New Vistas for Process Control:

Integrating Physics and Communication Networks

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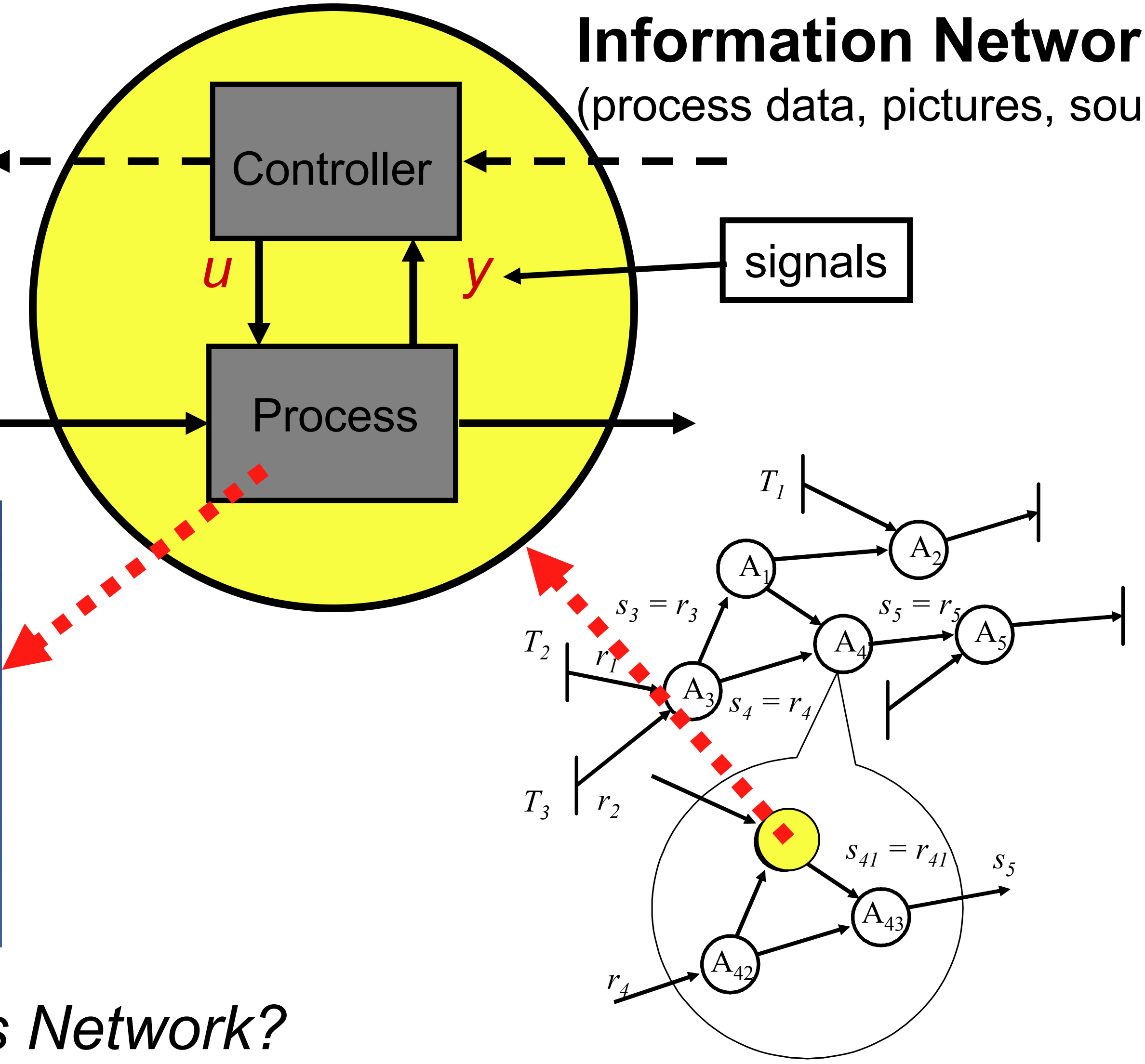
Information Network

(process data, pictures, sound,..)

Process Network

(energy and materials)



Controller

u

y

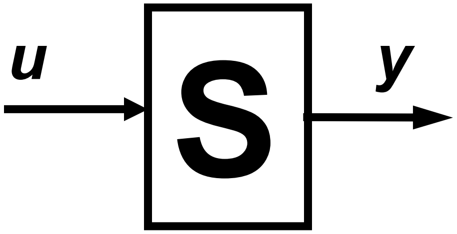
signals

Process

- *What is a Process Network?*
- *What is an observation (signal)?*
- *Is there a difference between process and information flow?*
- *Is a Process Network passive?*

Passivity Based Control

Control system:



$$
\begin{aligned}
\frac{dx}{dt} &= f(x) + g(x,u) \qquad \text{control system} \\
y &= h(x) \qquad \text{observations}
\end{aligned}
$$

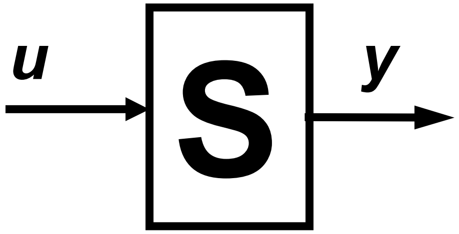
Example: MD with thermostat

strain

friction

$$
\begin{aligned}
\dot{r}_i &= v_i + \chi r_i \\
\dot{v}_i &= \frac{F(r_i)}{m_i} + \chi v_i - \alpha v_i \\
\dot{V} &= 3V\chi
\end{aligned}
$$

Definitions:



Storage Function : $V : \mathrm{x} \to \mathrm{R}^{+/0}$

$$\frac{dV}{dt} \le u^T y - \beta \|\varsigma\|_2^2, \text{ passive (dissipative) if } \beta \ge 0$$

$\beta > 0$

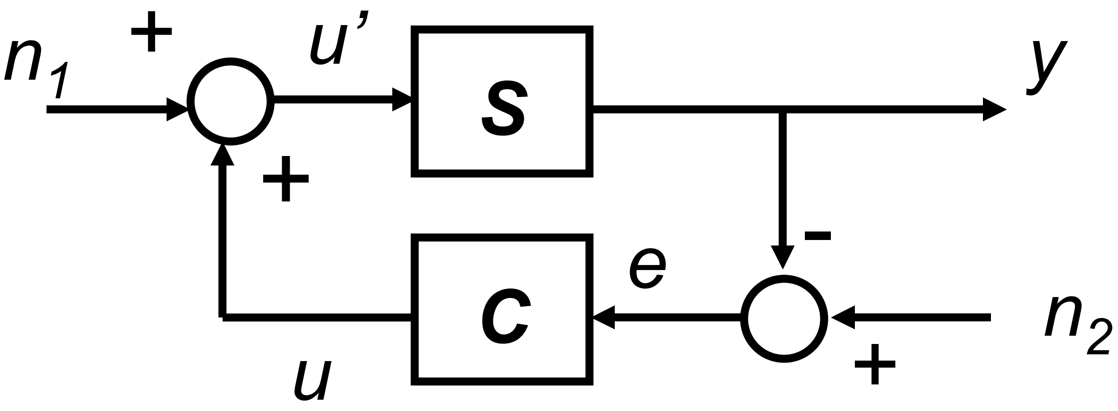
Input strictly passive if $\varsigma \to u$

Output strictly passive if $\varsigma \to y$

State strictly passive if $\varsigma \to \mathrm{x}$

$$\frac{dV}{dt} = u^T y, \quad \text{Lossless (Hamiltonian, } V \text{ is "Invariant")}$$

Passivity Theorem (Input-Output Theory)



A Feedback connection of a passive/lossless system ***S*** and a strictly input passive control system ***C*** is finite gain stable.

