Market-Driven Systems

Marknadsstyrda System

FRTN20

Lecture 1

Market-Driven systems

- **Aim**
  To teach the basic principles for automation systems in the manufacturing industries and their dynamic interaction with market factors such as variations in demand and prices for raw material, transports, and inventory. To give insight into current problems and trends of companies in region, through guest lectures and projects. Modern production companies interact with the market in many ways, some examples are international standards, industrial trends, fluctuations in demands, and variations in raw-material prices.

  Att ge kunskap om grundläggande principer för automationssystem i tillverkningsindustrin och dess dynamiska samspel med marknadsfaktorer såsom variationer i efterfrågan och priser för råvaror, transporter och lagerhållning. Att genom gästföreläsningar och projekt ge inblick i aktuella frågeställningar och trender hos företag i regionen. Dagens produktionsföretag interagerar med marknaden på många olika sätt, några exempel är internationella standarder, industriella trender, variationer i efterfrågan och råvarupriser.

Market-Driven systems

Aim II:

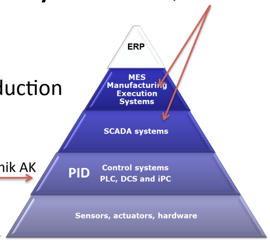
The course helps future managers to understand the role and value of control in modern companies as well as to give them an intuition about the parallels of controlling technical systems and managing an enterprise in the market. As such it helps to build a bridge between managers and engineers.

Kursens målsättning är även att hjälpa framtida ledare att förstå reglertekniks roll och värde i dagens företag, samt att ge förståelse för parallellerna mellan att styra ett tekniskt system respektive att leda ett marknadsföretag. På detta vis hjälper kursen till att skapa en bro emellan ledare och ingenjörer.

Market-Driven Systems

Aim III:

- To provide a management perspective on industrial production and automation systems
  - Part I



- To provide some tools and methods that are relevant for financial engineering in general
  - Game theory
  - Model-Predictive Control
  - Distributed Control using Price Mechanisms
  - Part II

Contents

- **Course Formalia**
- Production Systems
  - Continuous/Discrete/Batch Systems
  - Production Strategies
- Production Systems Models
  - Matematical Models – Topology
  - Enterprise Models
- Optimization in Production Systems
- Continuous Production Systems

Lecturers

- Charlotta Johnsson
  - Charlotta.johnsson@control.lth.se
  - 046-2228789
  - Course responsible
  - Lectures: 2,3,4,5,projects
  - **Lecture 1: Karl-Erik Årzen**
- Anders Rantzer
  - Model-Predictice Control
  - Distributed Optimization
  - Lectures 8,9
- Bo Bernhardsson
  - Game Theory
  - Lectures 10,11




Guest Lecturers

- Krister Forsman
  - Corporate Specialist at Perstorp Specialty Chemic
  - Industrial IT and Control
  - Lecture 6

- Anna Lindholm
  - ÅF Consulting
  - Industrial IT
  - Lecture 7

- Kurt Jörnsten
  - Prof at Norwegian School of Economics
  - Modern Production Management and Logistics
  - Lecture 12

Lectures

- 12 lectures
  - \+ one lecture where the projects are introduced
  - \+ one or two lectures for the project presentations
- Nominal lecture hours:
  - Tuesdays 10:15 – 12:00 in M:E
  - Thursdays 10:15 – 12:00 in M:D
- Changes:
  - First lecture: Thursday 26/3
  - Lectures on 15/4, 13/5 and 22/2 will be held in the department's Seminar room (M:2112B).
  - No lecture 25/5
- Hollidays (no lectures):
  - Easter: 2/4
  - Valborg: 30/4
  - Exam-period: 4-8/5
  - Kristihimmelsfärd: 14/5

Exercises

9 Exercises

Two exercises / week

- Wednesdays 8-10, M:X2a
- Fridays 8-10, M:L1

Changes:

- First exercise: 27/3
- Not used: 26/5
- Some exercise-sessions will be used for Guest lecturers or project-presentations

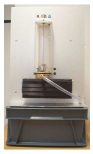
Holliday (no exercises)

- Easter: 3/4
- May 1st: 1/5
- Exam-period: 4-8/5
- Kristihimmelsfärd: 15/5

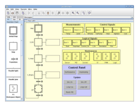
Josefin Berner

Olof Troeng

Laboratories



- Lab 1: Batch Control
  - 4 hours
  - Week 7/4 – 10/4
  - Sign up at the course homepage
  - Responsible: Josefin Berner



- Lab 2: Linear Progr. and MPC
  - 4 hours
  - Week 12/5 – 22/5
  - Sign up at the course home page
  - Responsible: Olof Troeng

Projects

- Two types:
  - "Industrial"
  - "Department"
    - Learn to know an industrial control system
- In groups of around 4
- Projects presented 16 Apr
- Projects presented during final week: 21-22/5
- Requirements:
  - Written report
  - Oral presentation

