Control and Optimization of Supply Chain Networks

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AIM : Formulate supply chain problem as a network (electrical circuit) and see what inferences we can draw.

GOAL: Self Optimizing Enterprise

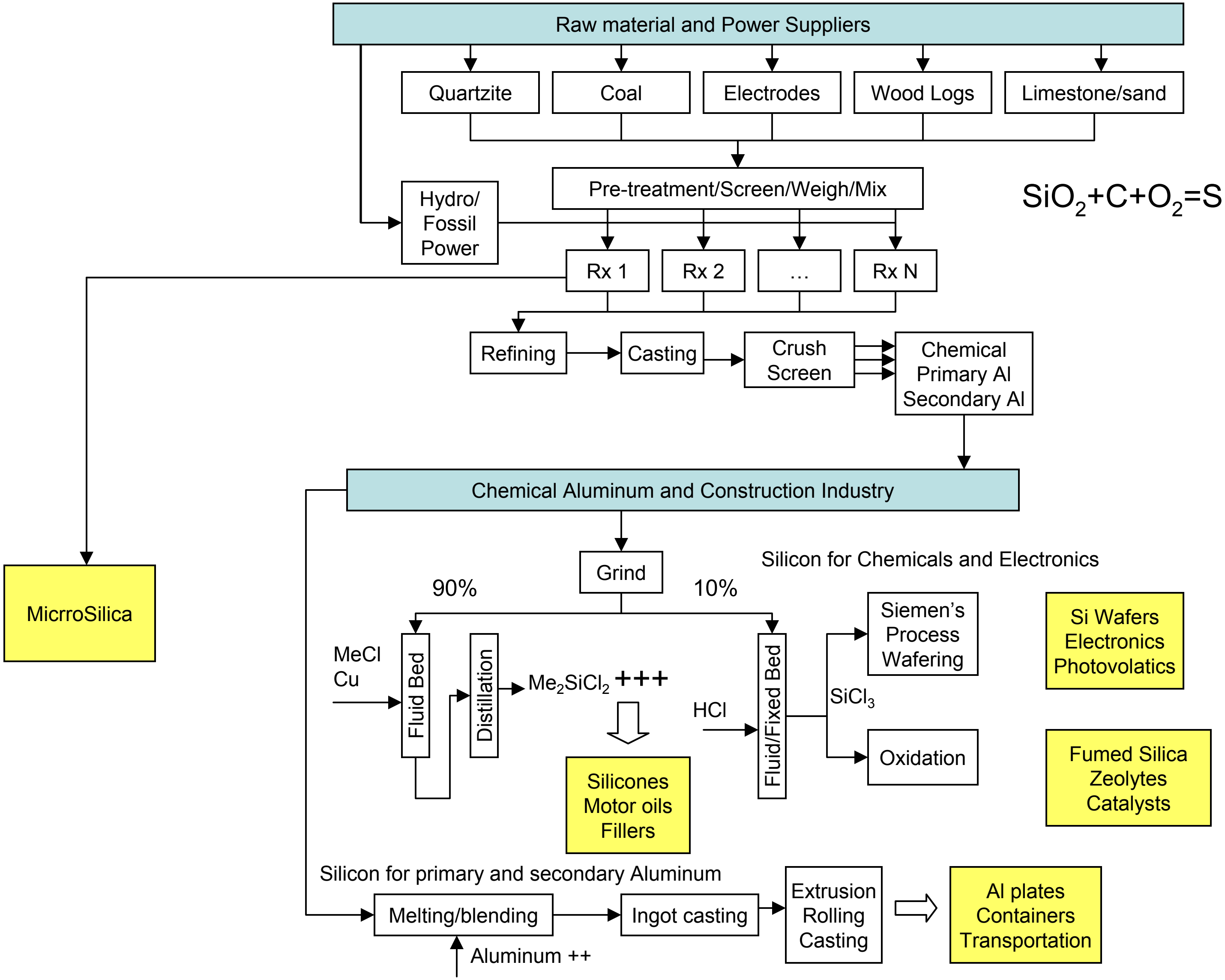
> *"..supply chain is a network of organizations involved through upstream and downstream linkages in different products and processes."*
>
> Christopher, 1998

Outline:

1. Motivating Example: Silicon production
2. The Supply Chain as a Process Network
3. The Self Optimizing Enterprise
4. Decentralized SCM main results
5. Centralized SCM (Perea-Grossman)
6. Industrial Case study # 2: Glass manufacture
7. Conclusions

1. From Si Manufacture to Finished Products

$$SiO_2+C+O_2=Si+SiO_2(a)+CO_2$$



Raw material and Power Suppliers

Quartzite

Coal

Electrodes

Wood Logs

Limestone/sand

Pre-treatment/Screen/Weigh/Mix

Hydro/
Fossil
Power

Rx 1

Rx 2

…

Rx N

Refining

Casting

Crush
Screen

Chemical
Primary Al
Secondary Al

MicrroSilica

Chemical Aluminum and Construction Industry

Grind

90%

10%

Silicon for Chemicals and Electronics

MeCl
Cu

Fluid Bed

Distillation

Me_2SiCl_2 +++

Silicones
Motor oils
Fillers

HCl

Fluid/Fixed Bed

$SiCl_3$

Siemen's
Process
Wafering

Oxidation

Si Wafers
Electronics
Photovolatics

Fumed Silica
Zeolytes
Catalysts

Silicon for primary and secondary Aluminum

Melting/blending

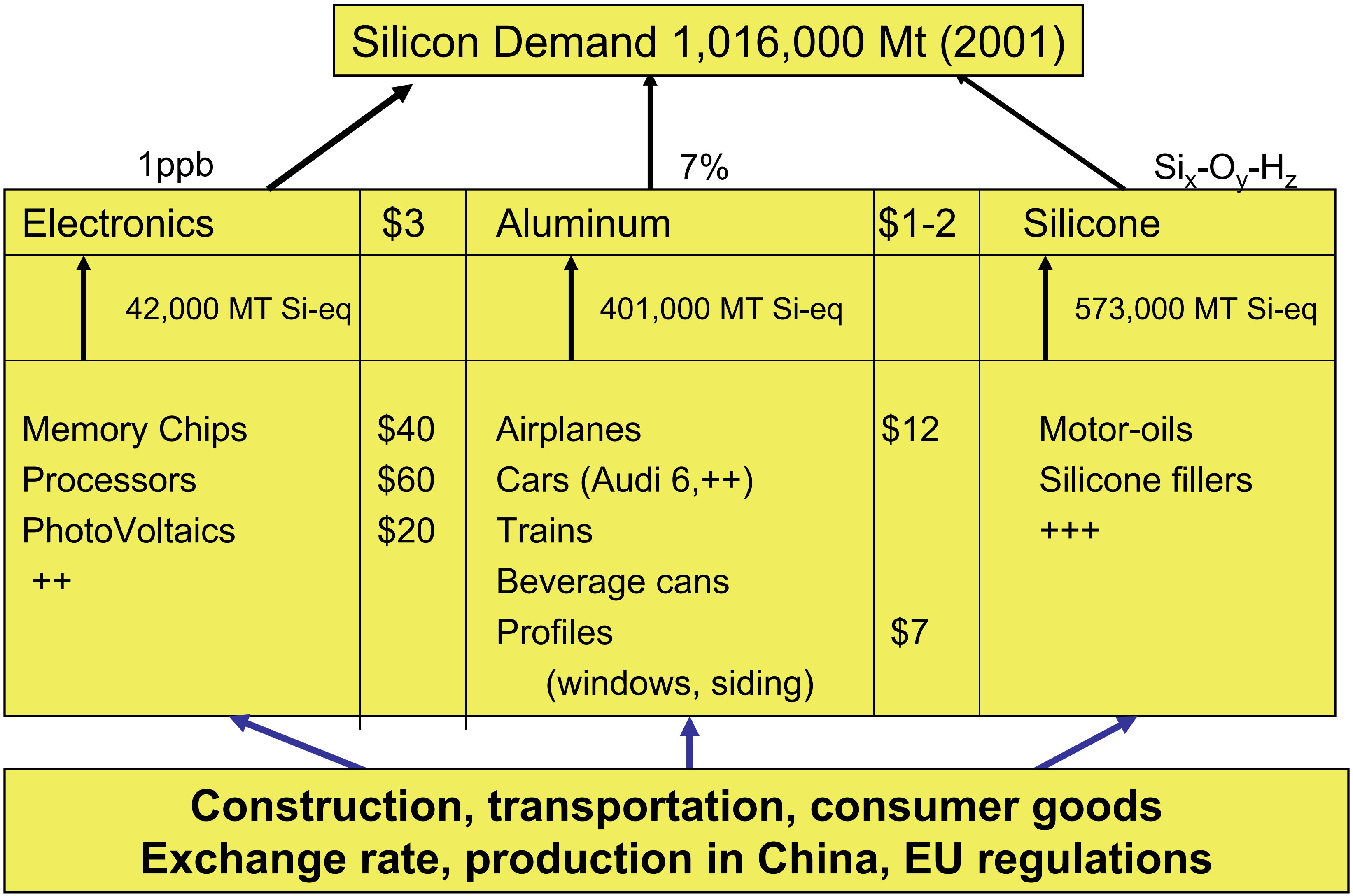
Aluminum ++

Ingot casting

Extrusion
Rolling
Casting

Al plates
Containers
Transportation

Silicon by Market Sectors



Silicon Demand 1,016,000 Mt (2001)