$$u = g_0 e, \quad \text{strictly input passive if } g_0 > 0$$

Proof

$$\frac{dV}{dt} \le (u + n_2)y - \beta\varsigma^2,$$ control system

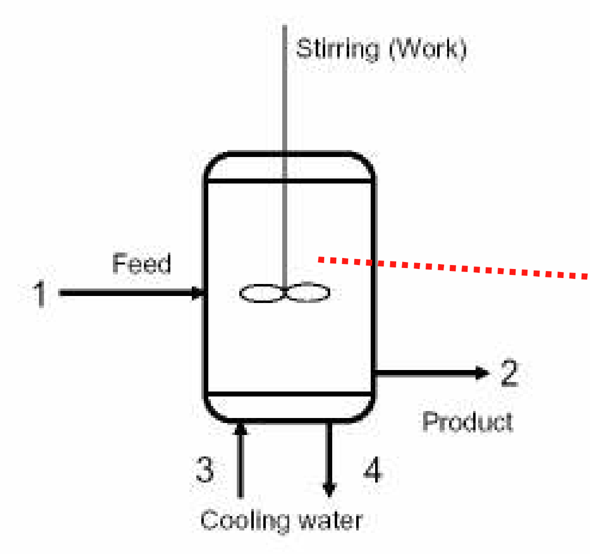
$$\frac{dW}{dt} \le (-y + n_1)u - g_0 e^2$$ controller

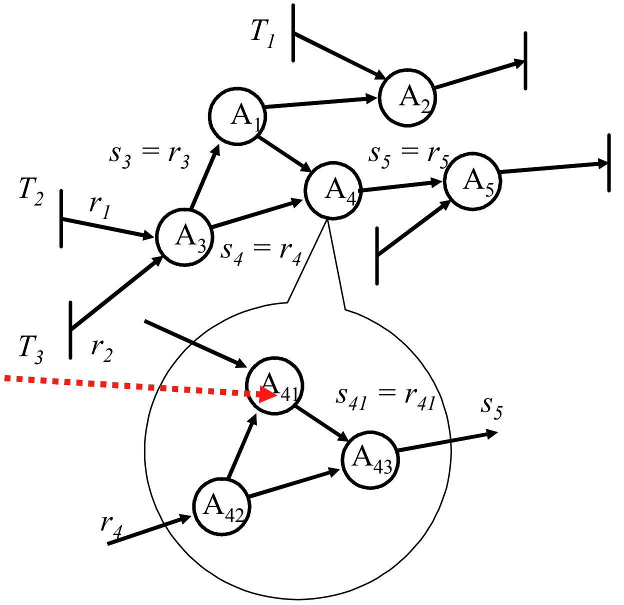
$$\frac{d(V+W)}{dt} \le \begin{pmatrix} n_1 \\ n_2 \end{pmatrix}^T \begin{pmatrix} y \\ u \end{pmatrix} - g_0 e^2 - \beta\varsigma^2,$$ closed loop system is passive

Q1. What Is a Process Network?

Graph, G = (P,T,F)

- Vertices (Processes, P_i, i=1,…,n_P)
- Vertices (Terminals connect to other processes, T_i, i=1,…,n_T)
- Edges (Flows, F_i, i=1,…,n_F)



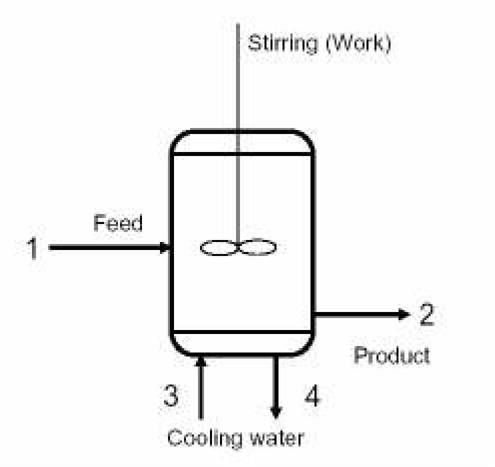


A1: It is a network of (chemical) processes

Processes

- Inventory *Z(x)* (material, energy, moles, charge,..) - HD1
- Potentials *w* (value, pressure, temp) - HD0

Conservation laws:



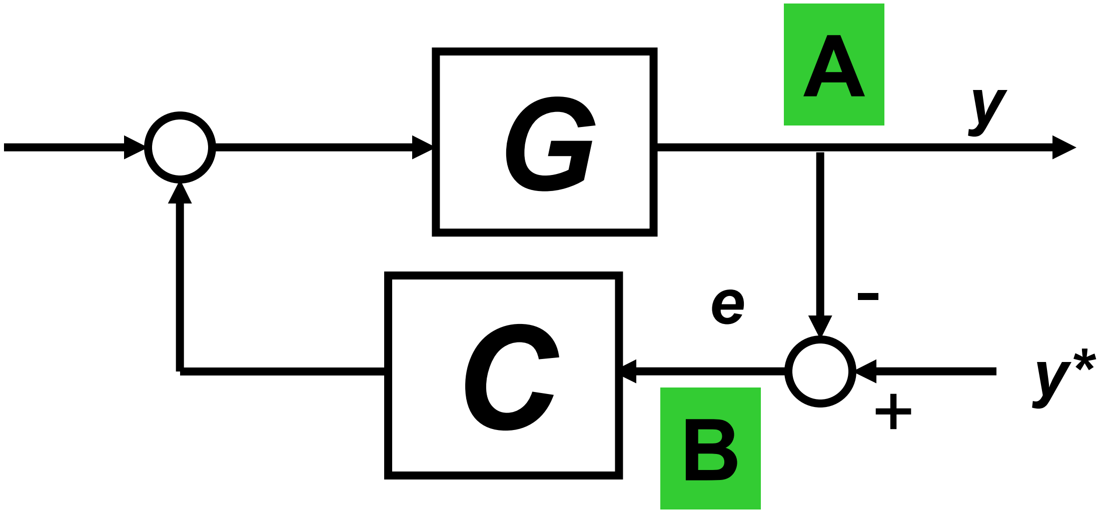
$$\frac{dZ}{dt} = p(Z) + \sum_i f_i(u), \text{ process system}$$

$$w = h(Z), \qquad \text{observations - signals}$$

A1: Z represents the state
A2: Exists *S(Z),* concave HD1

Z and *w* are dual (Legendre transform)

Q2: Is there a Difference between Process and Information Flow?



A Process Flow :

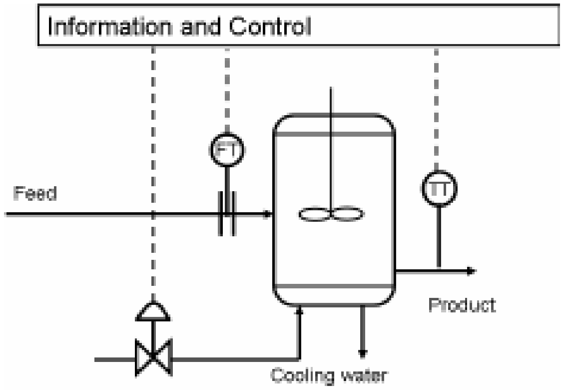
- Graph
- A and B: *x+y+z=0*
- A and B: *u+v+w=0*
- *Bond graphs/circuits*
- *MODELICA*

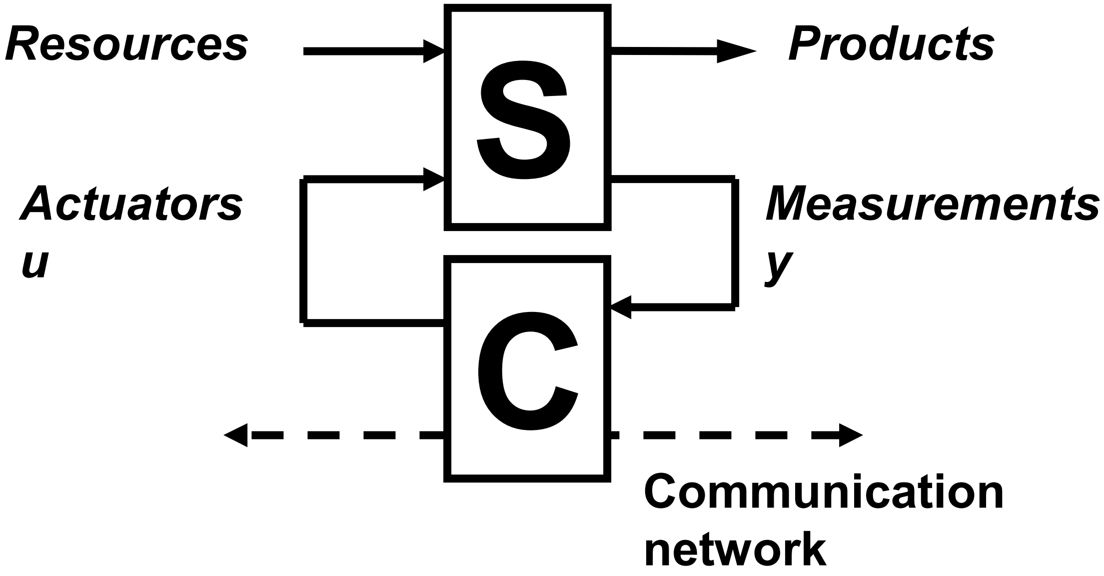
B Signal Flow:

- Directed Graph
- A: *x=z=y* *copy* *(intensive)*
- B: *x+y+z=0* *conservation (extensive)*
- *Block Diagram Algebra*
- *SIMULINK*

A2: Yes

The Two Port Representation: Transformation Processes




Resources

Products

S

Actuators
u

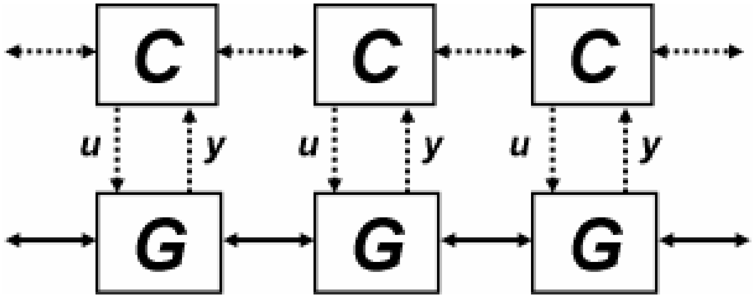
Measurements
y

C

Communication network

Signals are the Legendre transform of process variables

Q3: Is a Process Network Passive?



Theorem: $$\frac{dV}{dt} = -\sum_{\text{processes}} \overline{w}^T \overline{p} - \sum_{\text{connections}} \overline{w}^T \bar{f} - \sum_{\text{terminals}} \overline{w}^T \overline{p}$$

Like a Tellegen Theorem

Possibilities for passive feedback/feedforward

$$\bar{f} \mapsto \overline{w}, \quad \bar{f} \mapsto \overline{X}, \quad \overline{p} \mapsto \overline{w},$$

Intensive variable control
(Dual space)

$$\sum f_i \mapsto \overline{Z}$$

Inventory control
(Primal space)

A3: Qualified Yes, Depends on How Measurements and Actuators are Placed

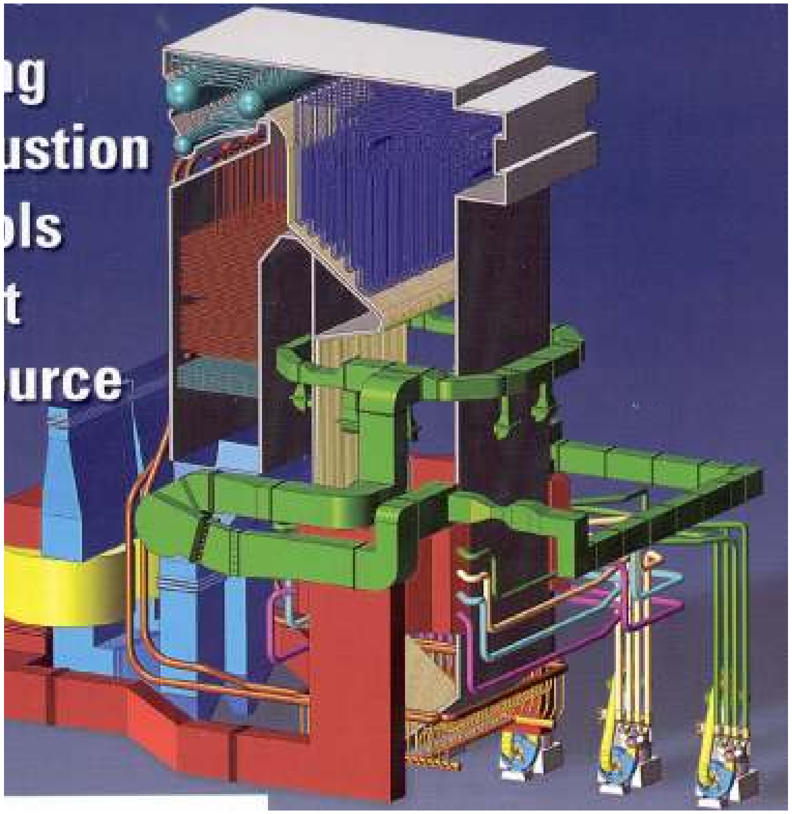
Literature Background

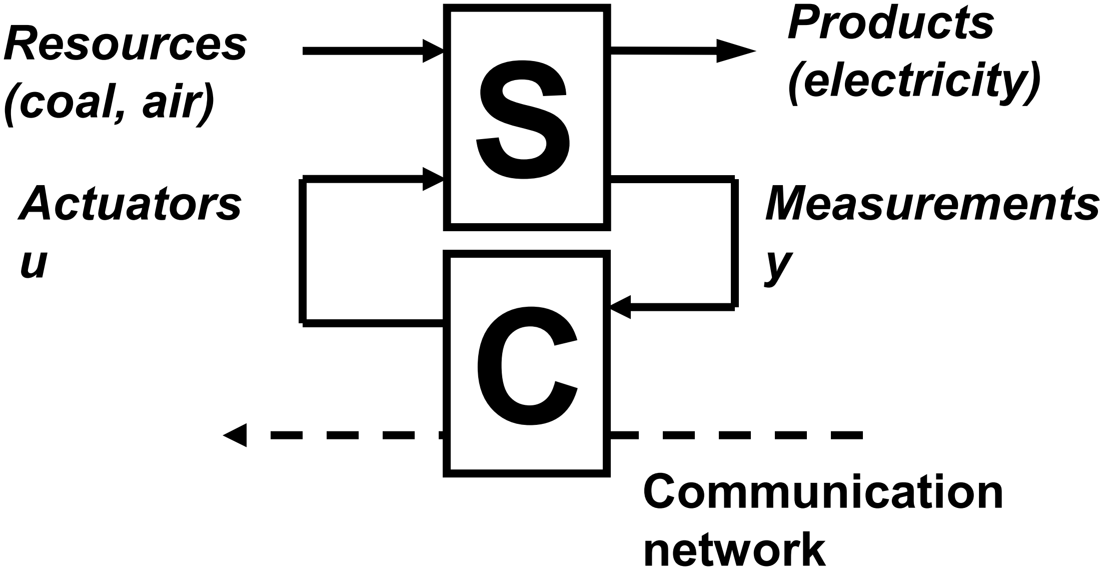
- Circuit theory and analog computers (1950ies)
- Irreversible thermodynamics (1950 - 60ies)
- Bond graphs (1960’ies)
- Thermodynamic networks (1960 - 70ies)

Application Domains

- **Power Plant Control**
- Decentralized Adaptive Control
- (Particulate systems/stat .mech.)
- (Supply chains)
- Financial and Business systems
- Integrated Operation

Power Plant Control





Resources (coal, air)

Products (electricity)

