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Optimal Operation: Scheduling, Advanced Control and their Integration

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FOCAPO / CPC 2012

Power and productivity for a better world™ ABB

A global leader in power and automation technologies
Leading market positions in main businesses

- 130,000 employees in about 100 countries
- $32 billion in revenue (2010)
- Formed in 1988 merger of Swiss and Swedish engineering companies
- Predecessors founded in 1883 and 1891
- Publicly owned company with head office in Switzerland

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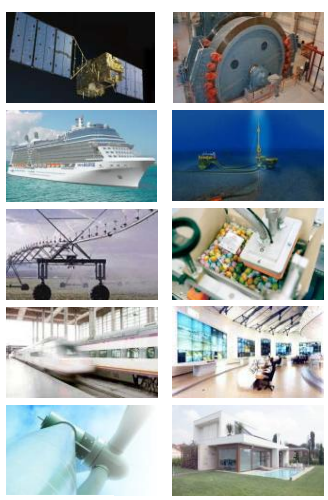
Power and productivity for a better world
ABB's vision

As one of the world's leading engineering companies, we help our customers to use electrical power efficiently, to increase industrial productivity and to lower environmental impact in a sustainable way.

Power and automation are all around us
You will find ABB technology…



orbiting the earth and working beneath it,

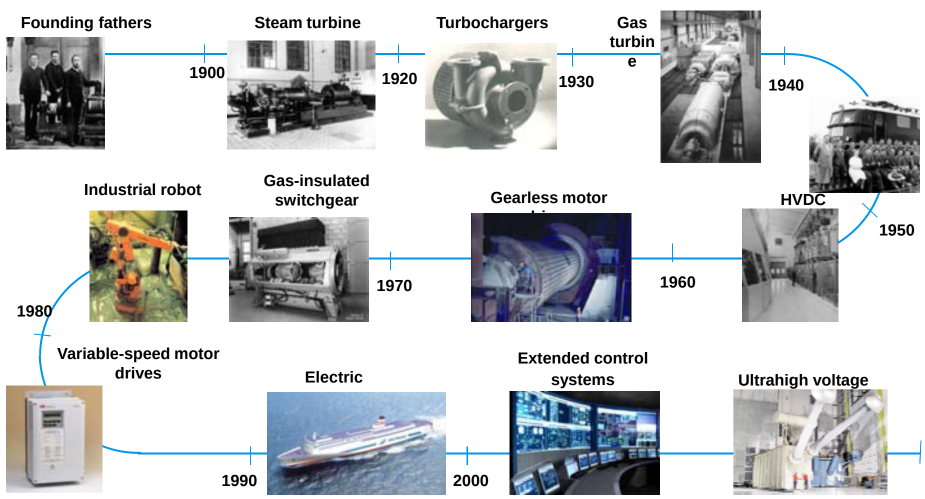
crossing oceans and on the sea bed,

in the fields that grow our crops and packing the food we eat,

on the trains we ride and in the facilities that process our water,

in the plants that generate our power and in our homes, offices and factories

Shaping the world we know today through innovation
Pioneering technology since 1883



Outline

- Challenges and opportunities in Industrial production management
- Scheduling and control – status and similarities
- Integration of scheduling and advanced control
- From loosely integrated systems to collaborative production management

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Production Management @ Industry
Hardware

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Production Management @ Industry
Hardware with Integration

How to run the process more intelligently?

Production Management

Industrial plants need more than only hardware & integration!

Information overflow: Focus on what is relevant!

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Production Management @ Industry
Functionalities and Goals

ERP

(mainly supporting business functions, strategy and targets)

Production cost

Equipment health & condition

Product quality

Energy efficiency

Inventory, safety, …

Control

(execution layer, data collection, short-term decisions)

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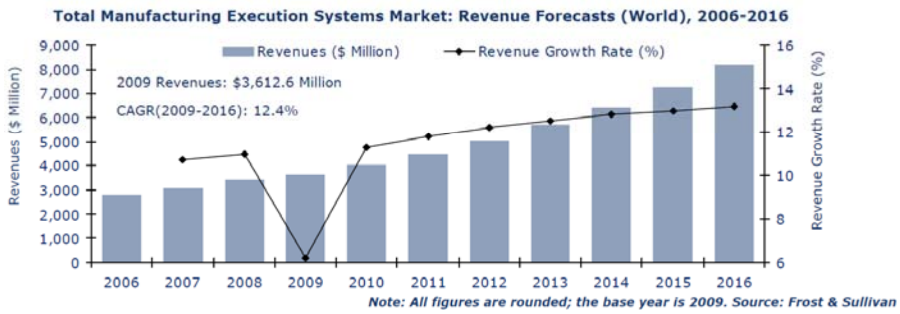
Production Management
Market Trends (ARC)

The CPM market posted strong growth over the past few years spurred by favorable economic conditions. This trend is expected to continue over the next five years as the market reaches more than $2.8 billion by 2011, representing an overall growth rate of about 12 percent.

