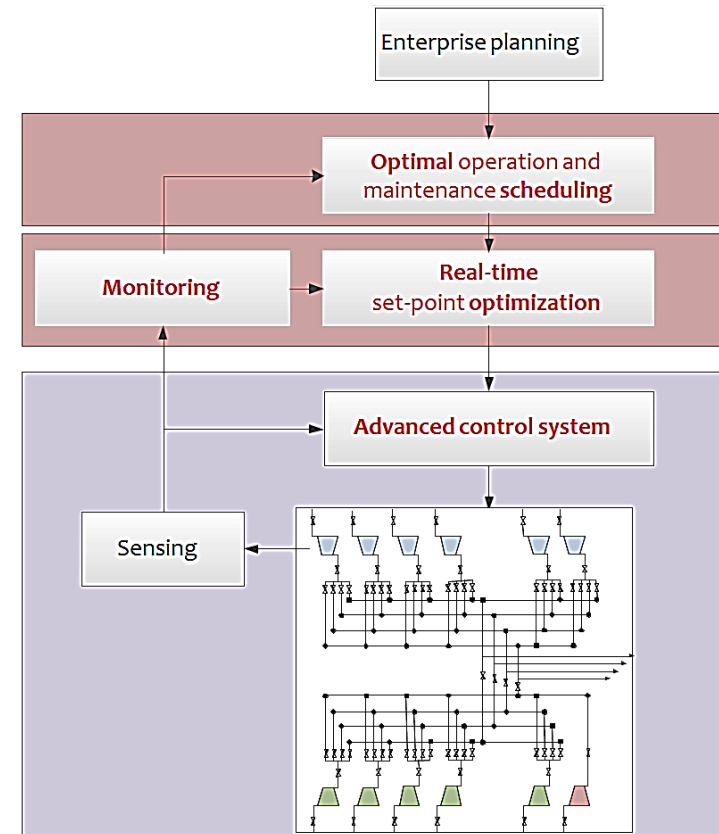
Task: Optimization of centrifugal compressor operation and maintenance

- Lead: IMPERIAL Xenos (ESR-F ), Thornhill (PhD supervisor), Martinez-Botas
- Others: BASF Ciccioiti (ESR-E), Bouaswaig, Geist, Kahrs; STATOIL Lunde, Bindingsbø

Outcomes :

- Condition monitoring and optimization have been integrated for:
  - » condition-based maintenance scheduling
  - » real-time optimization (RTO) with adaptive monitoring of compressor performance
- Condition based maintenance optimization reduced costs in a large scale case study
- Real Time Optimization (RTO) reduced the power consumed in an industrial trial

Secondments to BASF and Statoil





# WP2: Technical details

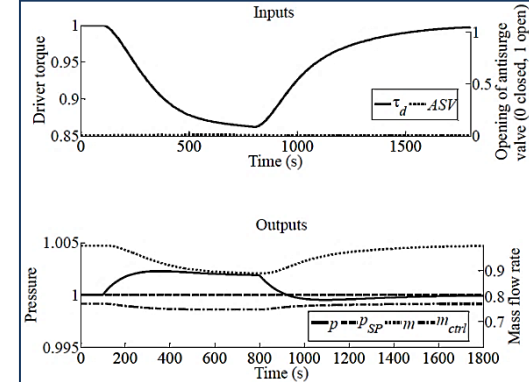
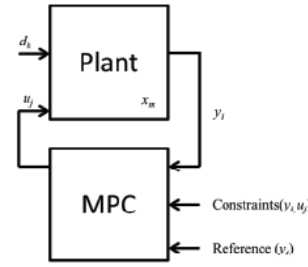
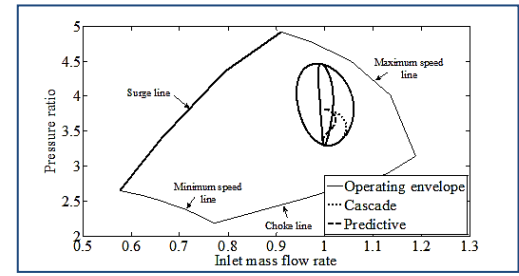
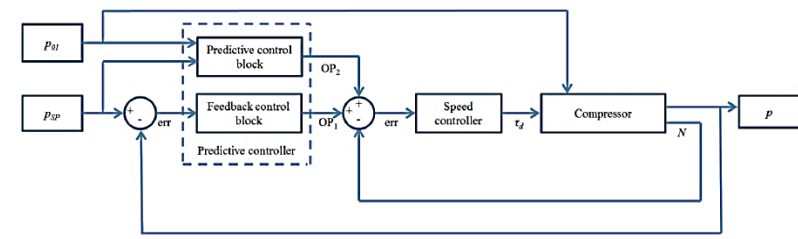
## Sara Budinis, IMPERIAL