Exams

- Monday June 1, 14-19, MA:10D-E
- Wednesday August 19, 8-13, MA:10E
- Closed book exam

Course Material

- Folder with
  - Course texts
  - Copies of slides
  - Exercises with solutions
  - Lab manuals
- Free of charge
- Handed out today
  - Incomplete
  - You will complete it yourself using material handed out at the lectures
- Course material also available through the course home page
  - User name: control
  - Password: sunryspif (write it down, not in your handouts)

CEQ

- *”What has this course to do in the I-programme’s Finance and Risk specialization (too much automation)?”*
  - A specialization must contain a certain width and not all (probably very few) of you will end up in the finance sector.
  - Production system are a very important part of Swedish industry and several of you will probably end up as managers in the producing industry
  - An effort has been made this year to motivate the course better and to connect the two parts of the course
    - New material about production strategies, production systems models, and optimization-based planning and scheduling
    - More time for the game theory material

CEQ

- *”Course material system did not work well. Few students managed to fill their binders with all the material.”*
  - All material that is handed out and in the binder is also available for download from the home page
  - We don’t charge anything for the binder and the material in it

CEQ

- *”A lot of grammatical errors and bugs in the lecture notes and the exercises”*
  - The lecture notes and exercises have been revised

Contents - Check

- Course Formalia
- **Production Systems**
  - Continuous/Discrete/Batch Systems
  - Production Strategies
- Production Systems Models
  - Matematical Models – Topology
  - Enterprise Models
- Optimization in Production Systems
- Continuous Production Systems

Market-driven systems

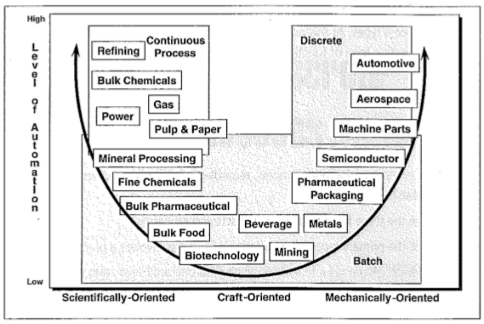
- System = industrial production
- Market-driven = interaction with the surroundings/market
  - Prices
  - Demands
  - Competition
  - Laws and regulations
  - Standards and guidelines
  - Trends

Industrial production

What industrial production sectors are there?

- Food & Beverage
- Pharmaceutical
- Metal
- Pulp & paper
- Chemical and PetroChemical
- Refining
- Automotive
- Biotechnology
- Machine parts
- Etc…

Industry vs Automation level



Industrial Production

The industrial production systems all have the same overall goal; to make money!

- This is done by transforming raw-materials into products through the utilization of material, energy, equipment, personnel/manpower.
- Minimize CAPEX and OPEX
  - CAPEX – Capital expenses
    - Costs associated with the acquirement or upgrade of physical assets such as equipment, property, or industrial buildings.
  - OPEX – Operating expenses
    - The ongoing cost for running a product, business, or system
- However, the continuous, discrete and batch production processes are different in key aspects of their operations.

Industrial production

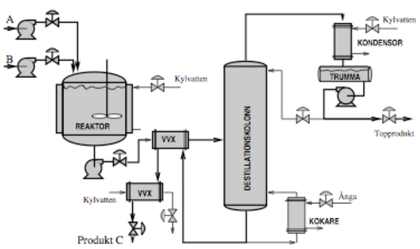
How can the production be performed?

- Continuous
- Discrete
- Batch

=> There are three types of production processes

Continuous Production Processes

In a continuous production process the raw materials are consumed in a continuous stream and a product result as a continuous outflow.



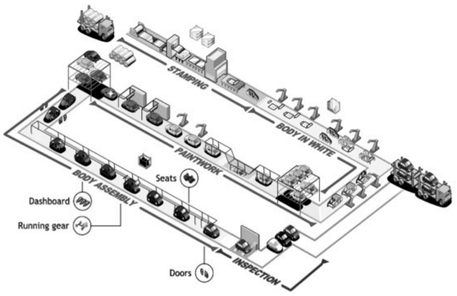
Continuous Production Processes

General Characteristics of continuous production processes:

- Continuous flow of material (often fluid-based).
- Continuous production of product, i.e. continuous outflow.
- Open-ended production runs.
- The process is most often ”invisible”.
- Disassembly-oriented production is not unusual.
- The equipment operates in steady-state.

Discrete Production Processes

A discrete production process is the assembly of piece parts into products. The product is a discrete entity.



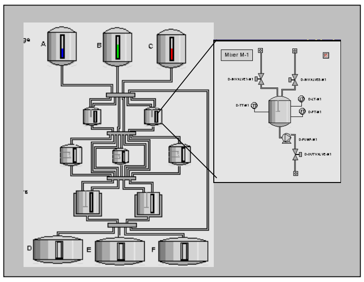
Discrete Production Processes

General Characteristics of discrete production processes:

- Discontinuous production of product, i.e. discrete output.
- Discontinuous flow of material (often pieces and parts).
- Assembly-oriented production.
- Staged production through work cells
- Well defined production runs.
- The process is most often ”visible”.
- The equipment operates in on-off manner.

