Design and Scheduling of Flexible Processing Systems: An Optimization Approach

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Overview

- Objective
- Flexible Processing Systems
- Problems & Challenges
- Systems Approach
  - Processes, Resources, Operating Conditions
- Generic Problems Representations
- Scheduling
- Design
- Supply Chains
- Conclusions & Future Work

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Objective

Develop generic models for the design and scheduling of flexible process systems

Solution of Real Problems

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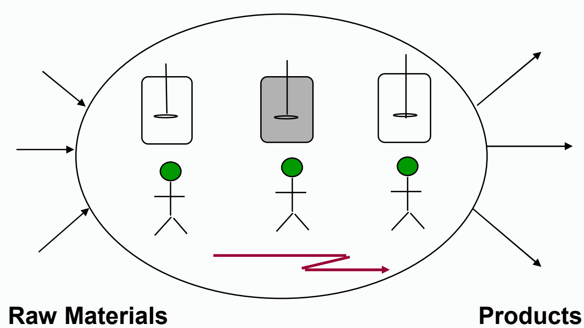
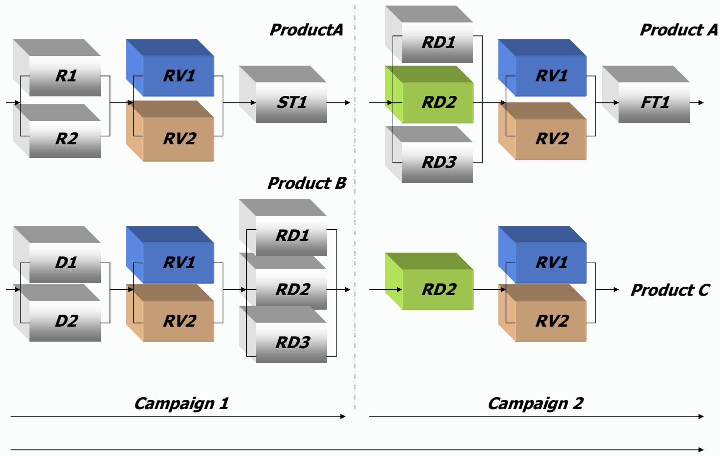
Flexible Process Systems

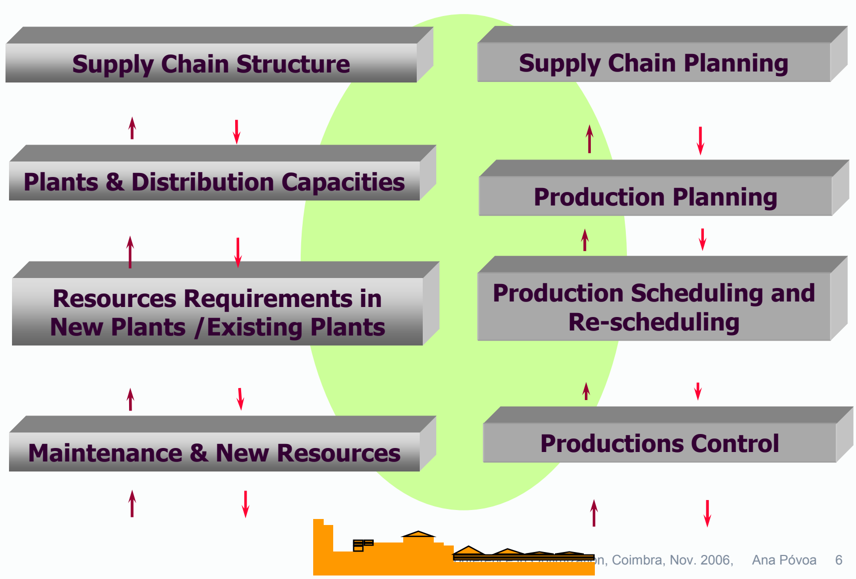
- **High variety of Products**
- **Low Volumes**
- **Batch and Semi-Continuous Operations**
- **Multipurpose Resources**



Flexible Process Systems



Flexible Process Systems : Design + Operation



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Process Industries: Motivation

- Diversity of Applications
- Complex Production Processes
- Improvement of Processes Efficiency
- Client Satisfaction
- Costs Reduction

→ **Decision Support Systems**

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Problems & Challenges

- How to design these plants?
- How to manage the plants resources?
- How to design and manage the associated supply chains?