- Task: Control systems for centrifugal CO<sub>2</sub> compressors
  - Lead: IMPERIAL Budinis (ESR-J), Thornhill (PhD supervisor), Martinez-Botas
  - Others: ESD Hodder

### Outcomes :

- Models developed and verified against state-of the art simulation from ESD
- Model-based analysis and simulation shows:
  - » Improvement in control
    - from integration of capacity and antisurge control
    - from model-based control using compressor map
  - » Impact of the high density of super-critical CO<sub>2</sub> during antisurge recycle



### Secondment: ESD Training Simulation Ltd



## WP2: Technical details

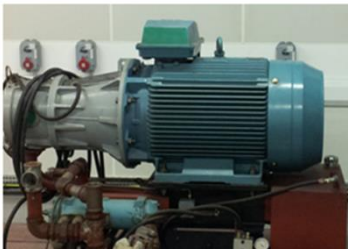
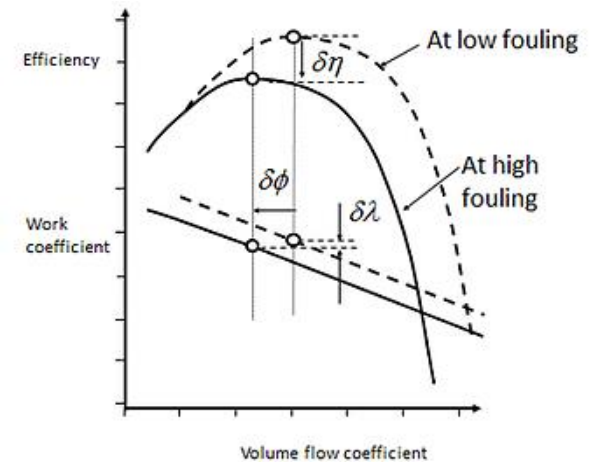
Esperanza Barrera-Medrano, IMPERIAL



- Task: Aerodynamic impact of fouling in centrifugal compressors
  - Lead: IMPERIAL Barrera-Medrano (ESR-F(ii)), Gozalbo (ESR-f(i)), Martinez-Botas (PhD supervisor). Others: BASF Bouaswaig

### Outcomes :

- Modelling analysis studies of:
  - » influence of fouled conditions on the performance parameters of the compressor
  - » influence of different fouled conditions over blade suction side/pressure side on the performance parameters
- Experimental study with real fouling injection under different operation conditions.

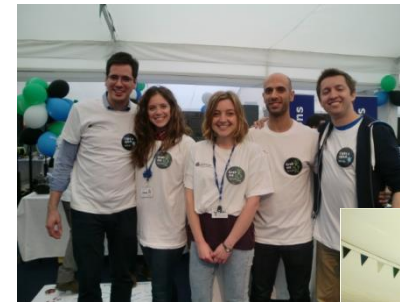
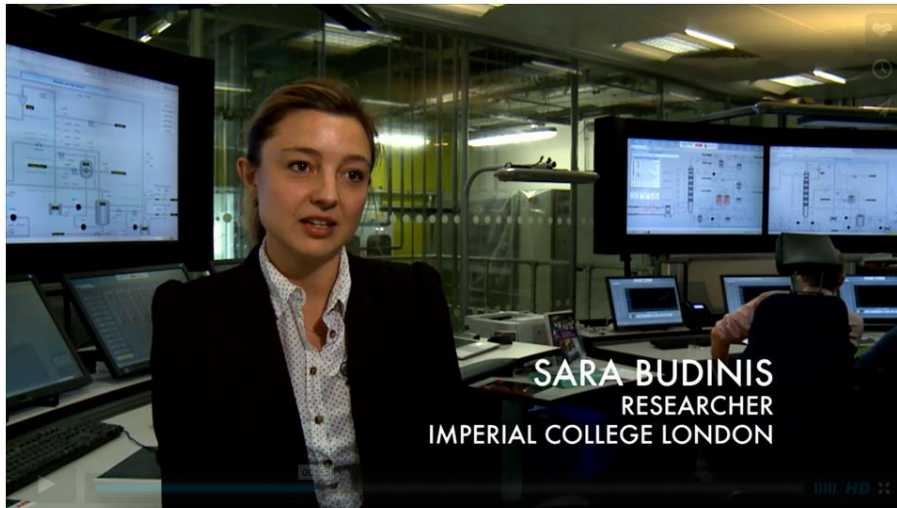