Batch Production Processes

In a batch production process the product is made in batches or lots.



Batch Production Processes

General Characteristics of batch production processes:

- Production of products in batches
- Discontinuous flow of materials.
- Production run determined by time/ end point.
- Production goes through steps of operations.
- Fluid and dry processing.

Production Strategies

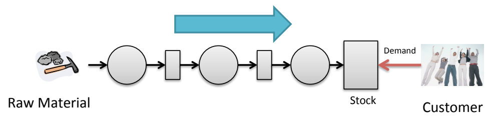
- Two main types:
  - Make-to-stock

    A traditional production strategy used by businesses to match production with consumer demand forecasts. The make-to-stock (MTS) method forecasts demand to determine how much stock should be produced. If demand for the product can be accurately forecasted, the MTS strategy can be an efficient choice.

  - Make-to-order

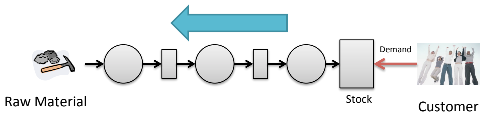
    A business production strategy that typically allows consumers to purchase products that are customized to their specifications. The make to order (MTO) strategy only manufactures the end product once the customer places the order. This creates additional wait time for the consumer to receive the product, but allows for more flexible customization compared to purchasing from retailers' shelves.

Make-to-stock



- Push model
- Necessary when it takes longer to produce than the customer is willing to wait
- Relies on the accuracy of demand forecasts.
  - Inaccurate forecasts will lead to losses stemming from excessive inventory or stockouts.
- Approaches:
  - MRP (Material Requirements Planning), MRP II (Manufacturing Resources Planning), ERP (Enterprise Resources Planning), SCM (Supply Chain Management)
- Using control terminology this corresponds to feedforward

Make-to-order



- Pull model
- Possible when the time to produce is shorter than the customers' acceptable waiting
- Downstream production units are views as customers to upstream production units
- Short change over/setup times a necessity
- Smaller batches → less inventory → shorter cycle times and faster detection of defects
- Approaches
  - Just in Time (JIT) production (Kanban, Toyota), Lean manufacturing, ...
- Using control terminology this corresponds to feedback

Make-to-Stock vs Make-to-Order

- In practice it is always a combination of make-to-stock and make-to-order
- Make-to-stock has a reputation of being slightly old-fashioned
- Make-to-order has been the focus of research the last 10-15 years
- However, the current low capital costs has made make-to stock more interesting again
  - Assuming that the product will eventually be sold
  - "Double-batching"

Contents

- Course Formalia
- Production Systems
  - Continuous/Discrete/Batch Systems
  - Production Strategies
- **Production Systems Models**
  - Matematical Models – Topology
  - Enterprise Models
- Optimization in Production Systems
- Continuous Production Systems

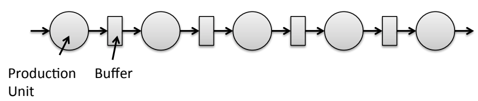
Production System Models

- Mathematical Models
  - Model-based
    - Design of production system, incl production units
    - Analysis
    - Planning and scheduling (optimization)
    - Reliability analysis
    - ....
  - A large variety of model types (deterministic/stochastic, discrete/continuous, linear/nonlinear)
- Enterprise Models
  - A "model" or a "framework" which represents the enterprise at one point in its life cycle, is needed. This "model/framework" is called an Enterprise Architecture.
  - Assist with planning and analysis of the enterprise, to select hardware and software products, to design organizational "reporting structures", and to study flow of materials and information through the enterprise.
  - The focus of this course

Mathematical Production System Models

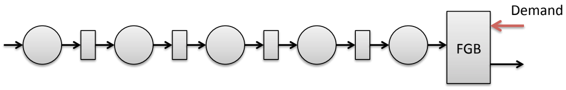
- Topology
  - Shows how the units/machines are connected and the flows within the system
- Machine models
  - Model the operation of the machines/units wrt. productivity, reliability, quality
- Media/product models
  - Models the behaviour/dynamics of the products flowing through the machines
- Buffer models
- Models for the interaction between buffers and machines
- Performance measures
  - Metrics quantifying the efficiency of the system operation

Topologies: Serial Production Line



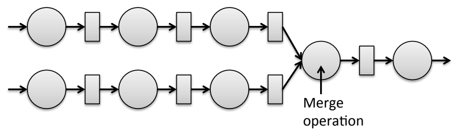
- Production units:
  - Machines, work cells, equipment units, process cell .....
- Buffers with storage capacity:
  - Material handling devices, e.g., boxes, conveyors, autonomous guided vehicles (AGVs), trucks, ...
  - Buffer tanks
  - Filter out production randomness (disturbances, variations, ...)