1ppb

7%

Si_x-O_y-H_z

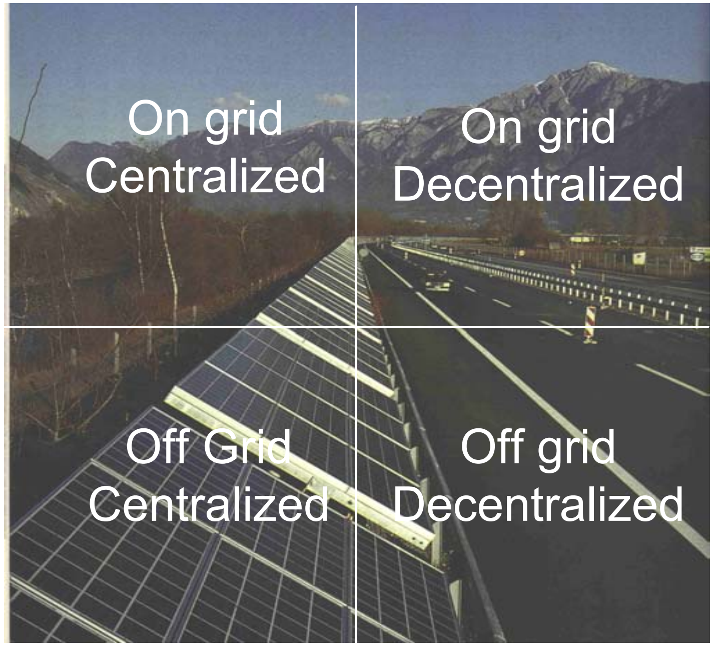
Electronics	$3	Aluminum	$1-2	Silicone
42,000 MT Si-eq		401,000 MT Si-eq		573,000 MT Si-eq
Memory Chips	$40	Airplanes	$12	Motor-oils
Processors	$60	Cars (Audi 6,++)		Silicone fillers
PhotoVoltaics	$20	Trains		+++
++		Beverage cans		
		Profiles	$7	
		(windows, siding)		

Construction, transportation, consumer goods
Exchange rate, production in China, EU regulations

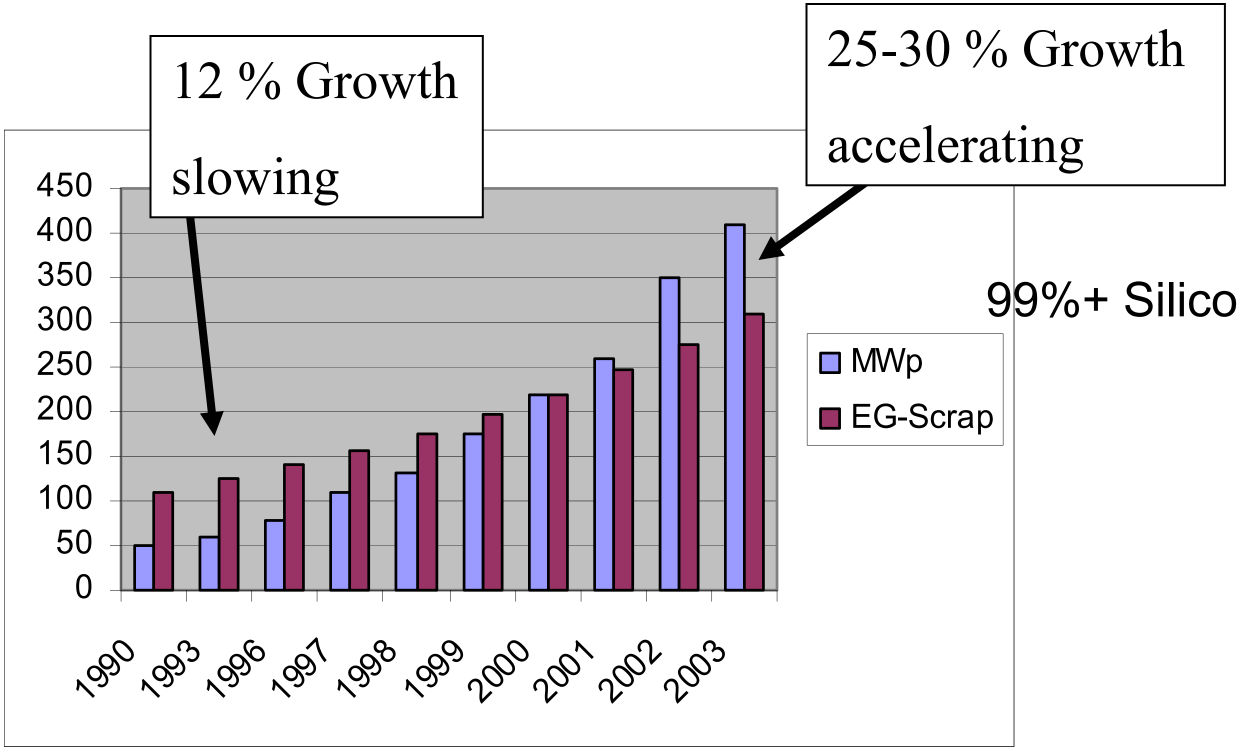
Financial Outlook: Silicon for PhotoVoltaics

- Clean, Renewable Energy from the SUN
- Silicon: 14-16% Efficiency
- 0.1 kWp per m^2
- 100 kWp per ton Silicon
- Government Incentives in
  EU, Japan and US

Current world wide SG-Si market ~$30M



Market Outlook Silicon for PhotoVoltaics



12 % Growth slowing

25-30 % Growth accelerating

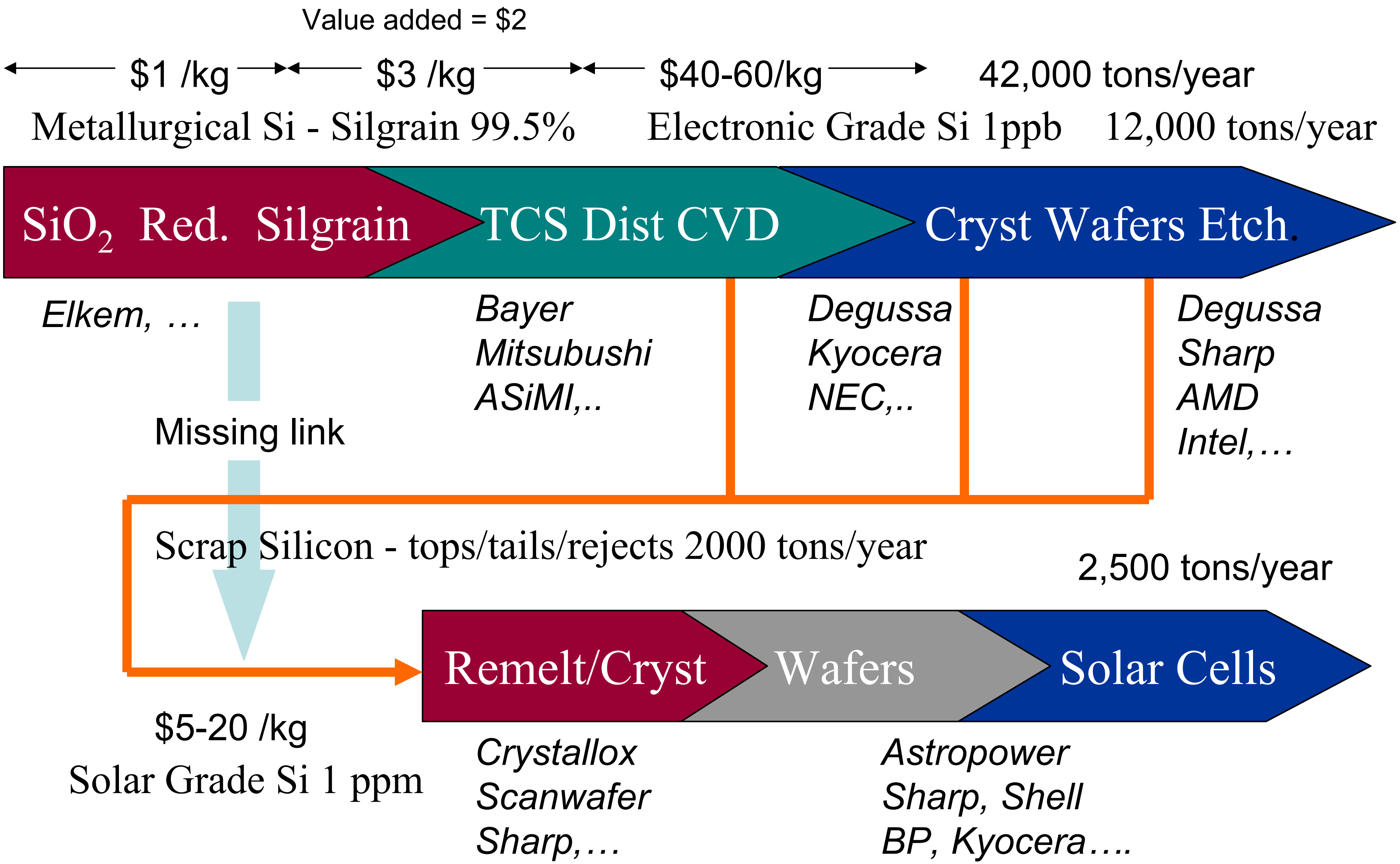
99%+ Silicon based

R&D Programs:

ELKEM
SGS
Bayer/Degussa
Dow Corning
Astropower
SHARP
ScanWanfer++

KPMG 1999: Economies of Scale and Better Production facilities can reduce Solar electricity generating cost by a factor of 3

The Supply Chain for EG-Si and SG-Si



Value added = $2

$1 /kg

$3 /kg

$40-60/kg

42,000 tons/year

Metallurgical Si - Silgrain 99.5%

Electronic Grade Si 1ppb

12,000 tons/year

SiO_2 Red. Silgrain

TCS Dist CVD

Cryst Wafers Etch.