- Secondments and collaborations and case studies

ESR	BASF	IMPERIAL	ESD	STATOIL
Cicciotti (BASF)	employer	PhD Secondments Joint papers	impact slides	
Xenos (IMPERIAL)	secondments case study joint papers	employer PhD	impact slides	visit case study joint papers
Budinis (IMPERIAL)		employer PhD	impact slides secondments case study impact video	
Barrera-Medrano (IMPERIAL)	site visit	employer PhD		
Biondi (ABB-DE)			input to impact video	



- Meetings and visits, network training, outreach
  - BASF site visit, organized by Cicciotti (ESR-E)
  - Outreach at Imperial Festival, coordinated by Barrera-Medrano (ESR-F)
  - Network-wide training on transferrable skills coordinated by Budinis (ESR-J)
  - Impact video created by ESD





	Cicciotti	Xenos	Budinis	Barrera-Medrano
Network training Transferrable skills	2 courses	2 courses	2 courses	1 course
Network training Technical skills	2	2	2	1
Internal courses	BASF training	12	18	4
External courses	2	4	4	2
Site visits	3	3	2	1
Languages	German	German Russian	French	

## Blogs and case study reports

- WP2 case study at BASF

The BASF SE case-study for the ENERGY SMARTOPS project

Matteo Ciccotti<sup>a,c</sup>, Dionysios P. Xenos<sup>b</sup>, Ala E. F. Bouaswaig<sup>a</sup>, Ricardo F. Martinez-Botas<sup>c</sup>, Nina F. Thornhill<sup>b</sup>

<sup>a</sup>BASF SE, Automation Technology, Advanced Process Control, 68163 Ludwigshafen, Germany  
<sup>b</sup>Imperial College London, Department of Chemical Engineering, Centre for Process Systems Engineering, SW7 2AZ London, UK  
<sup>c</sup>Imperial College London, Department of Mechanical Engineering, Turbomachinery Research Group, SW7 2AZ London, UK

**Keywords:** compressors, monitoring, optimization, energy intensive process

Operation and maintenance of gas compressors with electrical drives.  
 Dr Erling Lunde, Statoil ASA

[www.energy-smartops.eu](http://www.energy-smartops.eu)

Control and operation of industrial compressors  
 September 14, 2014

by *Sara Budinis*

What is the purpose of this project within Energy SmartOps?  
 One of the targets of Energy SmartOps is to operate and control industria...

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Can maintenance improve the operational performance of the processing plant?  
 August 18, 2014

• **Efficiency KPI** =  $\frac{\text{Efficiency}_{\text{current}} - \text{Efficiency}_{\text{ref}}}{\text{Efficiency}_{\text{ref}}}$

• **Reliability KPI** =  $\frac{\text{Number of startups/shutdowns} - \text{Number of startups/shutdowns}_{\text{ideal}}}{\text{Number of startups/shutdowns}_{\text{ideal}}}$

by *ESR-A, ESR-B, ESR-C, ESR-D, ESR-E, ESR-F*

A smaller group of ESRs is dealing with the development of methods related to the maintenance of the plant...

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## ... and blogs in the ESR's web site

Optimal operation of compressors in parallel  
 June 2, 2014

by *Dionysios Xenos, Nina F. Thornhill*

Important aims of the process industries are the increase in energy efficiency and reduction in CO2. Environmenta...

Industrial compressors  
 March 10, 2014

by *Matteo Ciccotti*

Compressors general

A compressor is a machine that increases the pressure of a gas. Compressors are important components of indust...

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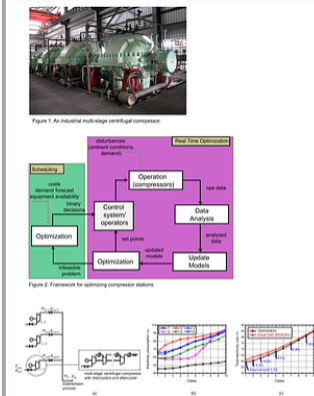
Performance deterioration in centrifugal Compressors: Fouling phenomenon  
 April 10, 2014

by *Maria E. Barrera-Medrano*

Introduction

Centrifugal compressors are widely used in industrial applications. Although industrial compressors are alwa...