- Few new plants are being built today
  - More revamping, automation system (CPM, MES) improvements
- First time the MES market is growing faster than DCS!
  - This puts lots of pressure also on integration



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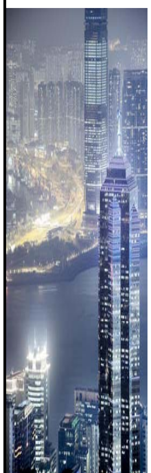
Arising Industrial Challenges
Flexibility vs. Cost Efficiency



- Industries enforced to lower operational costs: Global competition, smaller batch sizes, shorter campaigns, …
- Overall result "counts", need of increased information sharing
  - Merge earlier isolated optimization tasks (low-level vs. high-level objectives) → efficient algorithms
  - How to evaluate the overall result of complex nested problems ("KPIs")?
- Flexibility: Design of a process may need to be adapted to enable the production of various product portfolios
- Solution speed: Ensure fast solutions to complicated problems, instead of only focusing on the optimality
- Usability: How to build "PhD-free" optimization solutions?
- Increasing need for flexibility, compatibility, ease-of-use, robustness, demand for service solutions

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Arising Industrial Challenges
Energy and Emissions

- How to deal with energy?
  - Electricity grid is a huge and complex dynamic control system. Production need to be more energy efficient, flexible, and agile
  - Industrial demand side management focus expanding into production processes e.g. in process industries
- Regulations on emissions (CO_2, NOX, SO_2) difficult to manage without sufficient tools
- Energy and emissions are subject to politics and legislation and need to be considered across borders

Arising Industrial Challenges
Balancing Between Control Systems

Energy availability and pricing (smart grids) — **Grid control**

Production Management (P&S, APC)

Process variations, e.g. quality, yield, disturbances (DCS) — **Process control**

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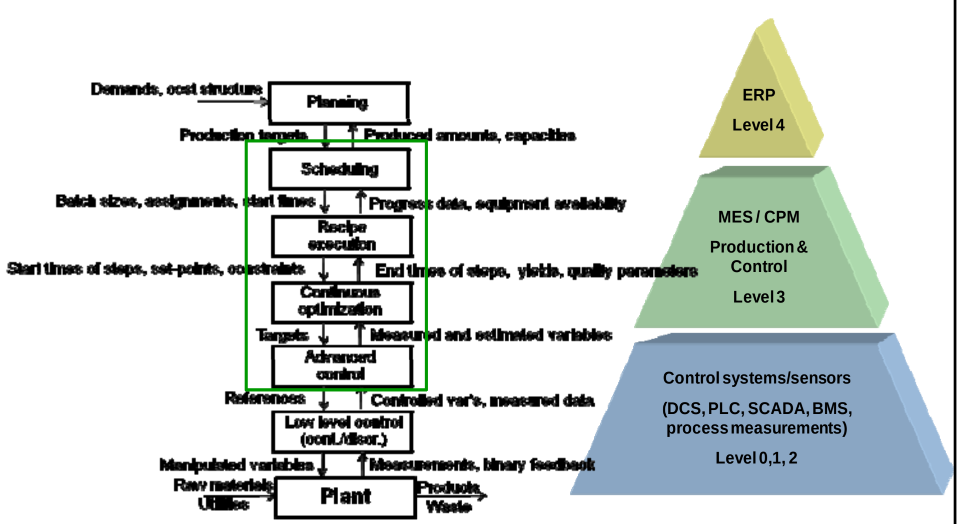
Scheduling and Control: Functional Hierarchy



Role of Control
Meeting the Specs – Optimizing the Performance

- Control handles continuous degrees of freedom online
- Control traditionally has the task to implement given set-points and to keep the operational parameters within specified limits in the presence of uncertainties
  - Ensure stability
  - React to disturbances and changing conditions
  - Implement transitions
- Advanced Process Control (MPC, NMPC) can go beyond this
  - Optimization of batch trajectories or changeovers
  - Minimization of production cost, energy consumption, maximization of throughput
- Role of control is more central for process operations than before (also reflected in the standard ISA-95)