Topologies: Serial Production Line with Finished Goods Buffer



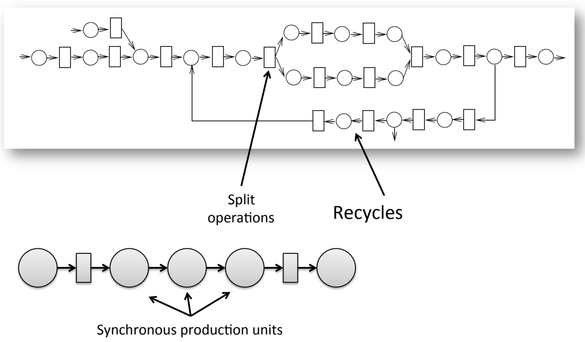
- FGB - Finished Goods Buffer
  - Inventory of finished products
  - Filter out production randomess (disturbances, variations, …)
  - Compensate for variations in demand

Topologies: Assembly Systems



- Two or more serial lines (”component lines”)
- Two or more merge operations
  - Components are assembled or mixed

General Topology

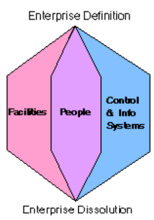


Enterprise Models

- A "model" or a "framework” which represents the enterprise at one point in its life cycle, is needed. This ”model/framework” is called an Enterprise Architecture.
- This framework can be used to assist with planning and analysis of the enterprise, to select hardware and software products, to design organizational "reporting structures", and to study flow of materials and information through the enterprise.
- Without an Enterprise Architectural model, executives, managers, and technologists in an enterprise are essentially "running blind": making decisions based on their personal perception of the enterprise which is often not shared with the rest of the organization.

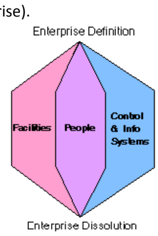
How can industrial production companies be modeled?

- PERA – Purdue Enterprise Reference Architecture
- PERA was defined in 1980s.
- The PERA generic enterprise model sees an enterprise as composed of three main components
  - Physically (Production Facility)
  - Organisationally (People)
  - Functionally (Control and information systems)
- UEML – Unified Enterprise Modeling Language
- UEML is an initiative funded by the European Research Programs FP5 and FP6.
- The aim is to provide an underlying formal theory for enterprise modelling languages. A major motivation was enterprise integration in the face of a wide variety of enterprise modelling languages.



PERA

- The PERA model describes the complete life cycle of an enterprise; from enterprise definition (what should the enterprise do), through conceptual engineering, preliminary engineering, detailed engineering, construction, to operations, and from operations through decommissioning to enterprise dissolution (tear down of an enterprise).



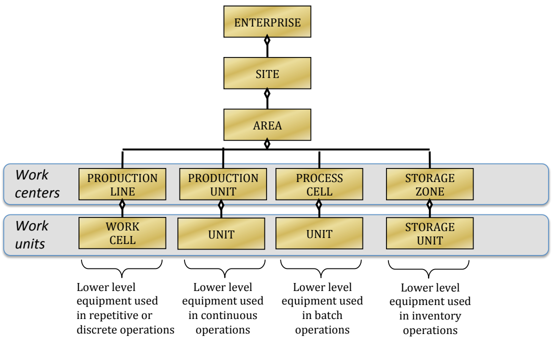
PERA

- Facilities: describes the structure of the company and its equipment. In addition to a generic physical structure, a more detailed structure is used:
  - continuous processing facilities are described with "Process Flow Diagrams"
  - discrete manufacturing is described wtih Material Flow diagrams.
  - batch processes are described by sequences.
- People: describes the people working at the company and the realtionships amongs them. The organizational structure may be represented by a series of "Org Charts".
- Control and Information Systems: may be represented through a Control and Information Architecture Diagram (CIAD) or a Control and Information Network Diagram (CIND).

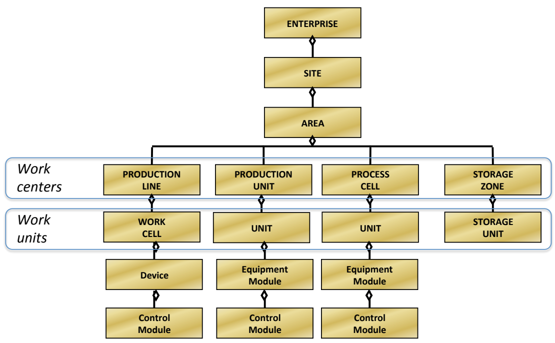
Organisational Model (People) of an Enterprise