Elkem, …

Bayer
Mitsubishi
ASiMI,..

Degussa
Kyocera
NEC,..

Degussa
Sharp
AMD
Intel,…

Missing link

Scrap Silicon - tops/tails/rejects 2000 tons/year

2,500 tons/year

Remelt/Cryst

Wafers

Solar Cells

$5-20 /kg

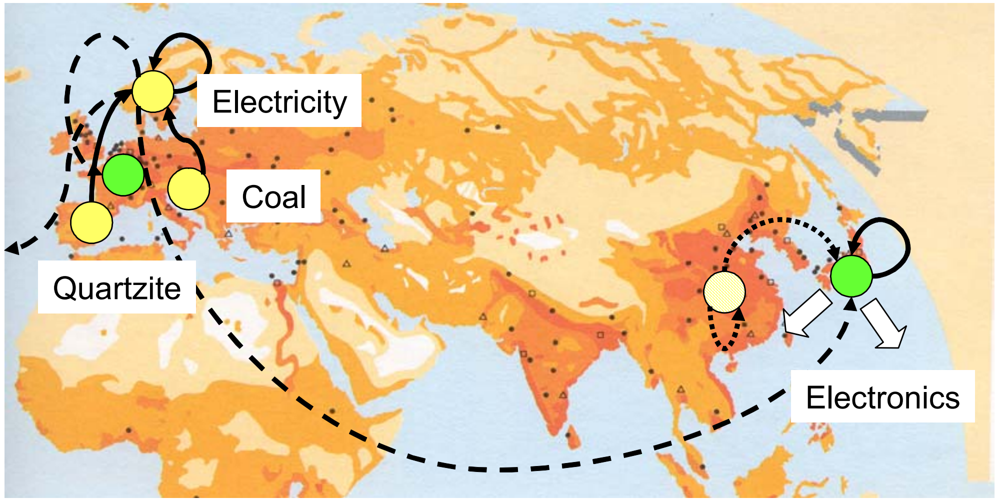
Solar Grade Si 1 ppm

Crystallox
Scanwafer
Sharp,…

Astropower
Sharp, Shell
BP, Kyocera….

2. Process Networks: A Brief Review.

Program: Establish an iso-morphism between process systems and network theory.



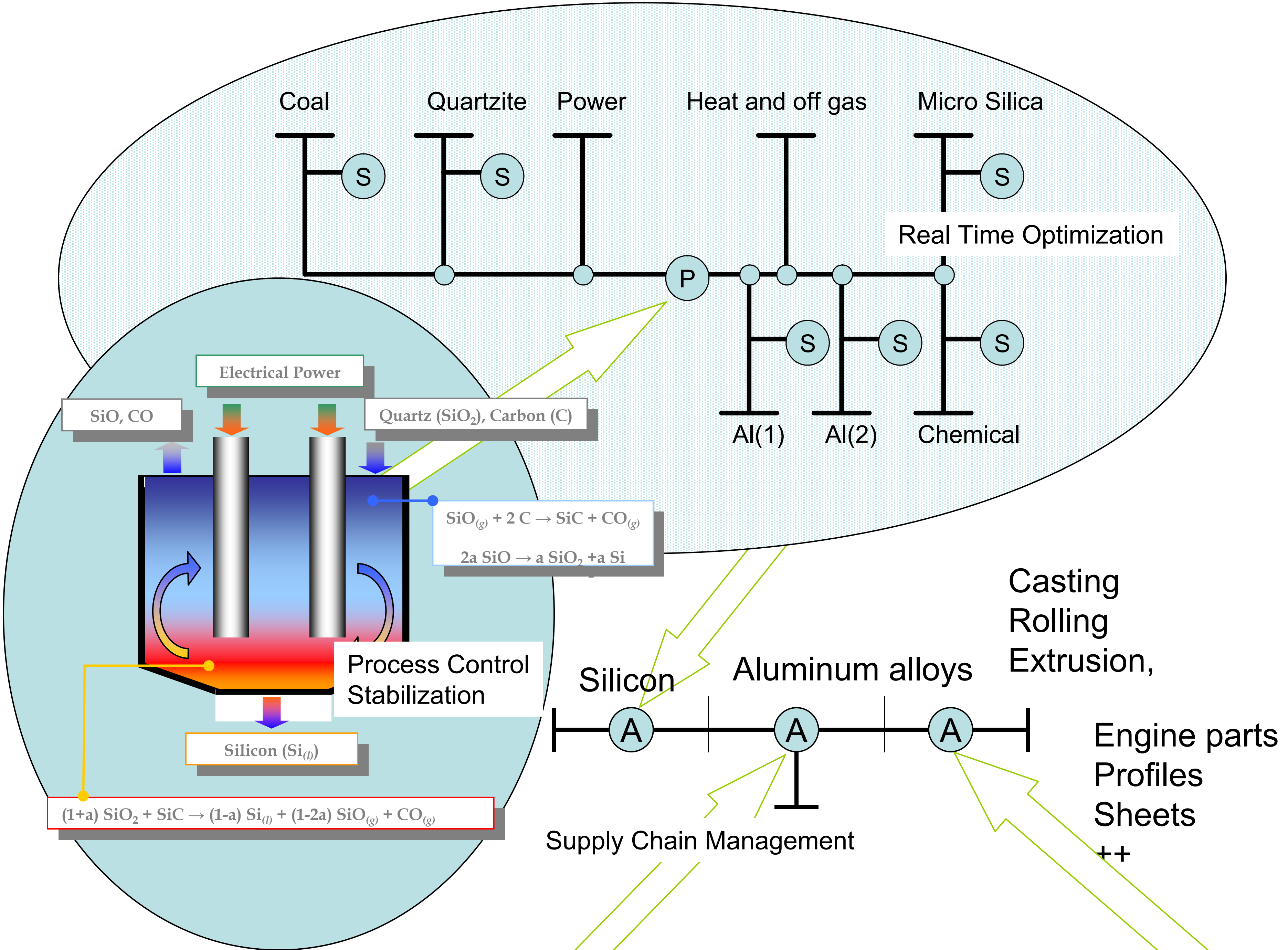
1. topology
2. transportation
3. shipping/receiving
4. manufacture
5. storage
6. forecasting
7. performance evaluation

Background: Circuit Analysis

Meixner	(Irreversible thermo.)	1960
Perelson	(Biology)	1970
Alonso Coffey Ydstie	(control, stability,..)	1997
Hangos, Cameron, Perkins	(modeling)	1999
Gilles	(modeling)	1998
+++		

Aims: *PDE’s replaced with ODE’s*
focus on topology
stability and control
optimization
distribution of computations
ease of modeling
modular software design
visualization
flows and ext. var. are additive
++++

All flow is caused by driving force (potential)



Coal

Quartzite

Power

Heat and off gas

Micro Silica

Real Time Optimization

Al(1)

Al(2)

Chemical

Electrical Power

SiO, CO

Quartz (SiO_2), Carbon (C)

$SiO_{(g)} + 2\,C \rightarrow SiC + CO_{(g)}$

$2a\,SiO \rightarrow a\,SiO_2 + a\,Si$

Process Control Stabilization

Silicon ($Si_{(l)}$)

$(1+a)\,SiO_2 + SiC \rightarrow (1-a)\,Si_{(l)} + (1-2a)\,SiO_{(g)} + CO_{(g)}$

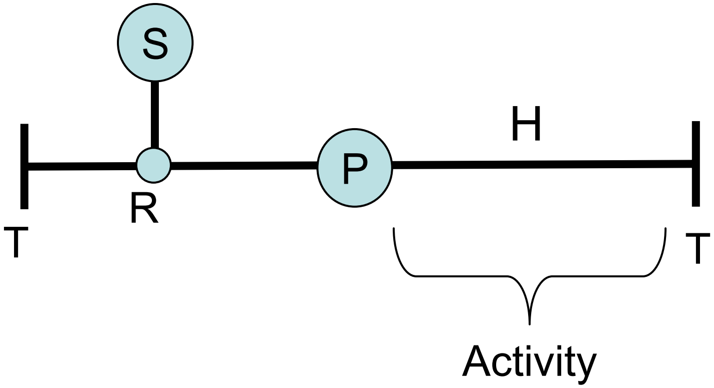
Silicon

Aluminum alloys

Casting
Rolling
Extrusion,

Engine parts
Profiles
Sheets
++

Supply Chain Management



P – production/manufacture
S – storage
T – terminals
R – routing
H – transportation

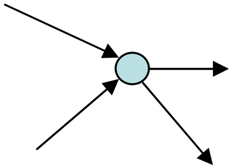
$$G=(P,S,T,R,H)$$

rate [units/time] , value generation [value/unit]

Assets $A = \{v,c,z\}$
Activities (flow of assets) $F = \{f,z\}$

v – extensive variable	(amount /charge)
c – intensive variable	(value/voltage)
f – rate of flow of an extensive variable	(flow rate/current)
z – characterization	(SKU, composition, etc.)