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State and Future of Advanced Control
A View from Germany

- MPC gains ground beyond the petroleum industry
- Advanced control is accepted as a major factor for competitiveness and the reduction of the consumption of energy
- Linear MPC is a mature technology
- NMPC is ready for application
- Optimizing control is the logical next step
  - Optimize - over a finite moving horizon - the (main) degrees of freedom of the plant with respect to process performance rather than tracking performance using rigorous models
  - Represent the relevant constraints for plant operation as constraints in the optimisation problem and not as setpoints
  - Maximum freedom for economic optimization

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Role of Scheduling
Coordinating the Use of Resources

- Production scheduling handles discrete degrees of freedom, often not tightly synchronized
- There exist lots of automated on-line discrete control functionalities for safety, error handling etc.
- Scheduling is usually done manually, sometimes with support by scheduling systems, often rule based
- Implementation is inevitably in a moving horizon fashion, as for MPC
  - However, sampling rates are low, usually lower than the resolution of the schedules – deviations accumulate
- Uncertainties/ disturbances are coped with by
  - Manual adaptation/ modification
  - Re-scheduling (easy if priority rules are used)

Scheduling vs. Process Control

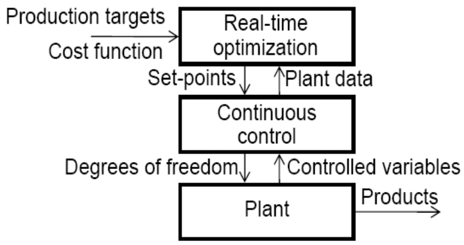
Process Control

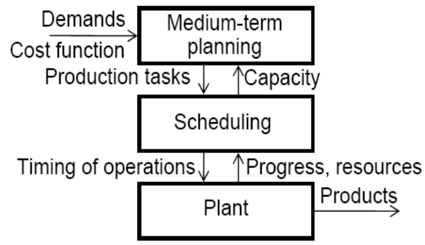
- Goals:
  - Minimization of the consumption of energy and resources
  - Maximization of throughput
- Constraints:
  - Product quality
  - Equipment limits, flow rates
- State (inertia) of the plant
  - Inventories (mass, energy)
  - Up/down of units
- Degrees of freedom
  - Flow rates (mass, energy) (Continuous functions of time)

Scheduling

- Goals:
  - Meeting of due dates and demanded quantities and qualities
  - Maximization of throughput
- Constraints:
  - Resources
  - Storage
  - Sequences in recipes
- State (inertia) of the plant
  - Current resource utilization
  - Current steps of recipes
  - Inventories
- Degrees of freedom:
  - Batch sizes
  - Start of operations on a resource (Discrete events or binary signals)

Hierarchical Decision Structures





- RTO layer
  - Optimization of set-points
  - Stationary but rigorous models
  - Low sampling rates
- Control layer
  - Dynamic approximate models
  - Fast sampling rates
  - Local absorption of uncertainty
- Integrated approach feasible for medium-sized problems

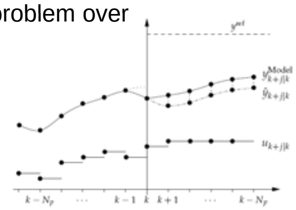
- Medium-term planning
  - Assignment of tasks to resources
  - Averaged, slot-based models
  - Low sampling rates
- Scheduling
  - Detailed assigment of tasks
  - Precise timing
  - Local absorption of uncertainty
- Integrated approach infeasible due to combinatorial explosion

Scheduling and Advanced Control
Common Features

- Production scheduling and advanced control, are reactive activities characterized by an information structure where the decisions are based on the information that is present up to a certain point in time and where new information arrives continuously
  - Delay depending on the response time of the algorithm
  - More frequent updates can be counter-productive
  - Late fixing of decisions advantageous
- Both tasks have to deal with uncertainty:
  - Model uncertainty: Outcomes of actions are not exactly known
  - Disturbances: External influences change the behaviour of the plant / the availability of resources
  - Future set-points / tasks can only be estimated
- Feedback must be used to cope with the uncertainties – to analyse the effect of feedback is the core of control theory, but hardly considered in scheduling at all