- Not included in the course

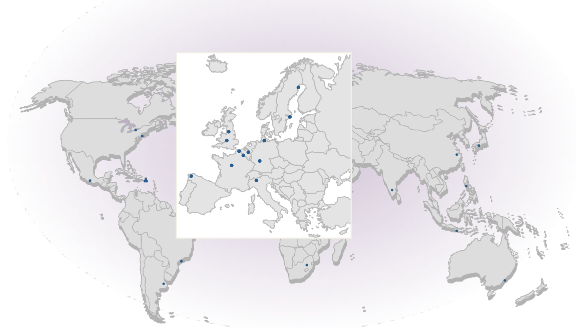
Physical Model of an Enterprise



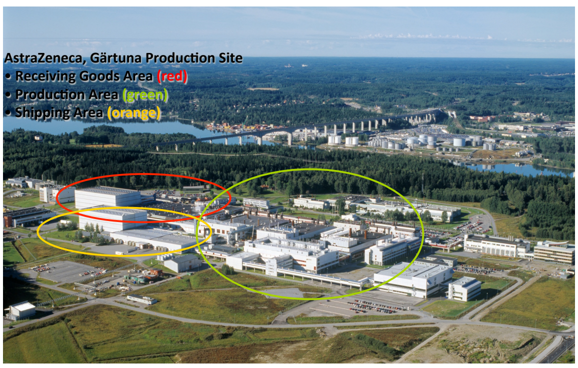
Physical Model of an Enterprise



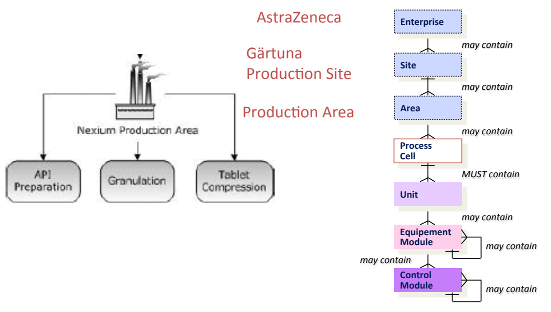
Example – AstraZeneca Production Sites



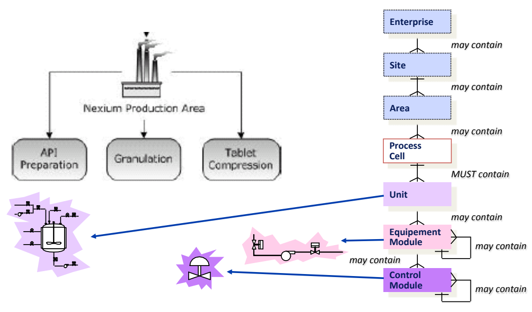
Example – AstraZeneca Production Areas



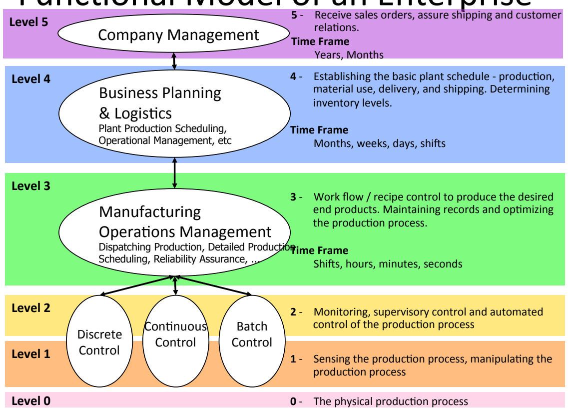
Example – AstraZeneca Process cells



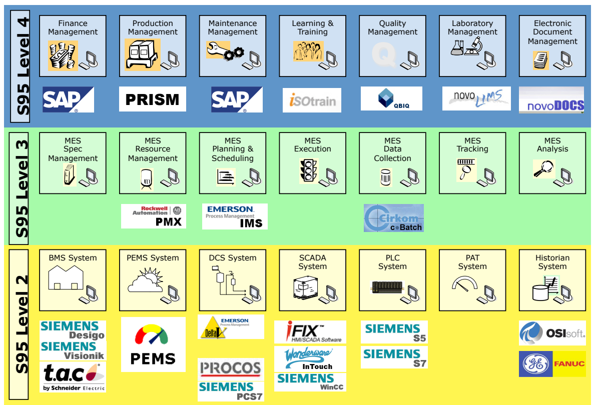
Example – AstraZeneca lower levels



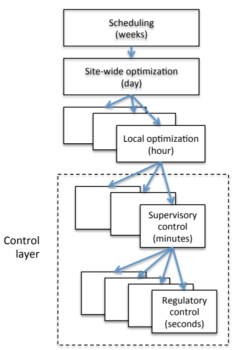
Functional Model of an Enterprise



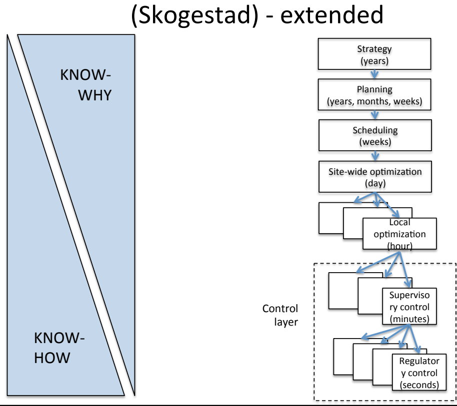
Functional Model – NNE Example



Typical control hierarchy of a chemical plant (Skogestad)