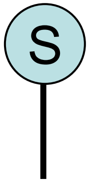
Routing point



$$\sum f_i=0$$

Material balance
Kirchoff current law

Storage



$$\frac{dv}{dt} = f$$

Storage
Capacitor

Inductor
Diode
+

Activity and terminals

$$Rf=w$$

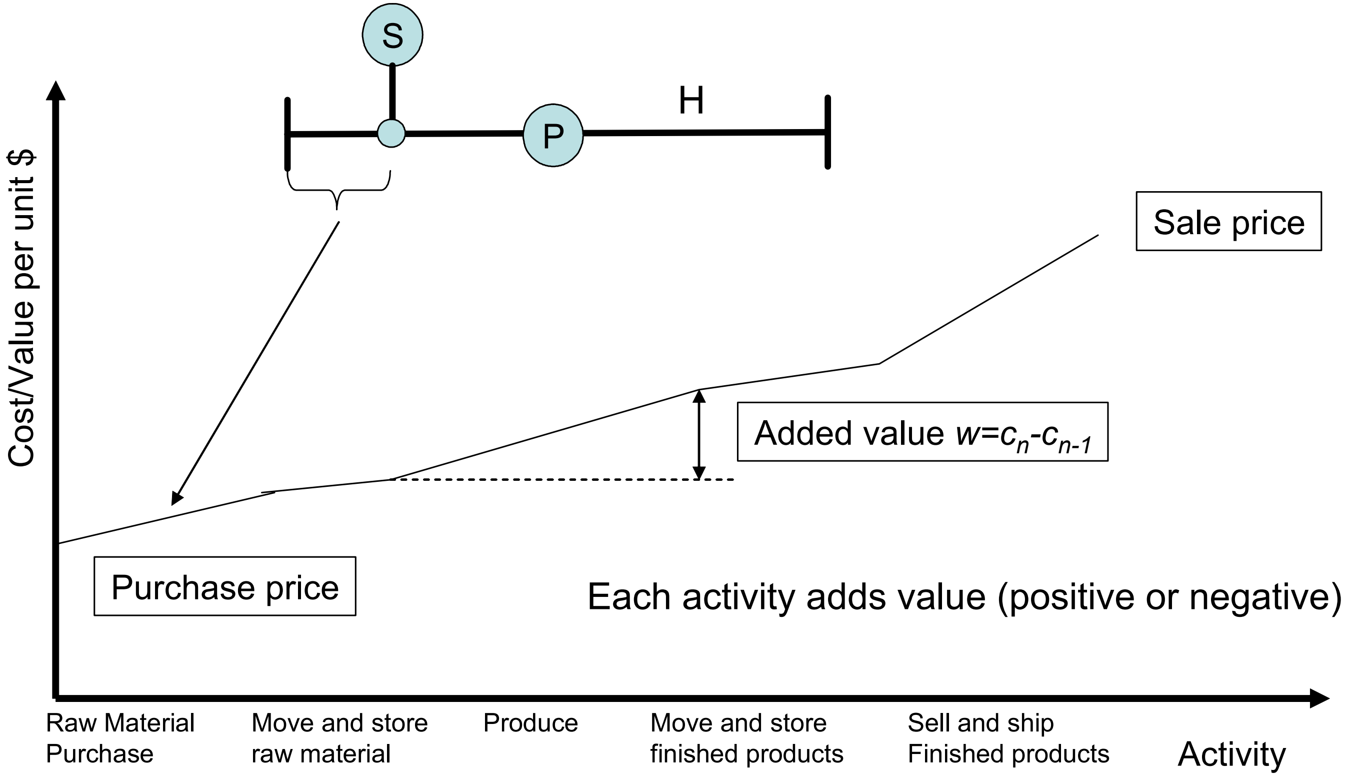
Fourier
Fick
Newton
Ohm’s Laws

Constitutive equations

Conservation Laws

Potential Flow

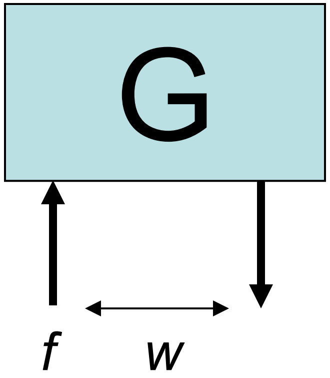
Activity Based Analysis – Value added as driving force



Each activity adds value (positive or negative)

Direction of flow: From low to higher value is *positive*
from high to low value is *negative*

Financial Implications:



Net (internal) activity Cost: $\pi = fw$

Cost (internal) of operations: $\Pi = \sum \pi_i$

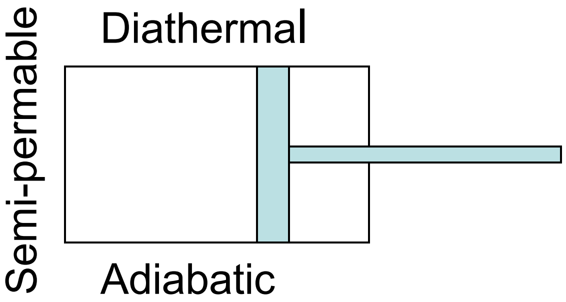
Net rate of profit [$/sec]: $P = T - \Pi$

Circular activity does not add value*:* $0 = \sum w_i$ (Kirchoff's voltage law)

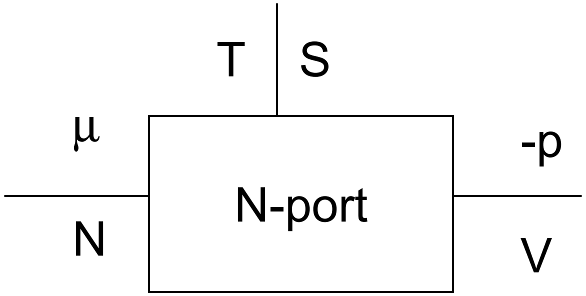
Cost/dissipation: $\pi \geq 0$ (2nd law of thermo)

-P plays the role of "energy"

Thermodynamics



Networks

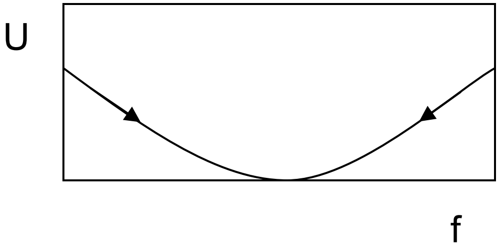


Conservation laws
Convex Energy function *U(N,S.V)*

Kirchoff's Current Law
Kirchoff's Voltage Law

Intensive variables via Legendre transform

$$\begin{aligned} dN_1 &= dN_2 \\ \mu_1 &= \mu_2 \end{aligned}$$

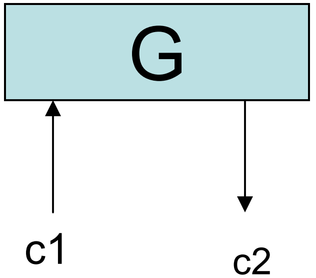


$$\begin{aligned} f &= (V, S, N)^T \\ w &= (-p, T, \mu)^T \end{aligned}$$

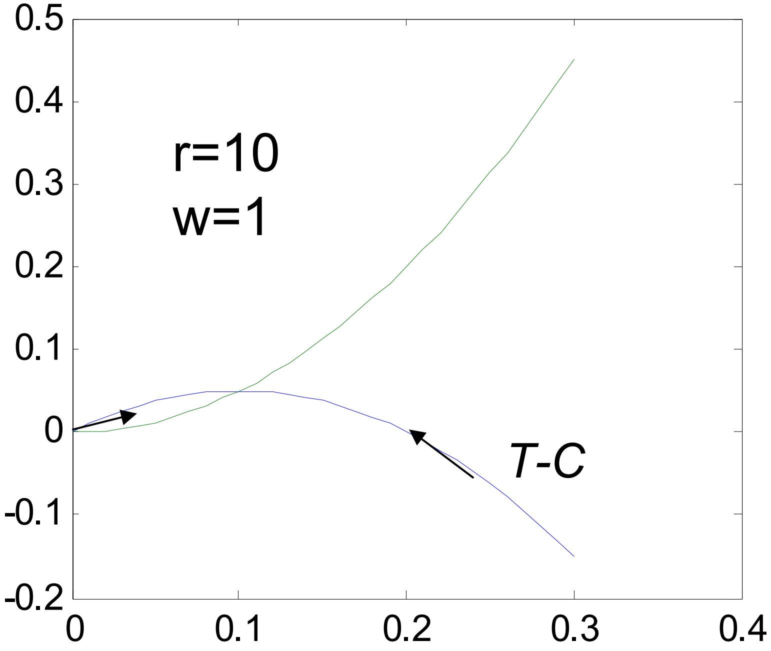
$$dU = (\mu_1 - \mu_2)dN = 0$$

Network builds itself into an energy minimizer!!!