Uncertainty Handling in Moving Horizon Optimization

- Moving horizon optimization (MPC)
  - Solution of an (open-loop) optimization problem over a finite horizon
  - Model errors are usually taken into account by a constant extrapolation of the errors between prediction and observation



- Limitation: Weak feedback, essentially open-loop optimization
  - Quality of the solution depends fully on the accuracy of the model
  - Feedback only enters by re-initialization (state estimation) and error correction (disturbance estimation) term

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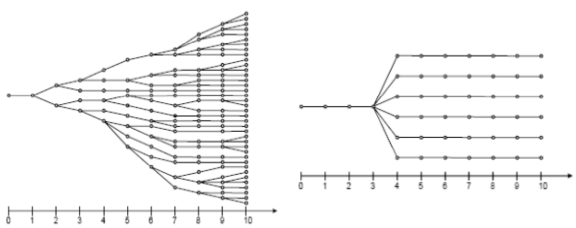
Multi- and Two-stage Decision Processes
Online Optimization is a Multi-stage Decision Process



- Re-scheduling/ standard MPC:
  Average (nominal) model for the future evolution used at each step
- Robust and stochastic optimization: Uncertainties modeled
- Robust optimization/ min-max MPC:
  Worst-case feasibility at each point
- Multi-stage stochastic optimization: Optimization of the expected value, exlicitly taking into account future actions
- Reduction to two-stage problem for computational tractability

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Multi-stage Optimization in Scheduling and Control

- Multi-stage formulation adequately represents the situation encountered in scheduling and control:
  - New information will be available in the future
  - Decisions have to be made “here and now“ based on available knowledge but the long-term evolution is taken into account
  - The future reaction to the new information (recourse) is included in the decision on the first-stage variables
  - The risk caused by possible future evolutions can be included in the formulation
- Disadvantage: Computationally expensive
  - Number of variables grows with the number of scenarios
  - Large MILP/ NLP problems
  - Scheduling: Hybrid algorithms (EA/MILP) for 2-stage problems

$$\min_{\mathbf{x},\mathbf{y}_1,\dots,\mathbf{y}_\omega} f(\mathbf{x},\mathbf{y}_1,\dots,\mathbf{y}_\omega) = \underbrace{\mathbf{c}^T\mathbf{x}}_{\text{1st stage costs}} + \underbrace{\sum_{i=1}^{\Omega} \pi_\omega \mathbf{q}_\omega^T \mathbf{y}_\omega}_{\text{expected 2nd stage costs}}$$

$$\text{s.t.}\quad \mathbf{A}\mathbf{x} \le \mathbf{b},\ \mathbf{T}_\omega \mathbf{x} + \mathbf{W}_\omega \mathbf{y}_\omega \le \mathbf{h}_\omega,$$

$$\underbrace{\mathbf{x} \in X}_{\text{1st stage decisions}},\ \underbrace{\mathbf{y}_\omega \in Y}_{\text{2nd stage decisions}},\ \omega = 1,\dots,\Omega$$

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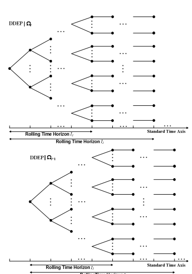
Multi-stage Optimization on Moving Horizons

- Scheduling: 2-stage formulation (Wu and Ierapetritou, 2007, Puigjaner and Lainez, 2008, Cui and Engell, 2009)
- Control: Robust multi-stage NMPC (Lucia et al., ADCHEM 2012)
- Long-term future can be represented by expected values



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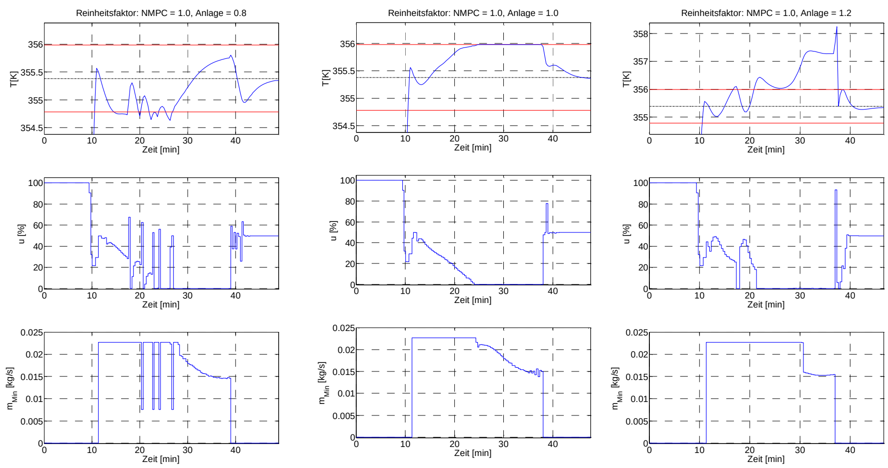
Chylla-Haase Reactor Example
Optimizing NMPC with Uncertainty