S

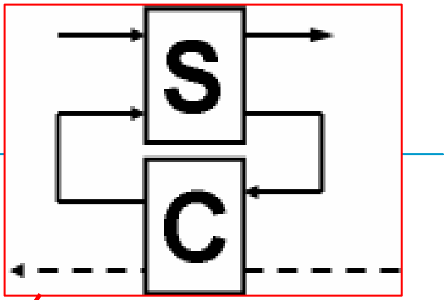
Actuators u

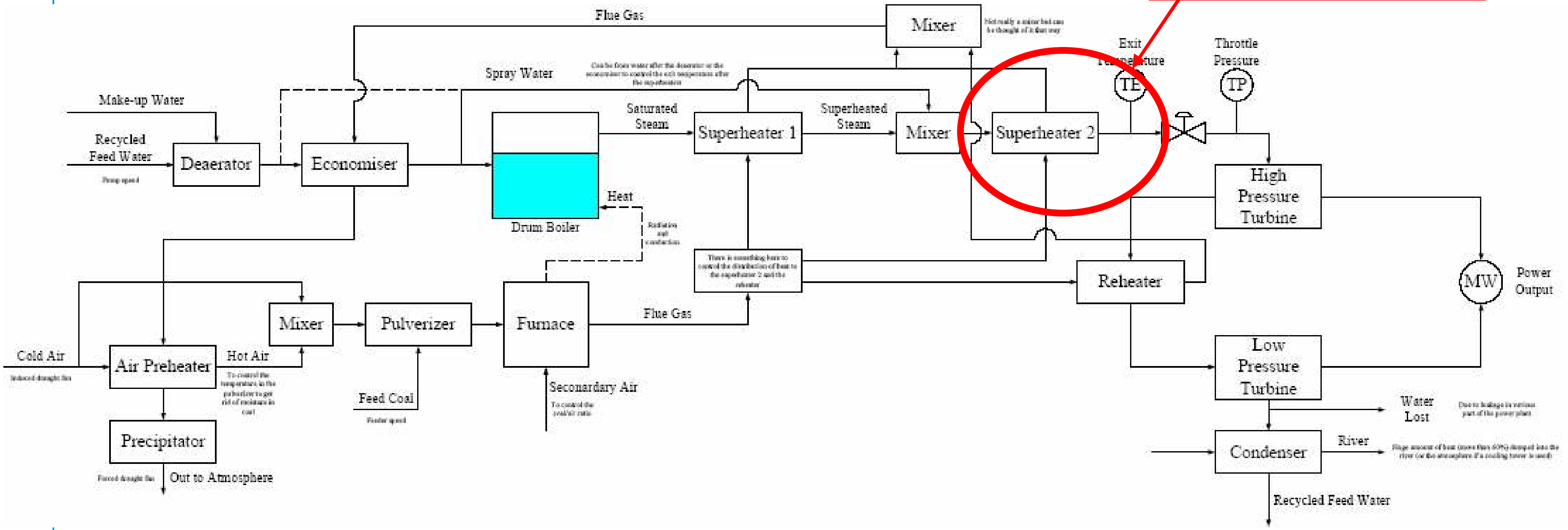
Measurements y

C

Communication network

Power Plant Control



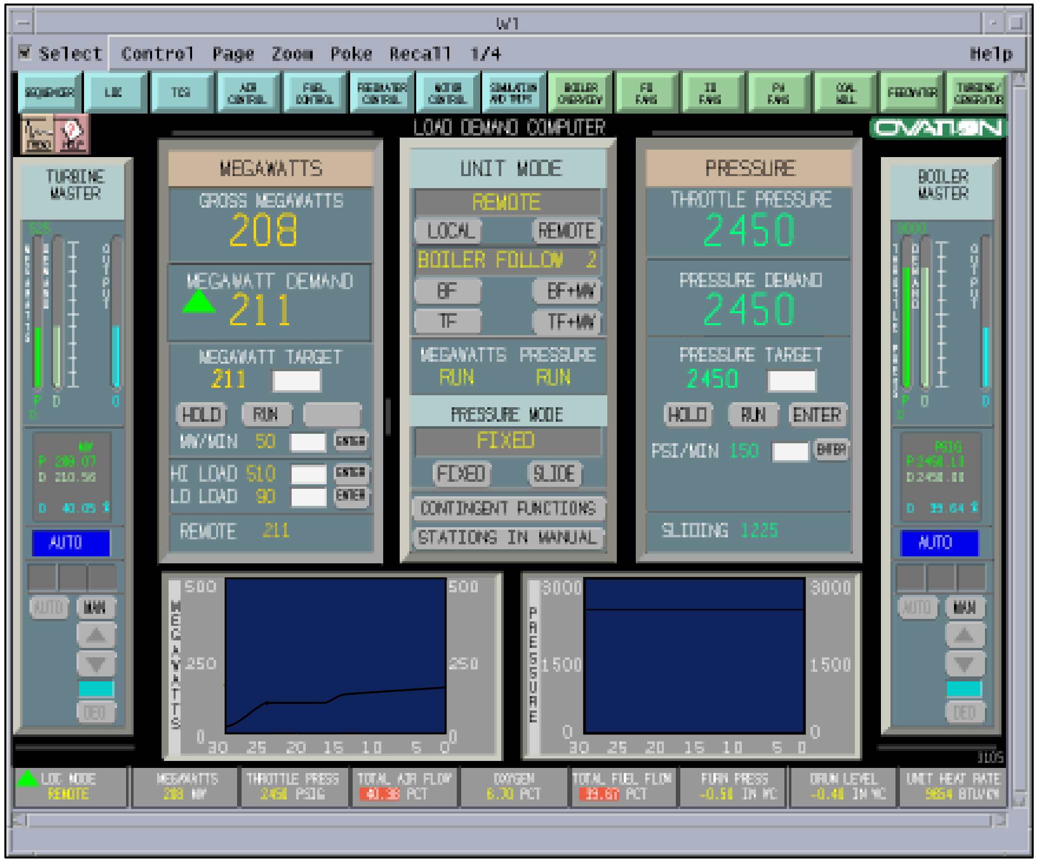


- **Decentralized Modeling and synchronization**
- **Unit Coordinated control**

Integrated Unit Master Approach

- Provides index for total control of unit
- Allows operator entered megawatt target and ramp rate
- Provides seven modes of unit operation
- Allows operator entered high and low limits
- Provides local and remote unit dispatch
- Built-in unit runbacks, rundowns and inhibits

Load Demand Dispatch



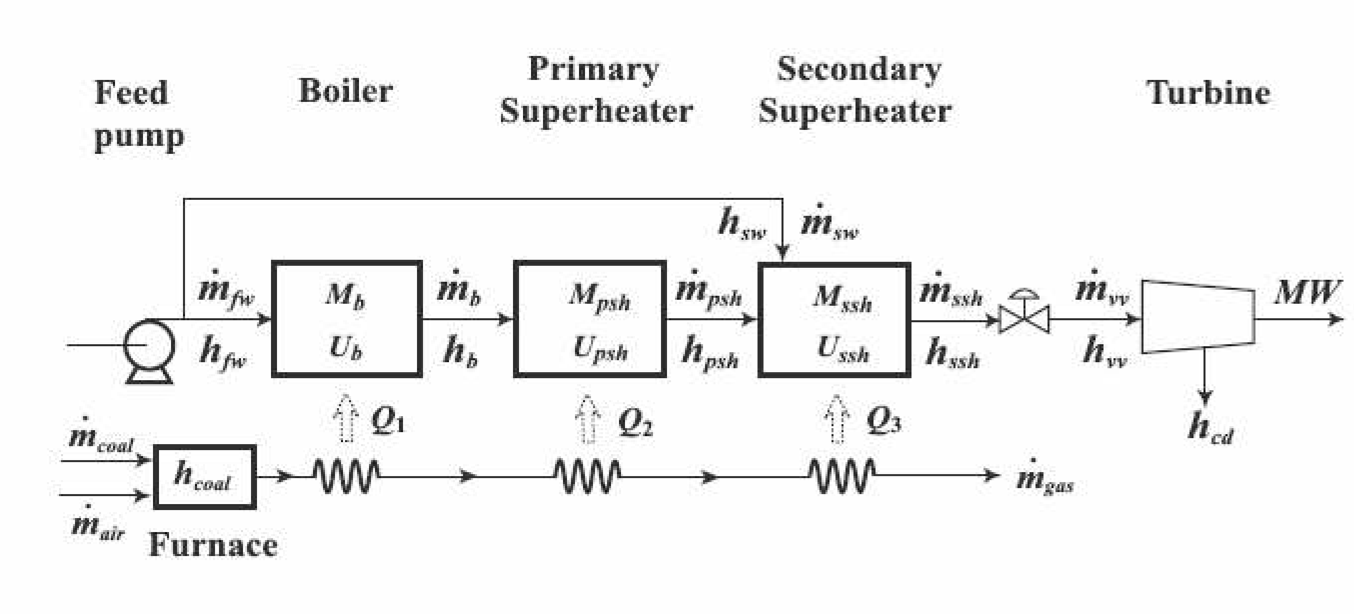
MEGAWATTS
GROSS MEGAWATTS 208
MEGAWATT DEMAND 211
MEGAWATT TARGET 211
MW/MIN 50
HI LOAD 510
LO LOAD 90
REMOTE 211