One port example



$$w = c_2 - c_1$$

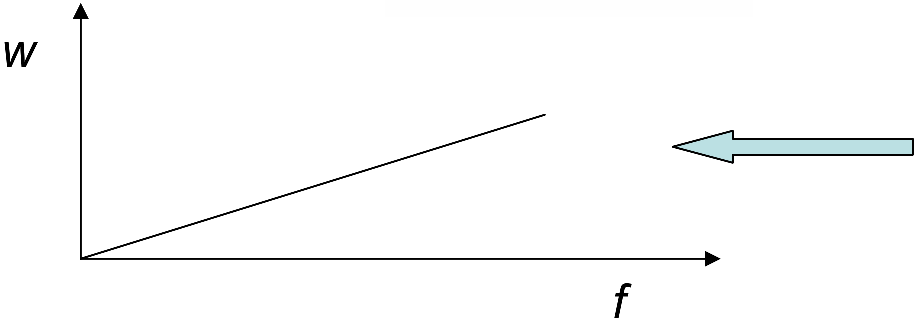


Supplied energy: $T = fw$

Dissipation: $C = \frac{1}{2} r f^2$

$$\max_f (T - C)$$

$$rf = w$$



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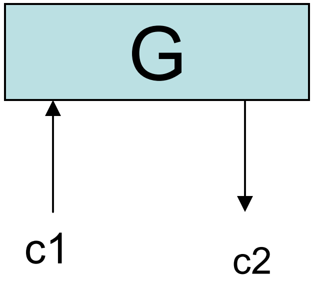
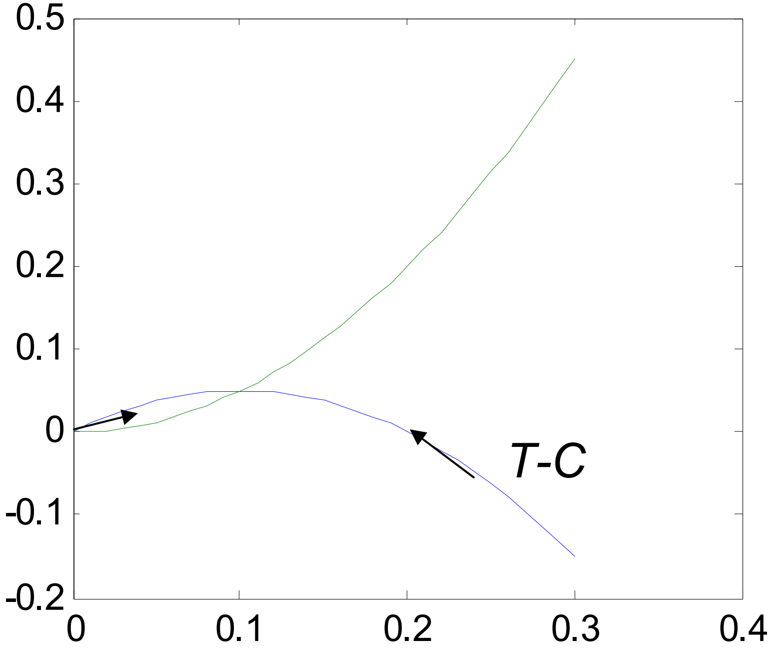


$$w = c_2 - c_1$$



Supplied energy: $$T = \sum_{\text{Terminals}} f w$$

Dissipation: $$C = \sum_{\text{Activities}} \frac{1}{2} r f^2$$

$$\max_f (T - C)$$

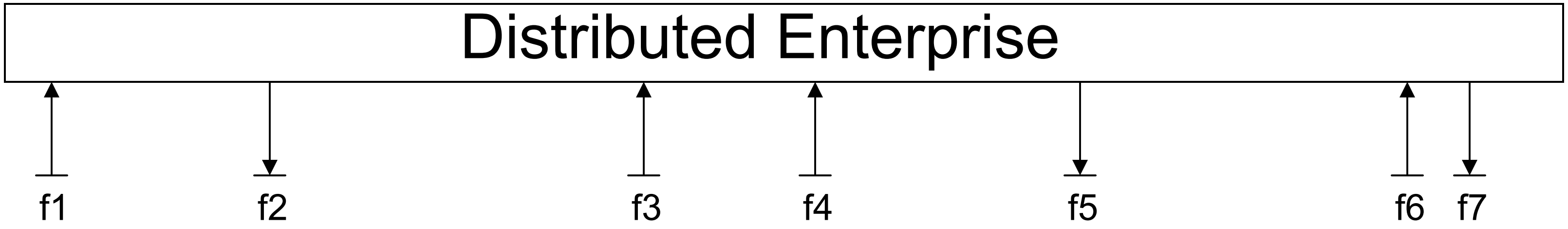
$$\Downarrow$$

$$r_i f = w_i$$

Generalizes to RLC and we get stability

3. The Self-Optimizing Enterprise

- One-ports (terminals, storage, production, activities, routers, +++)
- Conservation of assets (KCL)
- Circular activity does not add value (KVL)

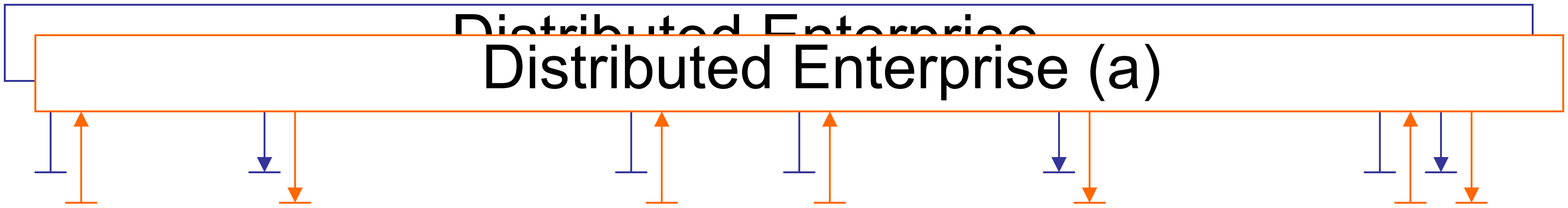


1. The enterprise consists of a (large) number of nodes.
2. Connected with the “world” at terminal points (boundary conditions).
3. Flows are the result of potential at the terminal.

Tellegen’s Theorem – a Topological Result

“Building the Self-Optimizing Enterprise”

- One-ports (terminals, storage, production, activities, routers, +++)
- Conservation of assets (KCL)
- Circular activity does not add value (KVL)



Distributed Enterprise

Distributed Enterprise (a)

Enterprises (a) and (b) have same topology.
Same enterprise in different states

$$\sum_{\text{Terminals}} f_i^a w_i^b = \sum_{\text{Activities}} f_j^a w_j^b$$

Flows and costs are orthogonal

Tellegen’s Theorem – a Topological Result

“Building the Self-Optimizing Enterprise”

- One-ports (terminals, storage, production, activities, routers, +++)
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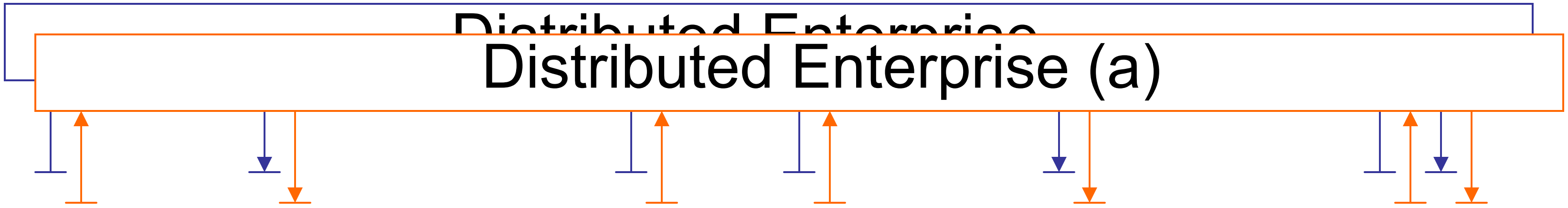


$\bar{f} = \Gamma f$ Network operator – filter, forecast, Fourier transform, expectation,..

$$\sum_{\text{Terminals}} \bar{f}_i^a \bar{w}_i^b = \sum_{\text{Activities}} \bar{f}_j^a \bar{w}_j^b$$