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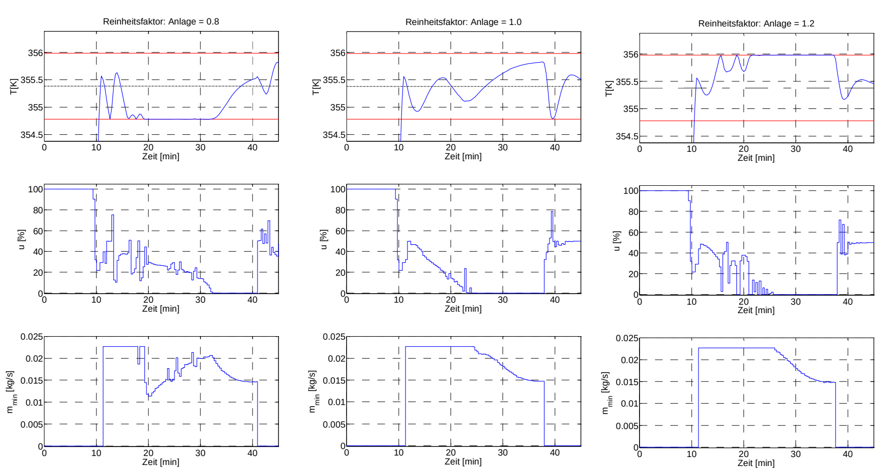
Chylla-Haase Reactor Example
Multi-stage optimizing NMPC with Uncertainty



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Production Management
Typical Hierarchy of Decision Levels

- Customer orders a product (normally in ERP system)
- Rough production planning is done, defining e.g. the weekly production targets (ERP or local system)
- Production orders are scheduled for a week considering finite capacities manually or automatically (scheduling systems)
  - Equipment assignments, sequences, timings
- Orders are dispatched to production (MES)
  - Detailed production steps are defined by the production recipes
  - Each stage (of the production recipes) is executed with given fixed set points (temperature, flow rates, pressure etc.)
- Distributed Control Systems (DCS) implement the given set points by feedback control
- Advanced process control may realize optimal trajectories, e.g. for feed rate maximization

Integration of Scheduling and Advanced Control
Examples of Opportunities

- Plan sequences that avoid costly changeovers and reduce the time and the lost product during transitions, e.g. grade transitions in polymer plants
- Avoid schedules that lead to operational problems
- Reduce maintenance needs and improve equipment life-time
- Flexible recipes – adaptation of processing conditions to the logistic situation of the plant and consideration of this option in the scheduling decisions
- Switching of optimality criteria depending on the resource utilization level
- Limitations of the consumption of utilities
- Better predictability in scheduling – use more detailed and timely information from the control layer

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How to integrate?

- Classical structure does not use the degrees of freedom optimally
- Monolithic integrated solutions are feasible (only) in cases with few integer decisions, e.g. changeovers in polymer production (3 posters at FOCAPO)
- Collaboration schemes through information exchange and shared objectives must be developed
- Optimization-based control will spread → can be used for predictive purposes within an overall collaborative optimization structure

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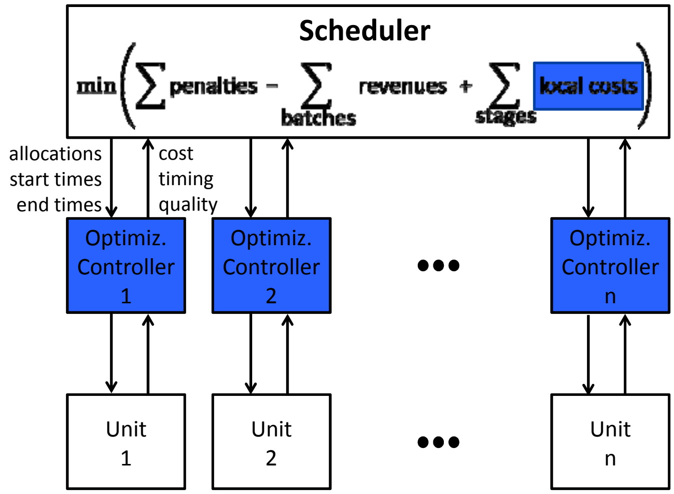
Integrated Distributed Scheduling and Control