Typical control hierarchy of a chemical plant (Skogestad) - extended



Contents

- Course Formalia
- Production Systems
  - Continuous/Discrete/Batch Systems
  - Production Strategies
- Production Systems Models
  - Matematical Models – Topology
  - Enterprise Models
- **Optimization in Production Systems**
- Continuous Production Systems

Planning and Scheduling

- Good planning and scheduling are often the key to successful production
- Decide
  - Amount of raw material
  - When to perform the production - scheduling
  - Which production units to use
  - Which operating point to use
  - How to do the closed loop control
    - Model-Predictive Control (MPC)
  - ……
- At several levels in the automation strategy

Optimization: General Formulation

General formulation:

objective function

s.t *constraints*

where are the ***decision variables***, are functions that depend on and are constants

A solution that fulfills the constraints and minimizes is called an ***optimal solution*** and is denoted

Linear Programming

(P) is a linear programming problem (LP) if

- all functions f, g_i are linear
- all variables x_j are continuous

$$\min z = \sum_{j=1}^{n} c_j x_j$$

$$\text{s.t} \quad \sum_{j=1}^{n} a_{ij} x_j \le b_i \quad i=1,..,m$$

$$x_j \ge 0 \quad j=1,..,n$$

More in Lecture 6

Integer Programming

- The problem is an ***integer programming problem* (IP)** when all the decision variables are integer variables
- The problem is a ***binary programming problem (0/1 problem)*** when all the decision variables are binary (boolean) variables
- The problem is a ***mixed integer programming problem* (MIP)** when it contains both integer and continuous variables
- The problem is a ***mixed linear integer programming problem* (MILP)** if, in addition, all functions involved are linear

Integer Programming *cont.*

- Integer programming problems are NP-complete (”very difficult to solve”), i.e.,
  - There are no guarantees that a solution will be found even it exists
  - There are no guarantees that a solution found is the global minimum
- Many of the planning and scheduling problems in discrete and batch production systems are of integer nature, typically different forms of search problems
  - Select which machine to use, which path to take, ….
  - Select the order in which things should be done
  - …..
- However, in may cases heuristics exist that in most cases will generate a feasible but not provable optimal solution

Nonlinear Problems

Problem (P) is nonlinear problem if at least one of the functions f, g_i is a nonlinear function

Nonlinear problems can be classified in different ways:

- Differentiable vs non-differentiable
  - A problem is differentiable if the functions involved have continuous first and second derivatives
  - Solution techniques using the Jacobian and Hessian may be used, e.g. variations of steepest-decent
- Convex vs non-convex

Convex Problems

The problem

$$\min_x f(x)$$
$$\text{s.t} \quad x \in X$$

is a ***convex problem*** if $f(x)$ is a ***convex function*** and X is a ***convex set***.

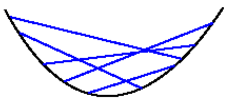
For a convex problem, each local optimum is also a global minimum

Relatively easy to solve

LP problems are convex, while nonlinear problems often are non-convex

IP problems are always non-convex

Convex Function

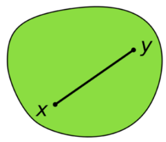


Convex function

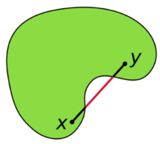
Non-convex function

- No line segment connecting two points on the function lies below the function at any point (in R)
- Extended to higher dimensions

Convex Set



Convex Set



Non-convex Set

A set $X \in R^n$ is a convex set if for any pair of points $x^{(1)}, x^{(2)} \in X$ and $0 \le \lambda \le 1$ we have

$$x = \lambda x^{(1)} + (1-\lambda) x^{(2)} \in X$$

Quadratic Problems

An important class of convex problems:

$$\min_x \ 1/2\, x^T Q x + c^T x$$
$$\text{s.t.} \quad Ax = b \quad \textit{equality constraint}$$
$$Ex \le d \quad \textit{inequality constraint}$$

where Q is symmetric and positive definite

Quadratic objective function and linear constraints

More in Lecture 6

Optimization in Continuous Production Systems

- In continuous production systems, e.g., in chemical process industries optimization is very common:
  - The objective function is often related to cost, energy consumption, ….
  - The equality constraints describe the performance of the system, e.g., material balances, production rates, …
  - The inequality constraints can define process specifications or constraints for feasible plans and schedules

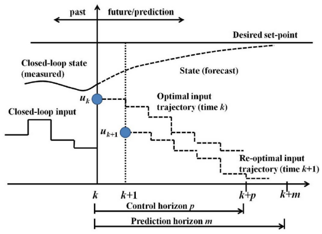
Model Predictive Control (MPC)

- A controller where the control signal is obtained through the solution of a convex optimization (LP or QP) problem
  - The problem is solved each sample
  - Dynamic optimization
- In the optimization problem
  - the **decision variables** are the control signals from the current sample, kh, up to the control horizon, $kh+H_c h$
  - the **objective function** penalizes the deviation between the process output (states) and their desired values over a prediction horizon
  - the **equality constraint** is the discrete-time linear process model
  - the **inequality constraints** are linear bounds on the states and the control signal
- The output of the optimization is