Filtered lows and costs are orthogonal

4. Decentralized SCM: Optimality Results

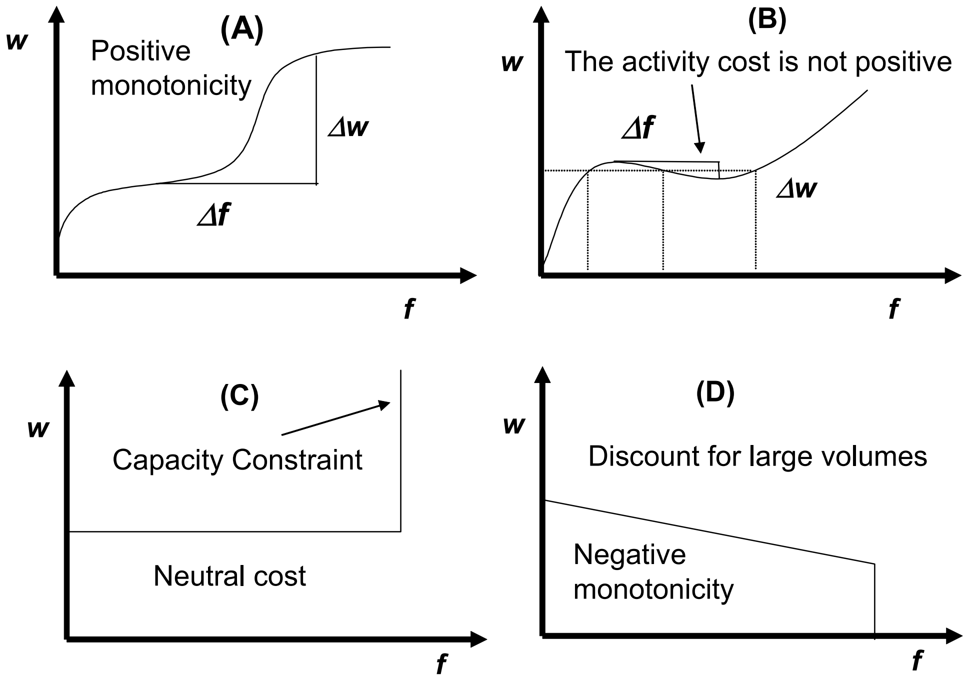
Assumptions: Assets are conserved
Circular activity does not add value

1. Existence and uniqueness of solutions if the routing policies are positive (negative).
2. Added value (cost) is stationary.
3. Added value (cost) is maximized (minimized) if the routing policies are negative.

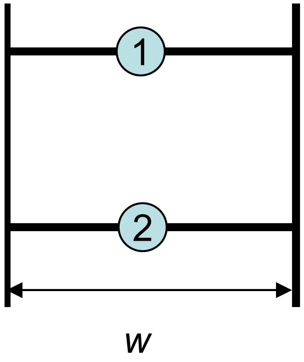
4. Decentralized SCM: Optimality Results

Assumptions: Assets are conserved
Circular activity does not add value

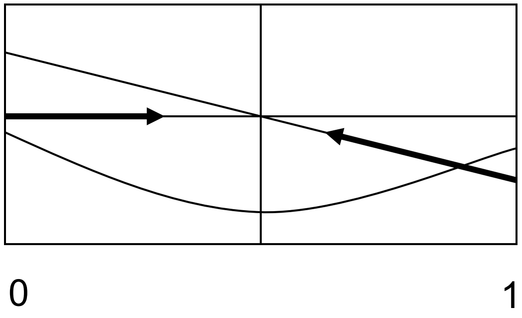
1. Existence and uniqueness of solutions if the routing policies are positive (negative).
2. Cost is stationary
3. Passivity can be used to investigate stability..



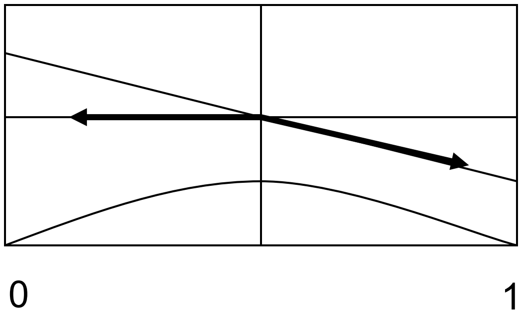
Load Balancing - Parallel Activities



Cooperative -stabilize



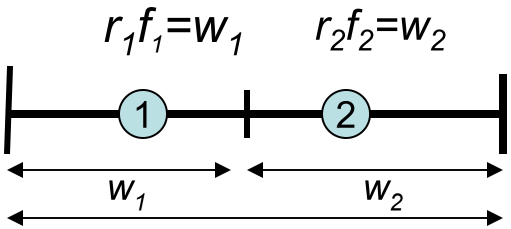
Competitive - unstable



Competitive markets give narrow margins and pressure to reduce cost to stay in business.

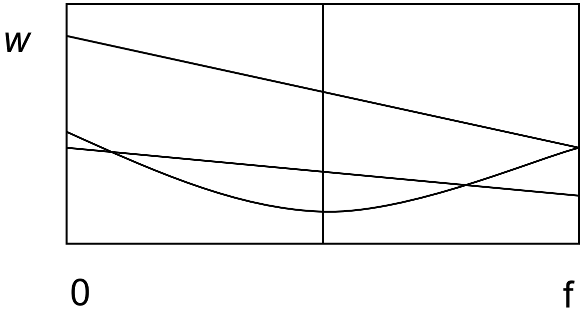
Develop new products and new processes.
Dominate market.
Seek (cost) advantage (geographical, sourcing,…..

Cost Balancing - Serial Activities



$w=w_1+w_2$
$f=f_1=f_2$

"Cooperative"



Advantageous <u>not</u> to share information

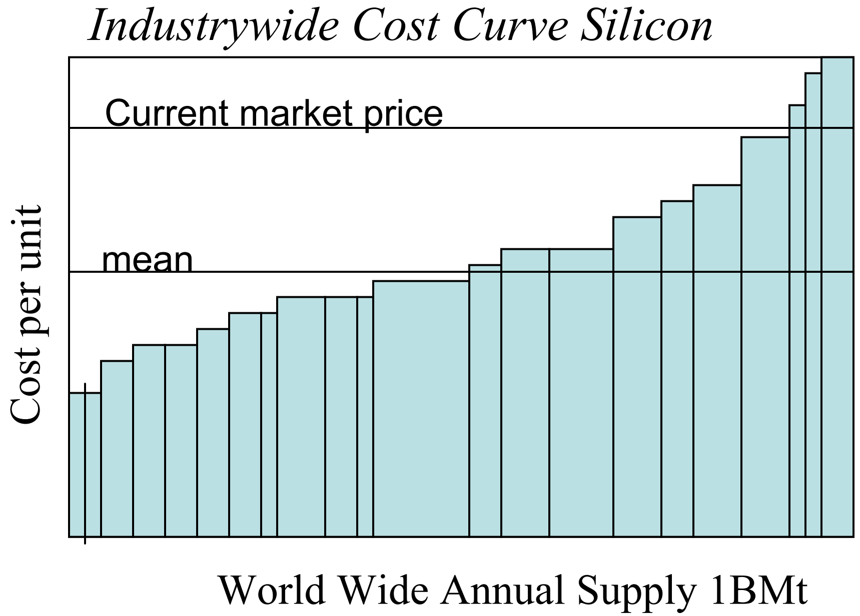
(may be too limited)

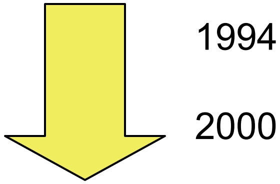
"Fair" transfer price::

$$w_1 = \frac{r_1}{r_1 - r_2} w \quad w_2 = \frac{r_2}{r_1 - r_2} w$$

Motivating Case Study: Silicon Production

- Better logistics and ERP systems
- New energy and raw materials contracts
- Better management of supply chain (smaller inventory)
- Better scheduling and production planning
- Better control and quality management (statistical methods, “6Sigma”)
- Stream line business operation (lean manufacturing)