UNIT MODE
REMOTE
BOILER FOLLOW 2
MEGAWATTS RUN
PRESSURE RUN
PRESSURE MODE
FIXED

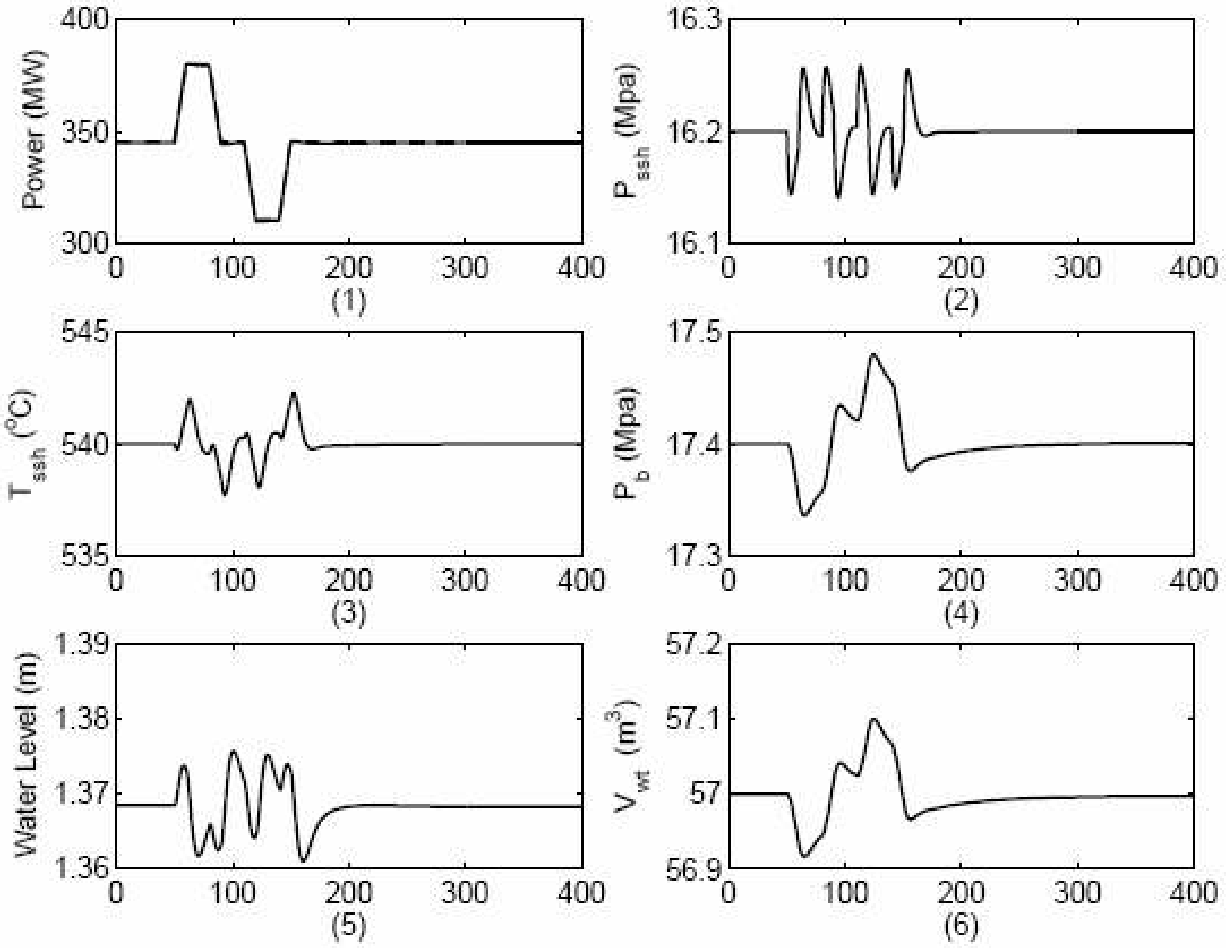
PRESSURE
THROTTLE PRESSURE 2450
PRESSURE DEMAND 2450
PRESSURE TARGET 2450
PSI/MIN 150
SLIDING 1225

LDC MODE REMOTE
MEGAWATTS 208 MW
THROTTLE PRESS 2450 PSIG
TOTAL AIR FLOW 40.38 PCT
OXYGEN 6.70 PCT
TOTAL FUEL FLOW 39.87 PCT
FURN PRESS -0.51 IN WC
DRUM LEVEL -0.48 IN WC
UNIT HEAT RATE 9854 BTU/KW

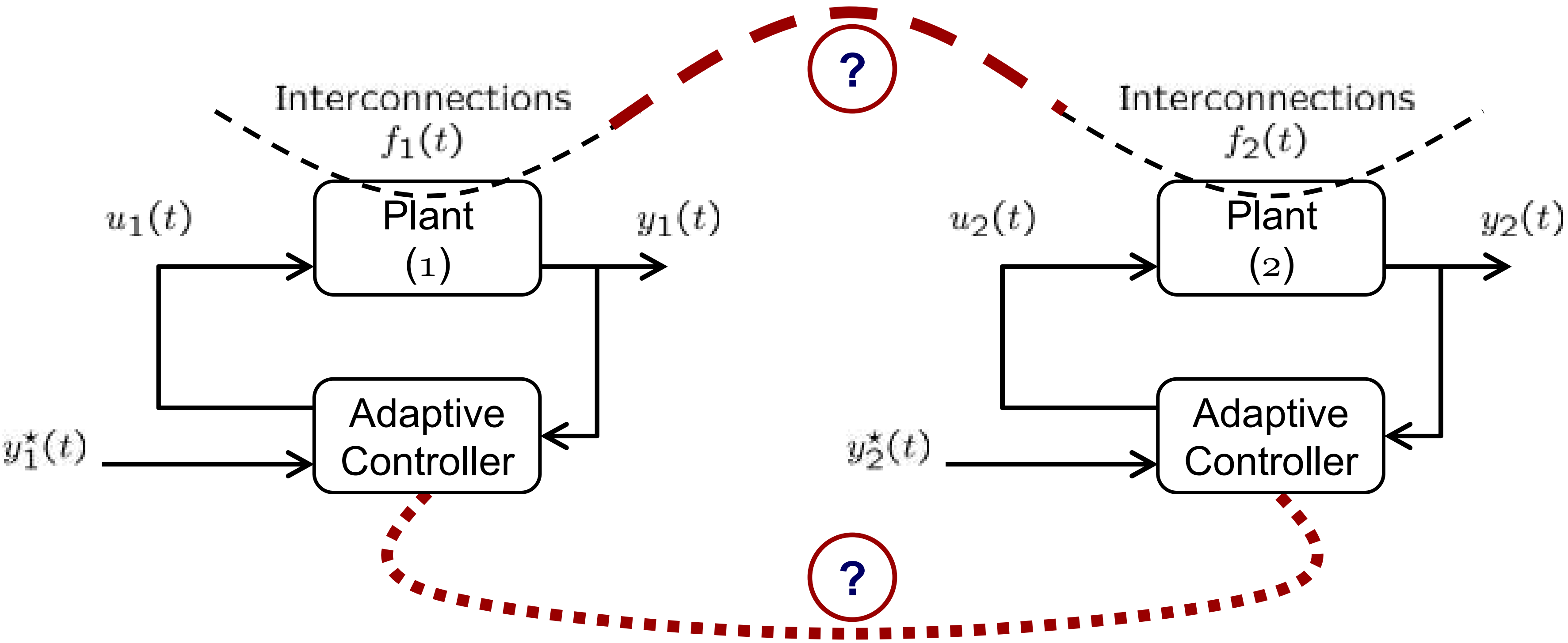
EMERSON.
Process Management


Feed pump
Boiler
Primary Superheater
Secondary Superheater
Turbine
h_{sw}
$\dot{m}_{sw}$
$\dot{m}_{fw}$
h_{fw}
M_b
U_b
$\dot{m}_b$
h_b
M_{psh}
U_{psh}
$\dot{m}_{psh}$
h_{psh}
M_{ssh}
U_{ssh}
$\dot{m}_{ssh}$
h_{ssh}
$\dot{m}_{vv}$
h_{vv}
MW
h_{cd}
Q_1
Q_2
Q_3
$\dot{m}_{coal}$
h_{coal}
$\dot{m}_{air}$
Furnace
$\dot{m}_{gas}$

Area Regulation Test
Decentralized Inventory Control



Decentralized Adaptive Control



1. Does control performance improve with communication?
2. Are (un-modeled) interconnections always bad?

Financial and Business Systems

The state of the company:

$$Z(x) = \left(\begin{array}{c} a \\ l \end{array}\right) \begin{array}{l} \text{assets} \\ \text{liabilities} \end{array}$$