$u(kh), u(kh+h), \ldots, u(kh+H_C h)$

- Only $u(kh)$ is used (sent to the process)
  - The **receeding horizon principle**
- At the next sample everything is repeated

Receeding Horizon



- Strengths:
  - Works for MIMO (multi-input, multi-output) systems
  - Allows inequality constraints on states
  - Can take known future changes in, e.g., set-points, into account (prediction)
- Often used at the supervisory level
  - Control signals are the setpoints of PID controllers at the control level
- More in Lecture 6

Optimization Techniques in Continuous Production Systems

	LP	MILP	QP	NLP	MINLP
Process Model Building				X	X
Process Design & Synthesis					
Heat Exchangers	X	X		X	X
Mass Exchangers	X	X		X	X
Separations		X		X	X
Reactors	X			X	X
Flowsheeting				X	X
Process Operations					
Scheduling	X	X			X
Supply Chain	X	X			X
Real-Time Optimization	X		X	X	
Process Control					
Model Predictive Control	X		X		
Nonlinear MPC			X	X	
Hybrid MPC		X			

Contents

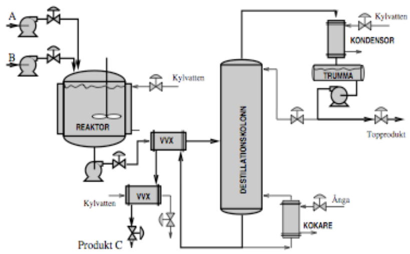
- Course Formalia
- Production Systems
  - Continuous/Discrete/Batch Systems
  - Production Strategies
- Production Systems Models
  - Matematical Models – Topology
  - Enterprise Models
- Optimization in Production Systems
- **Continuous Production Systems**

Continuous Production Processes

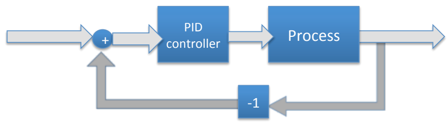
General Characteristics of continuous production processes:

- Continuous flow of material (often fluid-based).
- Continuous production of product, i.e. continuous outflow.
- Open-ended production runs.
- The process is most often "invisible".
- Disassembly-oriented production is not unusual.
- The equipment operates in steady-state.

Example of a Continuous Production Process



The basic control entity in continuous processing is the PID controller and the feedback control loop (Reglerteknik AK)



Initially, companies that became involved with the automation of continuous processes where companies that made instrumentations: Honeywell, Foxboro (today Invensys), Bailey (today Rockwell), etc

How do we control a plant?
Design of Process and Control System

Step 1: Selection of control-parameters: chose the measured-variables and sensors

Step 2: Selection of manipulated variables; select the actuators

Step 3: Control structure; combine the sensors with the actuators

Step 4: Selection of (optimal) working-point (arbetspunkt)

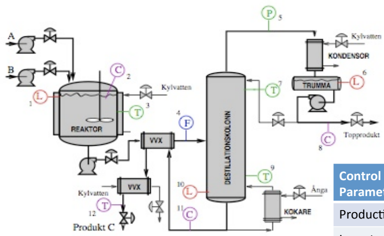
Step 5: Controller; selection of controller and tuning

Step 6: Evaluation: control, process and economy

Step 1:
Selection of Control Parameters

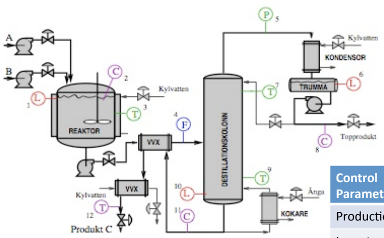
Control Parameter	What to measure
Production rate	Flow
Inventory-variables	Gas – pressure Liquids – level Solids - weight Concentrations - analysis Energy – temp or pressure
Surrounding variables	Temperature – temperature Pressure – pressure Concentration - analysis
Product quality	Physically - physical properties Chemical - analysis
Economics	

Step 1:
Selection of Control Parameters



Control Parameter	What to meassure
Production	
Inventory variables	
Surrounding variables	
Quality	

Step 1:
Selection of Control Parameters



Control Parameter	What to meassure
Production	Flow 4
Inventory variables	Level 1,6,10
Surrounding variables	Temperature 3,7,9 Pressure 5
Quality	Concentration 2,8,11 Temperature 12

Step 1: Sensors

- Should measure the control parameter
- Sensitivity and reliability
- Dynamic effects
- Cost
  - Common Examples: level-, flow–, temp- sensors and instruments for analysis

Step 2: Actuators

- The manipulated variables should be controllable
- Capacity, precision and reliability
- Dynamic effects
  - Common Examples: Valves, pumps

Step 3:
Control structure

What makes a process difficult to control?