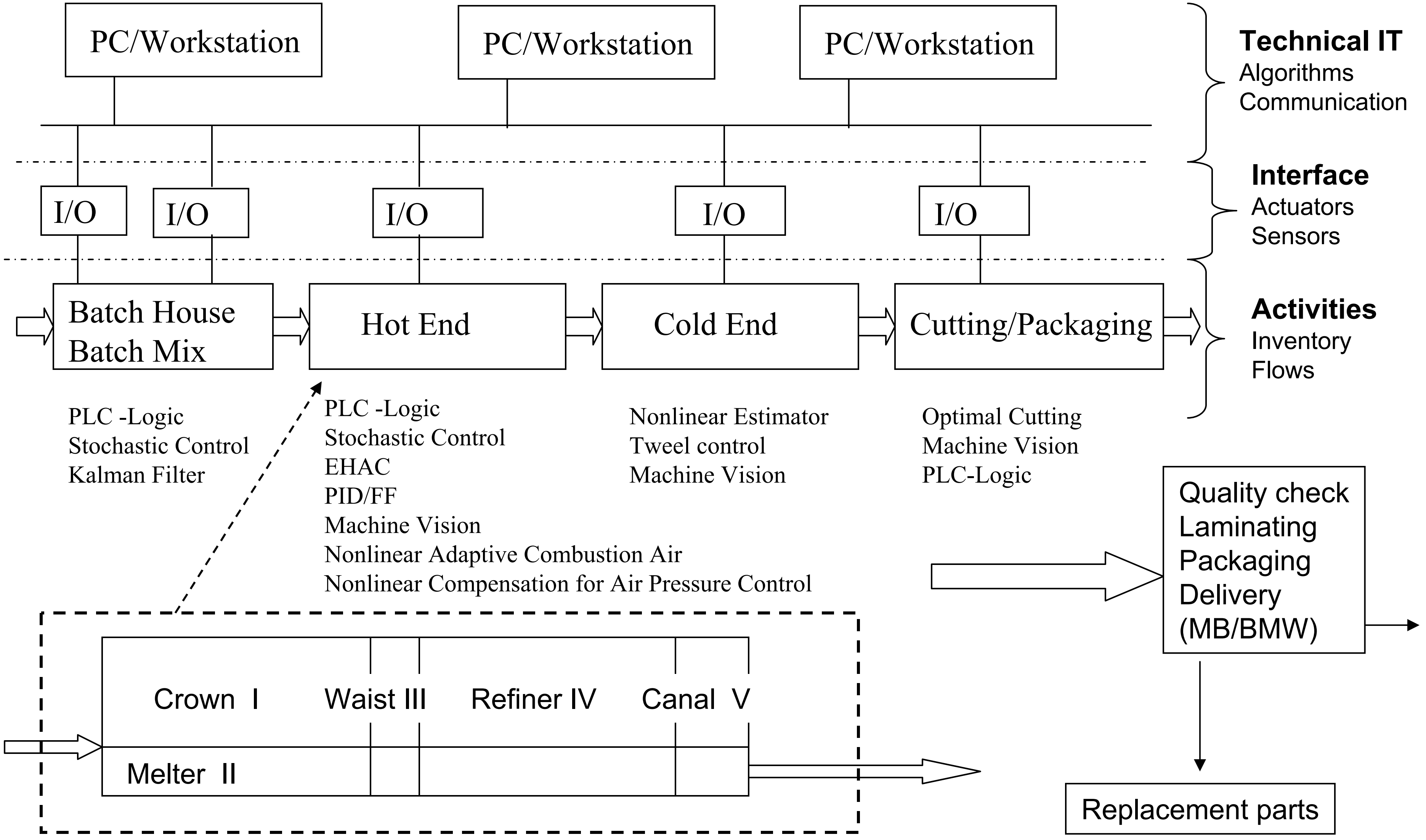




Savings: $80M per year

O. Sorli, CTO Elkem, 2000

Industrial Case Study #2: Glass Production



PC/Workstation

PC/Workstation

PC/Workstation

Technical IT
Algorithms
Communication

I/O

I/O

I/O

I/O

I/O

Interface
Actuators
Sensors

Batch House
Batch Mix

Hot End

Cold End

Cutting/Packaging

Activities
Inventory
Flows

PLC -Logic
Stochastic Control
Kalman Filter

PLC -Logic
Stochastic Control
EHAC
PID/FF
Machine Vision
Nonlinear Adaptive Combustion Air
Nonlinear Compensation for Air Pressure Control

Nonlinear Estimator
Tweel control
Machine Vision

Optimal Cutting
Machine Vision
PLC-Logic

Quality check
Laminating
Packaging
Delivery
(MB/BMW)

Crown I

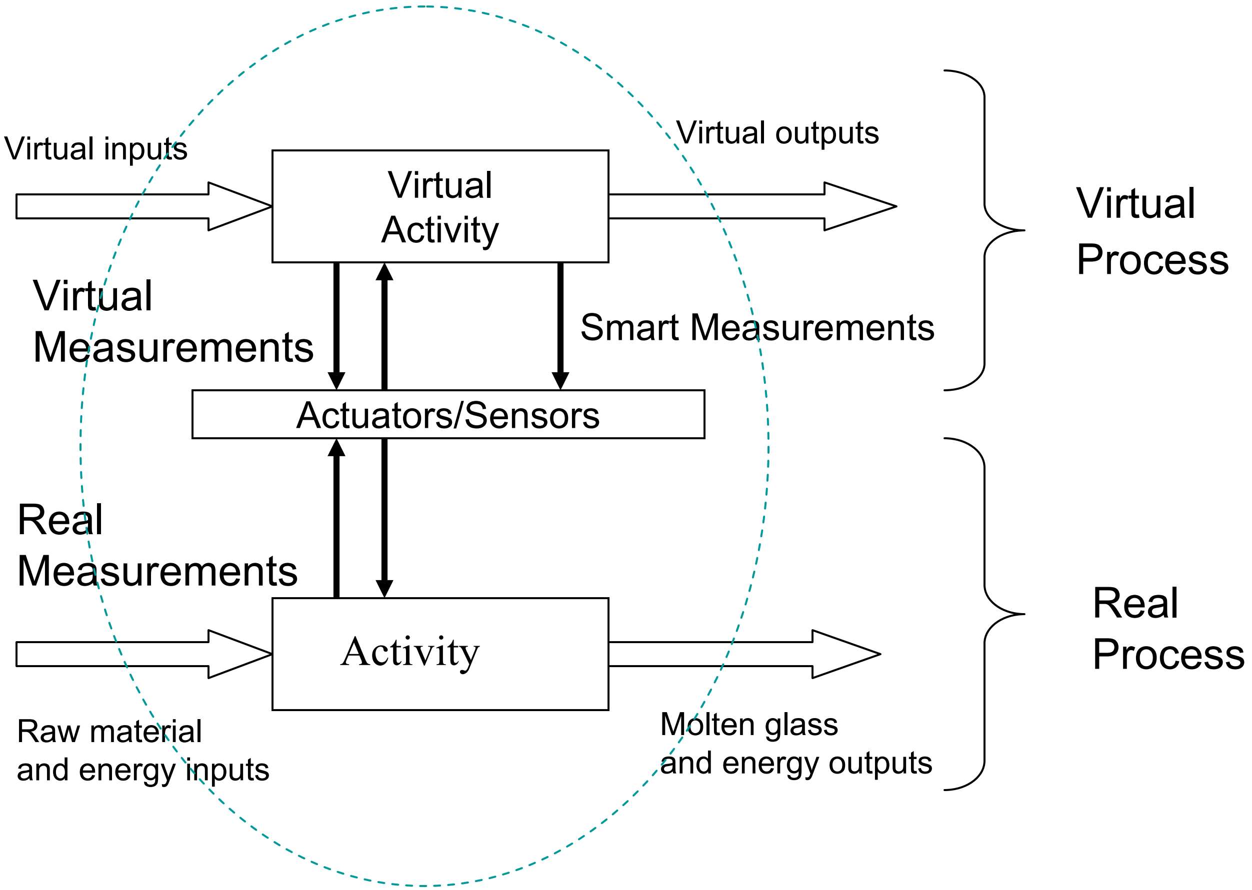
Waist III

Refiner IV

Canal V

Melter II

Replacement parts



Virtual inputs

Virtual Activity

Virtual outputs

Virtual Process

Virtual Measurements

Smart Measurements

Actuators/Sensors

Real Measurements

Activity

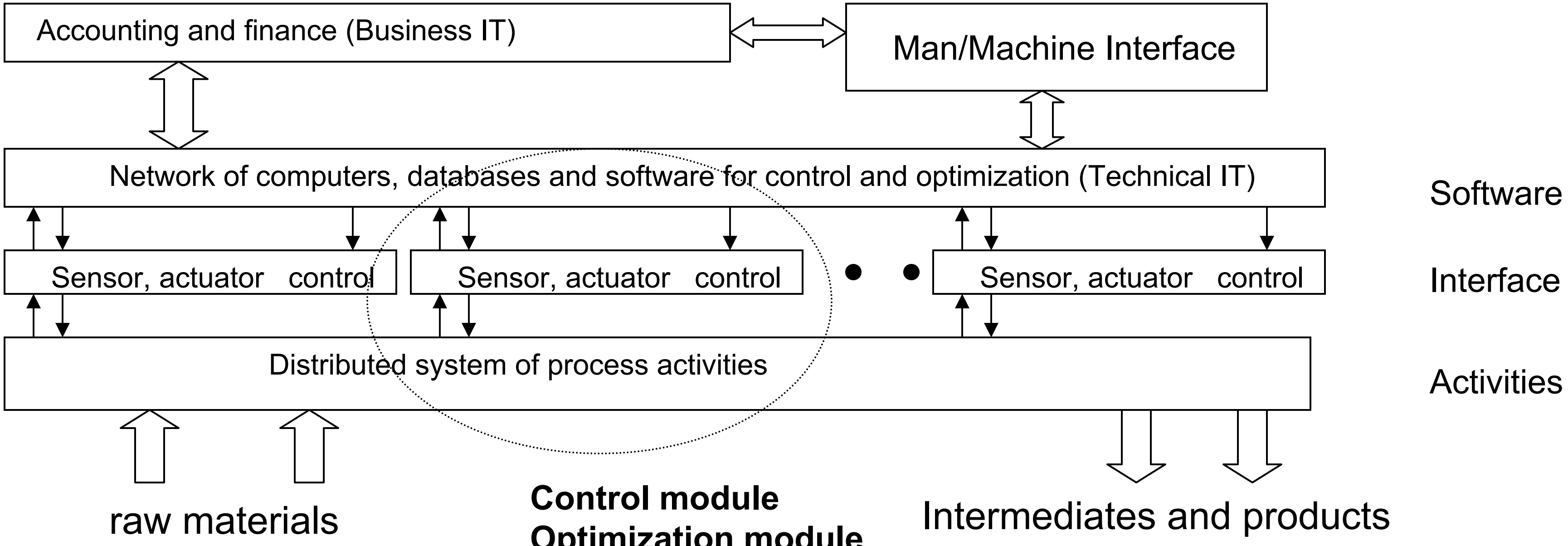
Real Process

Raw material and energy inputs

Molten glass and energy outputs

Sensor Module

Distributed Systems that Integrate Physics and Communication



Accounting and finance (Business IT)

Man/Machine Interface

Network of computers, databases and software for control and optimization (Technical IT)