Investment	Operations	Financing
Assets: Current Assets Fixed Assets + Other Assets **= Total Assets**	**Income:** Revenues - Cost of Sales = Gross Margin - Operating Expenses = Operating Result - Taxes **= Net Profit (Loss)**	**Liabilities/Net Worth:** Current Liabilities Long-term Liabilities +Shareholder equity **= Total Liabilities and Net Worth**

Total Assets = Total Liabilities and Net Worth

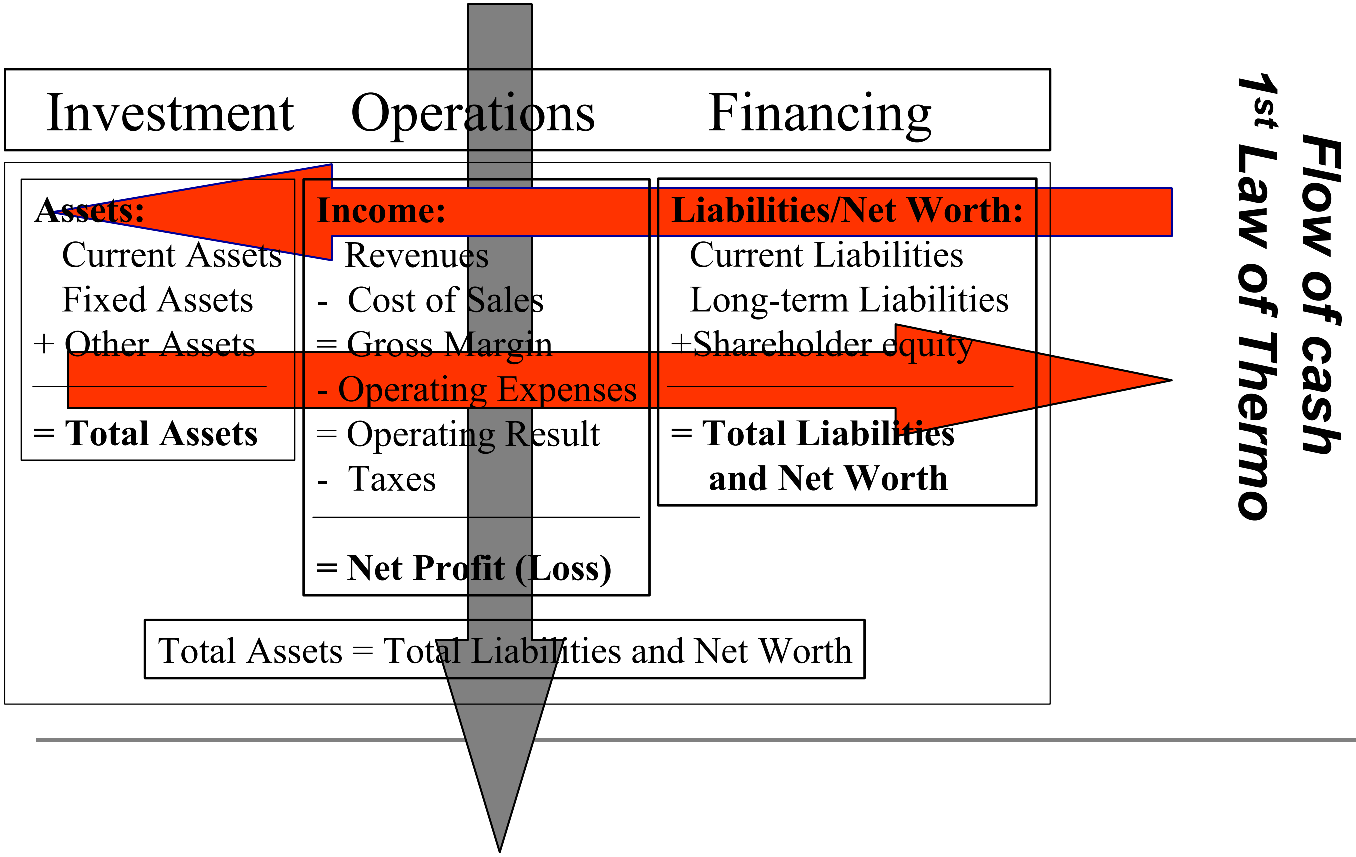
Intrinsic value *S(Z)*

(Warren Buffet)

$$w^{T} = \frac{\partial S}{\partial Z}, \qquad \text{value of inventory (intensive)}$$

$$T = \frac{\partial E}{\partial S}, \quad \text{value of cash}$$

Flow of products and services
(2nd Law of Thermo-All activities incur cost)



Investment Operations Financing

Assets:
Current Assets
Fixed Assets
\+ Other Assets

= Total Assets

Income:
Revenues
\- Cost of Sales
= Gross Margin
\- Operating Expenses
= Operating Result
\- Taxes

= Net Profit (Loss)

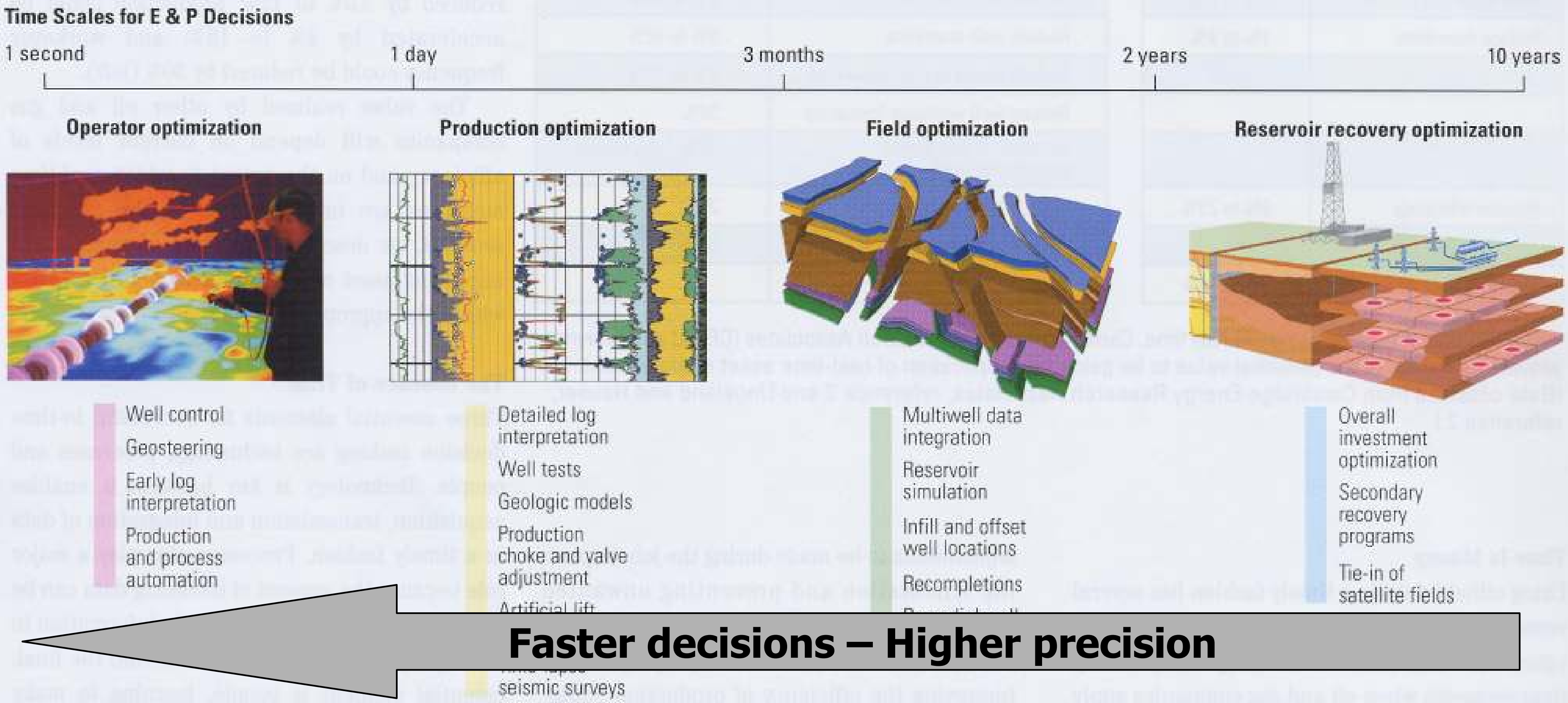
Liabilities/Net Worth:
Current Liabilities
Long-term Liabilities
+Shareholder equity