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### Other dissemination

- Journal papers and conference special sessions

### Evidence of impact

- Associated partner ESD made a video
  - » The whole Energy-Smartops project, with an emphasis on compressor projects  
<https://www.esd-simulation.com/blog/energy-smart-ops-esd>
- Publicity for latest research
  - » ESD has slides from Energy-Smartops to go into their course material and web site to show “Here is the latest research, the latest thinking”. The focus will be on compressors.
- Case studies with BASF and Statoil

### Evidence for achievement

- Papers in ASME, ESCAPE, AIChE conferences, and in international journals
- Industrial implementation at BASF
- Industrial case study with Statoil

## Highlighted publications:

- » Ciccioiti, M., Martinez-Botas, R., Romagnoli, A., Thornhill, N.F., Geist, S., and Schild, A., 2013, Systematic one zone meanline modelling of centrifugal compressors for industrial online monitoring applications, *ASME Turbo Expo 2013*, San Antonio, Texas, June 3-7 2013.
- » Ciccioiti, M., Xenos, D.P., Martinez-Botas, R.F., Thornhill, N.F., 2014, Performance monitoring of centrifugal industrial compressors using meanline modelling and recursive least-squares, *ASME Turbo Expo 2014*, June 16-20 2014, Düsseldorf, Germany.
- » Ciccioiti, M., Xenos, P.D., Bouaswaig, A.E.F., Thornhill, N.F. and Martinez-Botas, R.F., 2015, Physical modelling of industrial multistage centrifugal compressors for monitoring and simulation, *Journal of Mechanical Engineering Science*, *accepted for publication*.
- » Xenos, P.D., Ciccioiti, M., Kopanos, G.M., Bouaswaig, A.E.F., Kahrs, O., Martinez-Botas, R.F., and Thornhill, N.F., 2015, Optimization framework of compressors in parallel: real time optimization of compressors in chemical plants: an industrial case study, *Applied Energy*, 144, 51-63.
- » Xenos, D.P., Lunde, E., and Thornhill, N.F., 2015, Optimal operation and maintenance of gas compressor stations: an integrated framework applied to a large-scale industrial case, *AASME Turbo Expo 2015*, June 16-20 2014, Montreal, Canada, June 15-19, 2015.
- » Budinis, S., Thornhill, N.F., 2015, Supercritical gas recycle analysis for surge control of centrifugal compressors, *25th European Conference on Computer Aided Process Engineering (ESCAPE 25)*
- » Budinis, S., and Thornhill, N.F., 2015., Control of centrifugal compressors via model predictive control for enhanced oil recovery applications, *IFAC OilField 2015 Conference*
- » Ciccioiti, M., Xenos, P.D., Budinis, S., 2015 . Three PhD Theses, Imperial College London.

## INTENDED OUTCOME

Methods and algorithms aim to reduce the energy usage for gas compression. Optimization frameworks increase the system efficiency and reduce overall operational costs using monitoring information.

The monitoring information comes from algorithms which implement physical knowledge and reveal the gradual degradation of the compressors.

The outcomes include guidelines regarding the operation of supercritical carbon dioxide compressors and suggestions on the best recycle configuration of compressors.

## METHODOLOGY DEVELOPED

A real time optimization scheme deals with the model uncertainty as the models are updated online. A Non-Linear Programming (NLP) optimization problem is solved online in real time and it minimizes the operation cost.

A mixed integer linear programming optimization model describes the condition based maintenance and optimal operation for long term scheduling. This approach includes the adaptive monitoring of the health-state and performance of compressors.

Performance estimation based on experimental calculations of fouling in centrifugal compressors has been studied as well.

The response of the control schemes of compressors analysed by means of graphical representation and dimensionless indicators.

## MEASURE OF SUCCESS

The real time optimization (RTO) can decrease the power consumption of the BASF air compressor station compared to equal split industrial policy.

The physical models to be used for online performance monitoring methods can achieve accuracy of +/- 1%.

The use of the scheduling approach can achieve 10% reduction in the total costs of the operation when the maintenance of the compressors is considered as a degree of freedom into the optimization problem.

The analysis on the recycle of supercritical CO<sub>2</sub> compressor showed reduction of energy consumption by 37% and 7.3% for inlet and outer disturbances respectively.



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