- Time delays
  - The amount of time it takes for the process to react to the change
- Lag
  - A measure of how quickly a process repond to a change (e.g., volume of a tank).
- Non minimum phase (zeros in Right half plane)
  - The step response starts in a negative way.
- Slow feedback loop but quick dynamics in the disturbances

79

Step 3:
Control structure

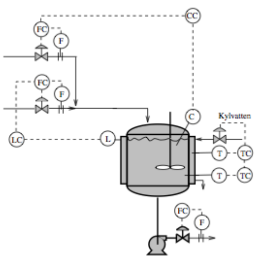
Might require process redesign:

- Replace sensors and/or actuators in order to modify the dynamics.
- Move the placement of sensors and/or actuators in order to avoid time delays.
- Add sensors in order to measure closer to important disturbances.
-

80

Step 3:
Control structure

There are several possible control structures.
One example is:



Pair sensors with actuators

- Production, F_{ut} – outflow
- Inventory, L_{ref} – inflow B
- Surrounding, T_{ref} – flow to the jacket
- Quality, C_{ref} – inflow A

81

Step 4:
Selection of working-point

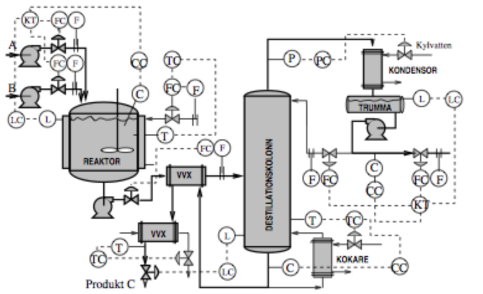
- What are suitable numbers on the reference variables?

Step 5:
Controller

- Select controller type (e.g. PID)
- Tune the controllers, i.e., find values for the P, I, and D variables of the controller.

82

Step 5:
Controller



83

Step 6:
Evaluation

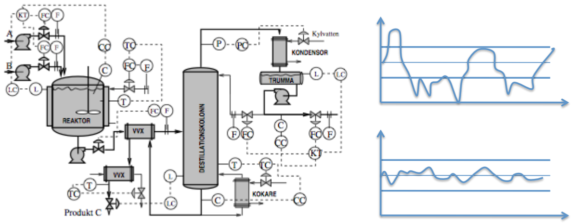
- Economics
  Is the budget for the process and control design phase met?
- Safety
  Is the plant safe enough to run?

84

Improvements of Continuous Production Plants

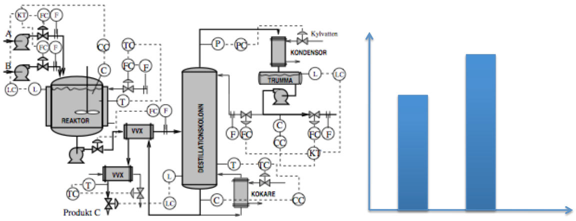
- Control performance
  The control performance is often regulatory, e.g. holding a measured and/or computed quantity at its desired value.
- Process performance
  The process performance is a measure of how well the process meets its objectives. This could for example be production rate.
- Economic performance
  The economic performance is measured in financial terms, e.g., financial production rate which is expressed as Money (Euros/dollars/SEK) per production time.

Control Improvement



The plant improves the control of concentration in the reactor. The variation in the concentration is reduced by 40% (**control improvement**)

Process Improvement



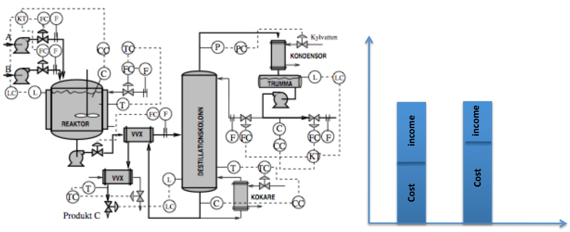
The plant improves the control of concentration in the reactor. The variation in the concentration is reduced by 40% (**control improvement**). The control improvements allow the elimination of delays for product analysis, so the plant can now turn out 10% more product per day (**process improvement**).

Process Improvement

Common process improvement factors:

- Higher output
- Lower utility cost
- Better yield
- Fewer unwanted byproducts
- Less labor
- Better quality

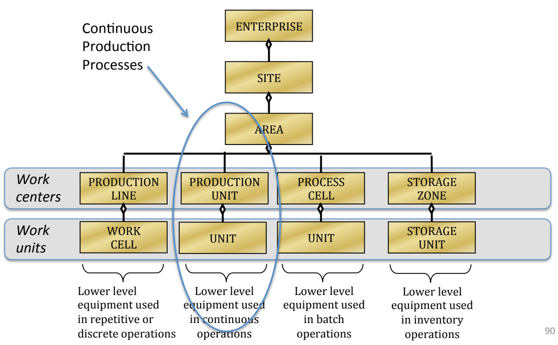
Economic Improvement



If there is market for the additional product, there will be an economical improvement.

If there is no market for the additional product, there will be an economical net loss since the aditional product will require additional raw material.

Physical Model of an Enterprise



Functional Model of an Enterprise