= Total Liabilities
and Net Worth

Total Assets = Total Liabilities and Net Worth

Flow of cash
1st Law of Thermo

Integrated Operation (IO) – Statoil-Hydro

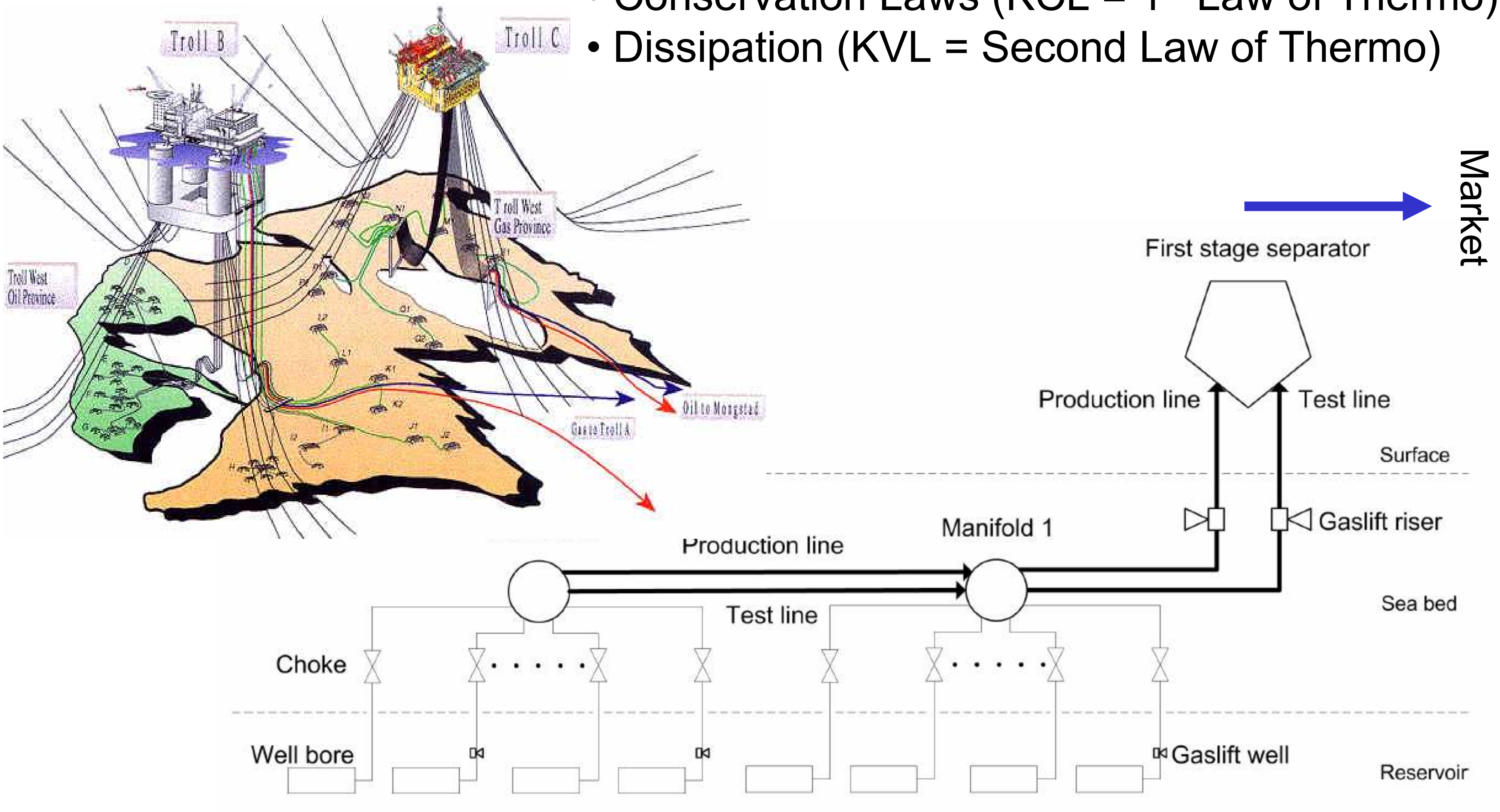


Faster decisions – Higher precision

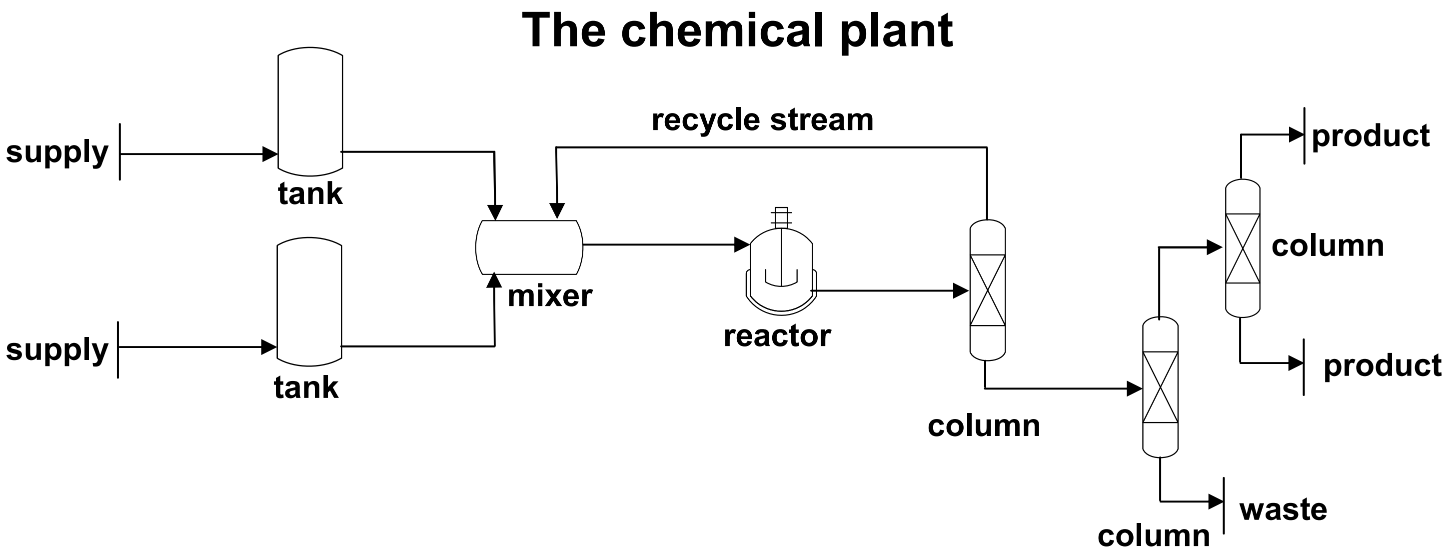
^ Time scales for exploration and production (E&P) decisions. From drilling and logging through completion and production, the decision time frame changes, but consistent among stages is the need to obtain data, make decisions and implement actions.

Oilfield Review 2006

- Conservation Laws (KCL = 1st Law of Thermo)
- Dissipation (KVL = Second Law of Thermo)