- Similar to two-stage stochastic scheduling with MILP subproblems

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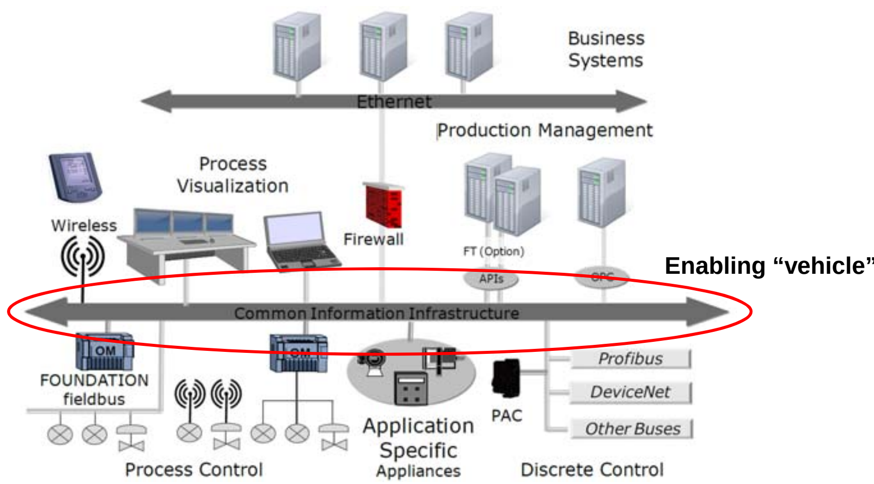
Implementation Architecture
Logical View of a Production System



(Source: ARC, 2010)

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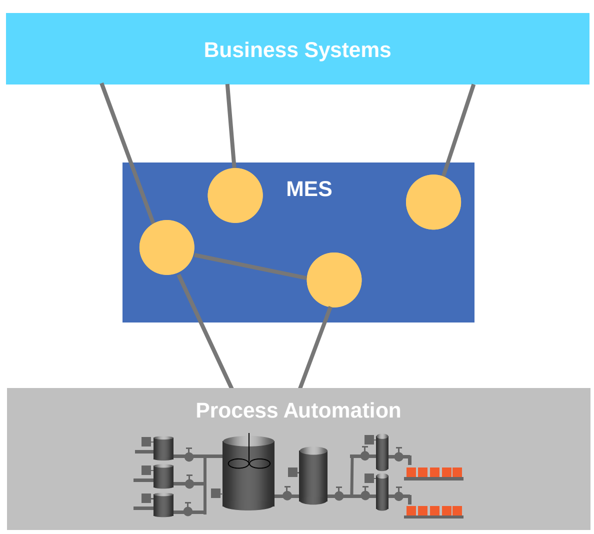
Evolution of Manufacturing Systems

FOCAPO 2008



Circa 1990

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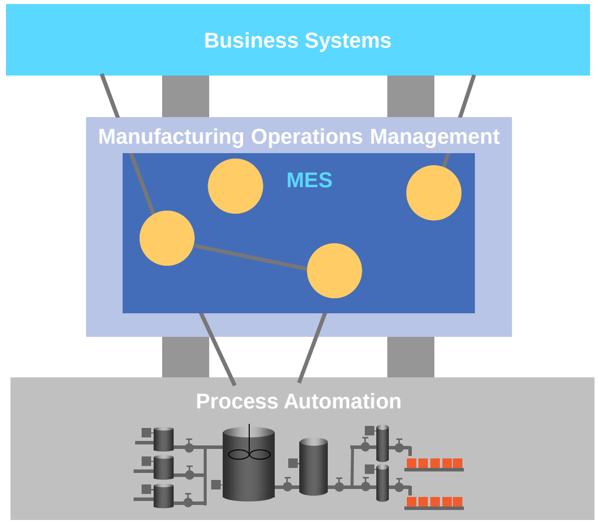
Evolution of Manufacturing Systems