Software

Sensor, actuator control

Sensor, actuator control

Sensor, actuator control

Interface

Distributed system of process activities

Activities

raw materials

Intermediates and products

Control module
Optimization module
6Sigma module
*****

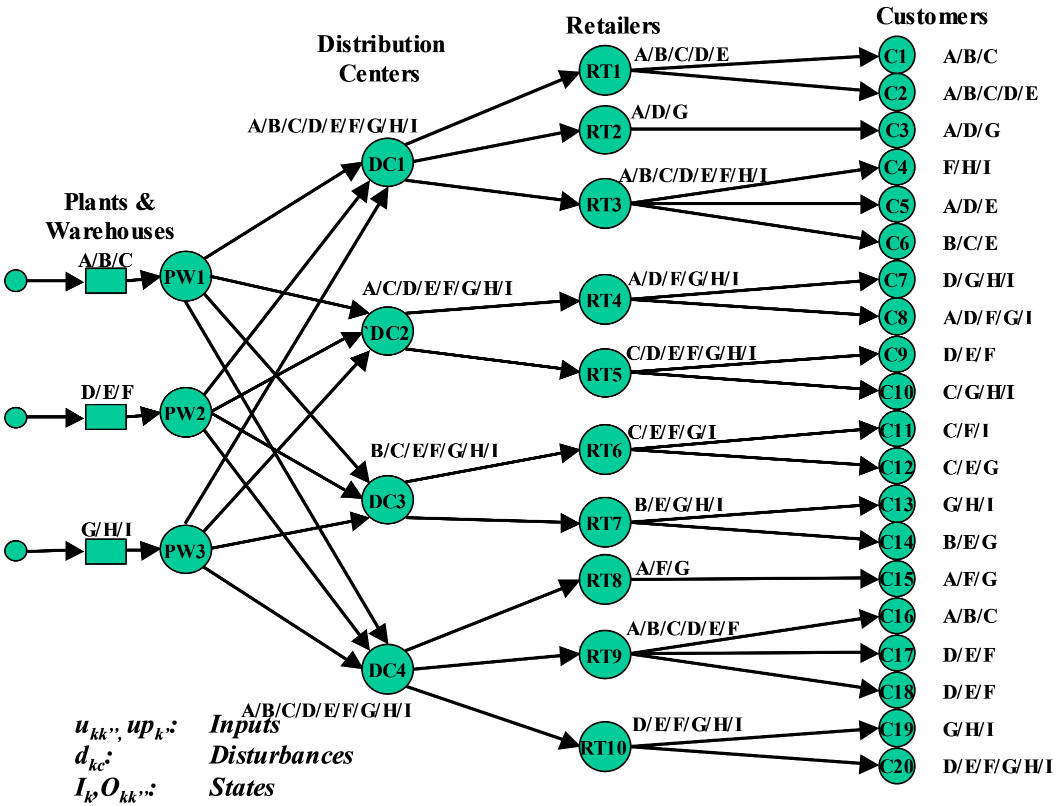
Estimated savings $35M per year

5. Centralized SCM using MPC

(Perea-Grossmann-Ydstie, 2002)

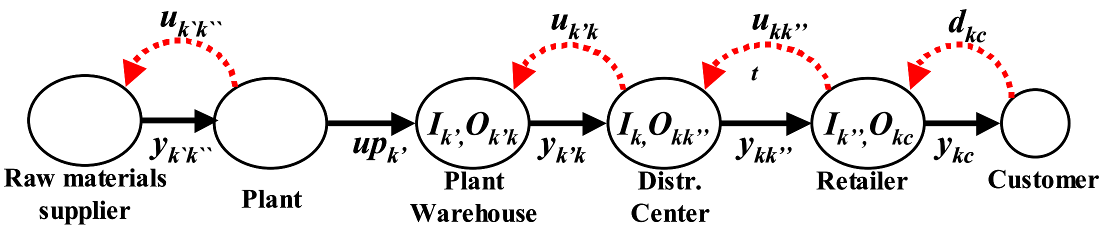
Plant and order delays
Discrete manufacture
Maximize profit

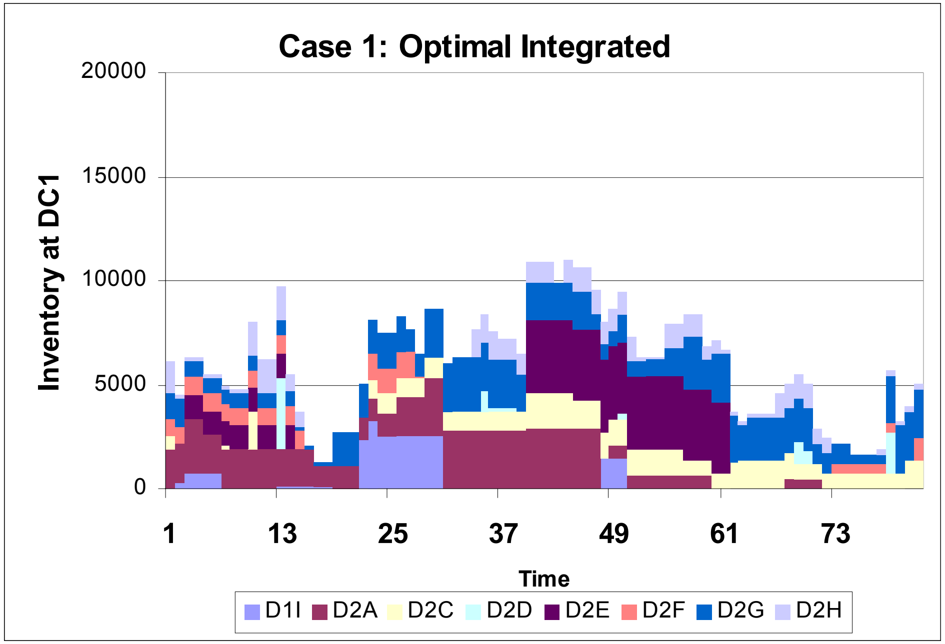
Solve using MPC strategy

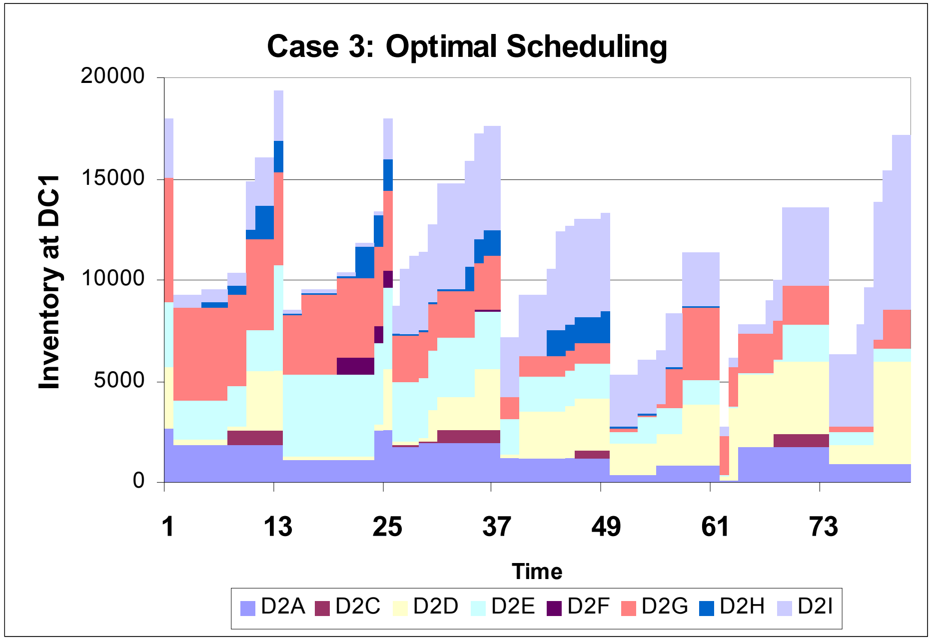


Material Flow (A, B or C)
Information Flow (Orders)

$u_{kk''}, up_{k'}$: *Inputs*
d_{kc}: *Disturbances*
$I_k, O_{kk''}$: *States*
$y_{kk''}, y_{k''c}$: *Outputs*







- Better balance of plant schedule and inventory levels in CSM.
- Centralized planning needed when the delays are long.
- Too short planning horizon T < 6 days gives myopic policy (plant shuts down).
- Policy insensitve to planning horizon for T .> 12 days.

Edgar Perea-Lopez, Grossmann Ydstie 2002.

GAMS / XPRESS-MP to solve MILP. Discrete time elements = 2hr.
Prediction horizon of 12 days (144 elements of 2 hr each).
Weekly updates updates of the demand,
MILP model with 1,296 binary, 85,898 continuous variables and 59,150 constraints.

Summary

- Practical control systems are built up from the bottom using distributed modules.
- Decentralized control and decision making can be “optimal” (self optimization).
- Parallel distributed computing is a reality. Numerical methods and software is needed to take advantage.
- Cutting cost vs new product and process.
- Margins converge and become smaller over time in a competitive commodity market.
- Large, “hybrid” dynamic system solved to optimality (mpc).
- Large savings possible
- But, there is no “silver bullet”. Broad spectrum of technologies need to be integrated with the process and Business IT system.

Acknowledgements:	B. Marshall	ALCOA Technical Center Pgh
	O. Sorli	ELKEM ASA
	T. Halmo	ELKEM ASA/Statoil
	Y. Jiao	PPG Inc Pgh