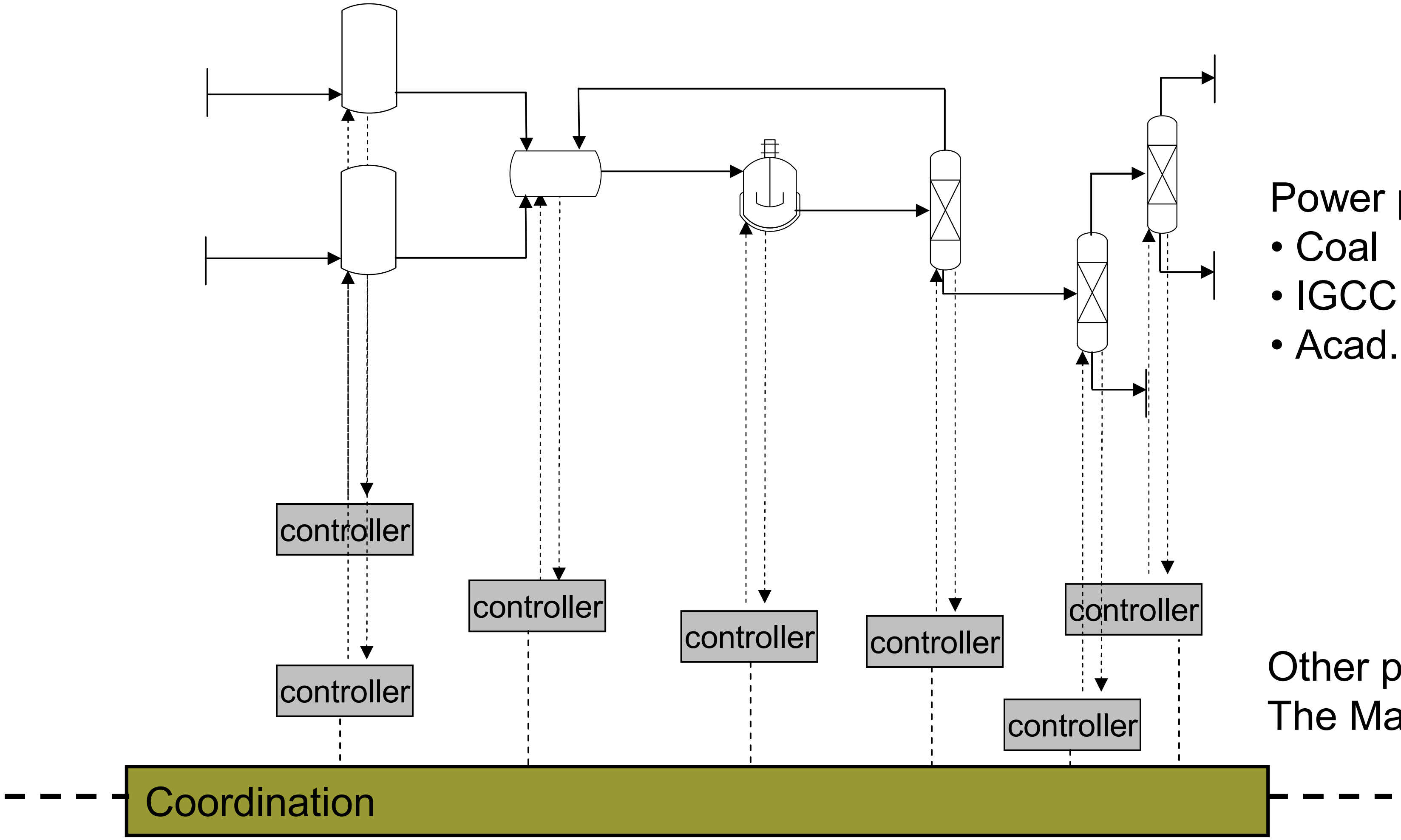


Decentralized Decision Making



Decentralized Decision-making:

Coordination- Move the Smarts Down



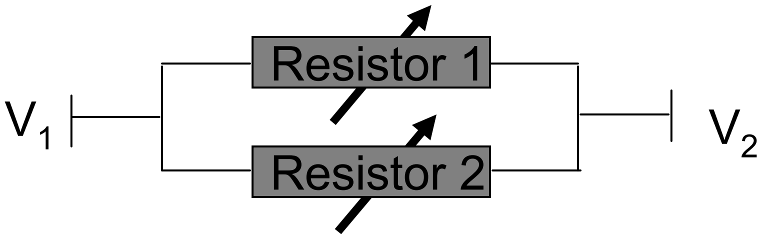
Power plants
- Coal
- IGCC (DOE)
- Acad. Prblms/

Other processes
The Market

Nature is Self-Optimizing

(“All Smarts Local”)

- Maxwell’s “theorem” of minimum heat (1871)
- Prigogine’s “theorem” of minimum entropy production (1947)
- Minimum dissipation and optimality in electrical circuits (Desoer/Director 1960ies-70ies)
- Thermodynamic networks (1970ies)



Network Theory: Optimality Top Down

The optimization problem:

$$\min \quad \sum_{i=1}^{n_f} W_i F_i = \mathbf{W}^T \mathbf{F}$$

Primal **1a) Conservation laws (KCL):**

$$\mathbf{AF} = \mathbf{0}$$

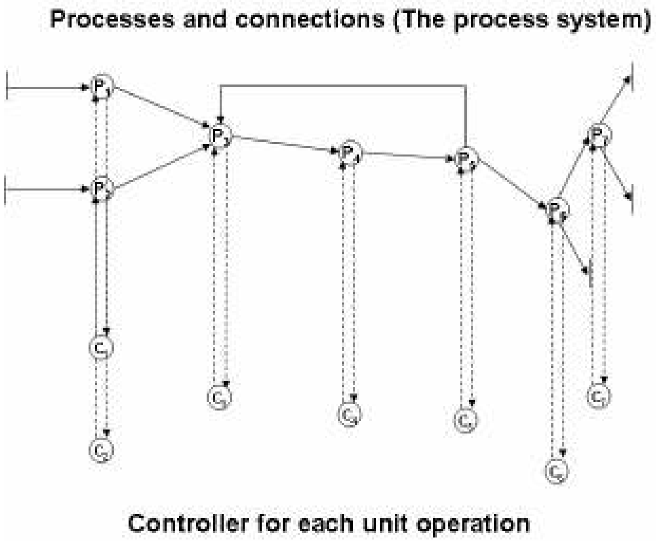
~~**Dual** **1b) Loop equations (KVL):**~~

$$\cancel{\mathbf{W} = \mathbf{A}^T \mathbf{w}}$$

2) Constitutive equations:

$$\mathbf{F} = \Lambda \mathbf{W}$$

3) Boundary conditions



Processes and connections (The process system)

Controller for each unit operation

Coordination

Network Theory: Optimality Top Down

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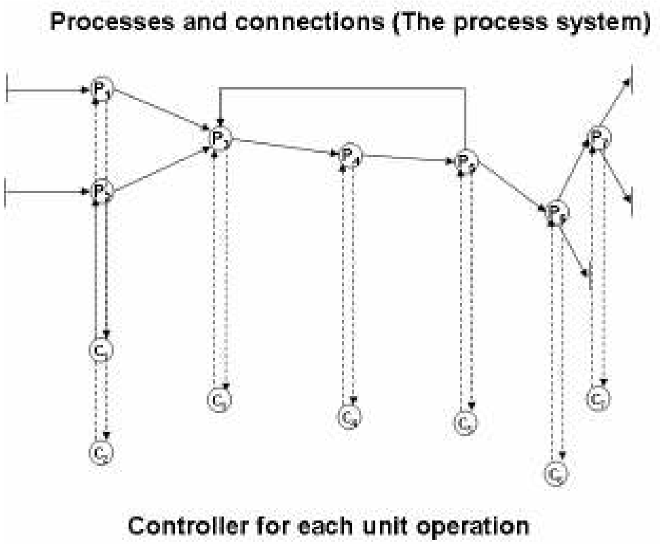

Coordination

Network Theory: Optimality Bottom Up

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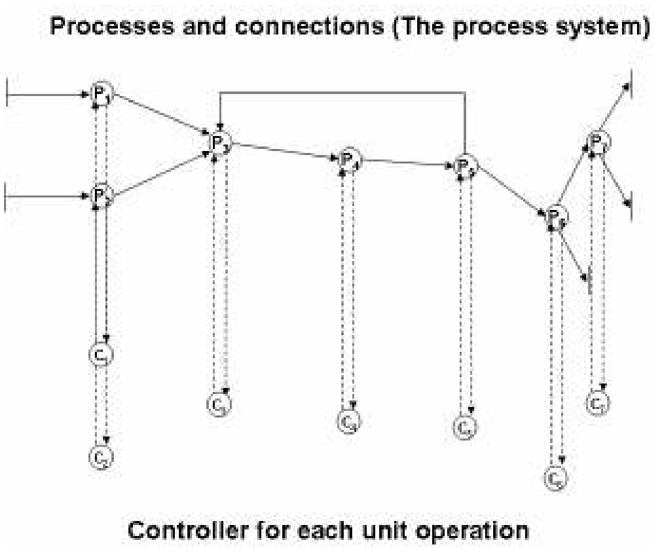

~~Coordination~~

Optimization build into “control” structure
(Toyota, GE 6-sigma, Alcoa,…..)

Conclusions

- Two port description proposed to represent the interface between (process) systems and signals (the information system)
- Conservation laws and passivity theory can be applied for stability analysis of process networks
- Stability and (Global) optimality follows from passivity theory if flow is derived from a “convex potential”