Circa 2000

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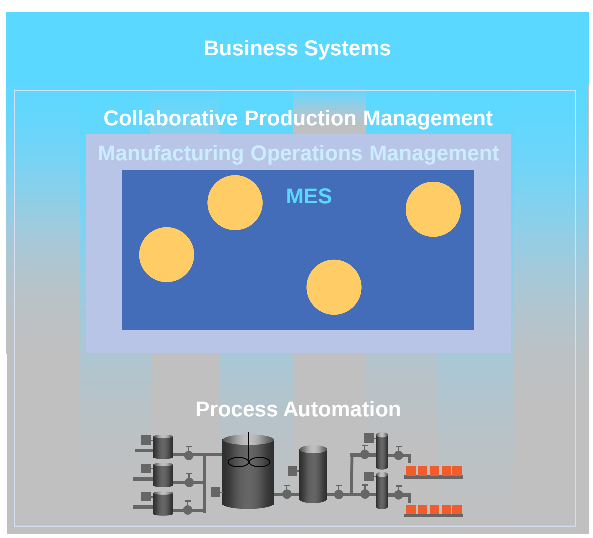
Evolution of Manufacturing Systems



Today

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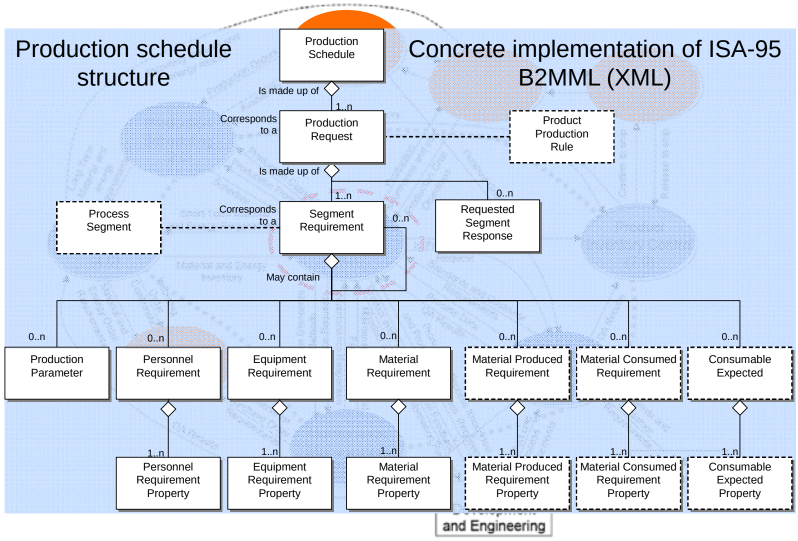
Production Management Functions
ISA-95 Purdue Reference Model

= Not core PM functionality but communication important!

= Core PM functionality



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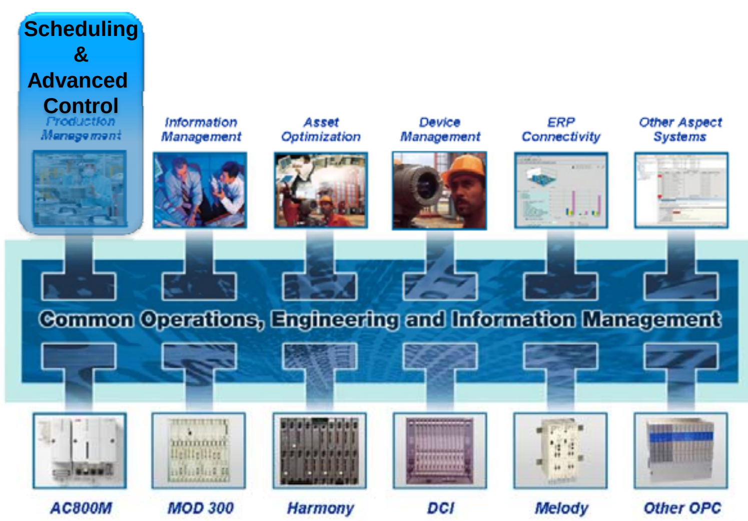
Collaborative Production Automation System
Common Information Infrastructure



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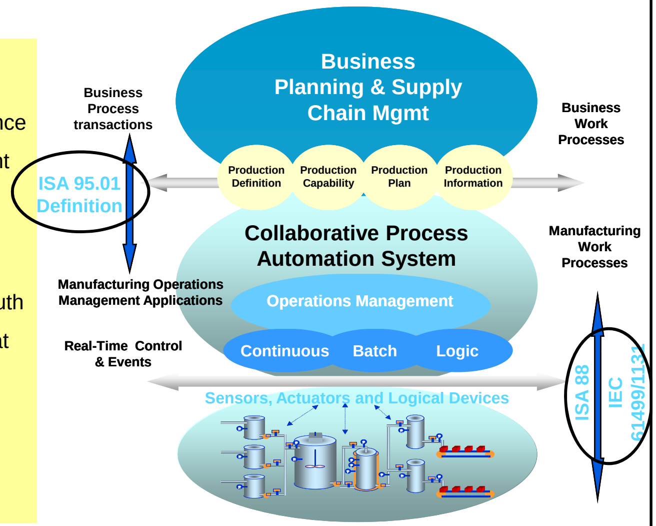
Collaborative Production Automation System (CPAS)
Bringing All Together in a Systematic Way

- CPAS Guiding Principles (ARC Advisory Group):
  - Extraordinary Performance
  - Continuous Improvement
  - Proactive Execution
  - Common Actionable Context
  - Single Version of the Truth
  - Automate everything that should be automated
  - No artificial barriers to information
  - Common Infrastructure based on standards



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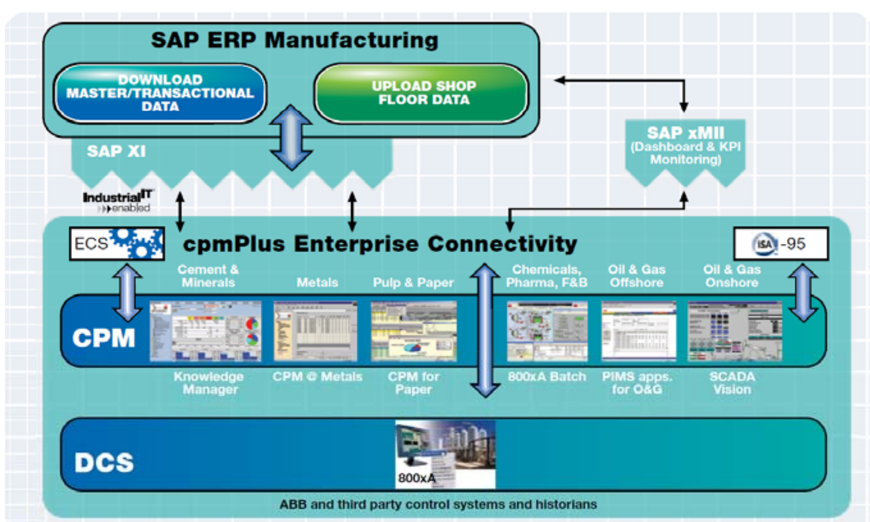
Existing Industrial SW-Landscape
Across the Enterprise - from DCS to ERP



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Integration of Scheduling & Control System
Collaboration of Several Factors

Industries
- Metals
- Pulp & paper
- Minerals
- Chemicals
- Pharma
- Food & Bev
- Discrete
- Power generation
- Utility networks (electricity, water, gas, …)

Plant Levels
- Factory site
- Production
- Process

Technologies
- Decision support
- Scheduling
- Production optimization
- Advanced control
- Asset management
- Alarm management
- Supervision & diagnosis
- MES

PM solution

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Scheduling, Advanced Control and their Integration
Main Challenges for the Implementation

- Modeling: Integrated solutions require high-fidelity representations of both scheduling problem and dynamics
- Optimization algorithms: Solution time & robustness
- Interaction with the user / human operator: Solutions not accepted by the operators are not used in the long term
- Automation systems and components: Often large systems contain modules from multiple companies. Integration requires open data structure
- Systems engineering. The design of integrated systems is a challenge for which no guidelines are available:
  - Roles of system components?
  - Intelligence on which levels?
  - Who triggers whom (communication)?
  - How to balance requirements?
  - Convergence?

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Scheduling, Advanced Control and their Integration
Keys to success

- Focus not only on models but on integrated solutions
- Cross-competencies needed for best-of-breed solutions!
- Closer collaboration between Academia and Industry
  - Academia cannot avoid standards
  - Industry must provide „real“ problems to the wide community
- Marketing very important!
  - Research needs investments!
  - Alone difficult to sell optimization, how to sell integrated optimizations → simplify, illustrate
- Systematic evaluation of benefits (KPIs)
- Do not artificially separate systems – all is production management – focus on the functionalities

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Thank you!

Questions?

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