SYSTEMS APPROCH → OPTIMIZATION…

The Model

- Develop the model for the problem;
  - Parameters definition
  - Sets definition
  - Variables definition
    - Binary (ex. Use or not the resource ?)
    - Continuous (ex. Batch sizes ?)
  - Constraints definitions
  - Objective definition

Complex Optimization Problems
Mixed Integer Linear/Non-Linear Formulations
(MILPs & MINLPs)

Solution Methods

- Heuristics – generic rules used to evaluate alternatives (FIFO, …).
- Meta-Heuristics – algorithms (e.g. simulate annealing, Tabu search, Ant colony, …).
- Artificial Intelligence – Ruled based methods, agent methods.
- Constraint Programming
- Mathematical Programming – MILPs and MINLPs models, use of optimization algorithms (e.g. GAMS/CPLEX, XPRESS)

Combination of Methods (Hybrid)

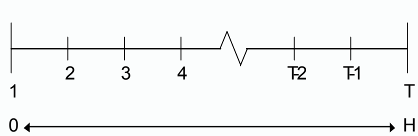
Key Components

- **Tasks** – activities that *transform* the materials:
  - Processing
  - Storage
  - Transport …
- **Resources**:
  - Processing and storage equipments,
  - Transport
  - Man-power
  - Utilities …
- **Time** :
  - External - Production versus external demand
  - Internal – Production Planning & Scheduling

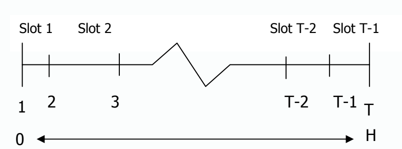
Treatment of time

- The activities (tasks) must occur such that the problem objectives are attained and no restrictions are violated
  - The use of the resources by the tasks and its availability along time must be analyzed

Discrete Time



Continuous Time



Discrete vs. Continuous Time

- Discrete Time
  - Tight mathematical formulations
  - Large models – small discretisation of time
  - Processing times independent of the batches.
- Continuous Time
  - Loose mathematical formulations
  - Smaller models – less points within the time grid
  - Time grid points determined by the model
  - Processing times may be dependent of the batches

Problems Representation (Pantelides, 2004)

Problems are very complex and very diverse … need a diverse set of techniques to match problem characteristics

OR

Distinctions between different industrial design & scheduling problems are not really sharp … uniform representations can be used

Scheduling

Given:

- ❑ Process description
- ❑ Plant flow-sheet
- ❑ Resources suitability –tasks / materials
- ❑ Operating constraints
- ❑ Production demands
- ❑ Costs/Values
- ❑ Times of operation

Determine:

- ❑ Optimal operation: scheduling

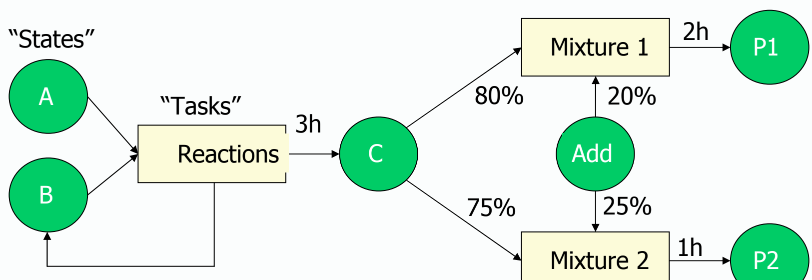
So as to:

- ❑ Optimize an objective function

Min. Delays / Max. Prod./ Min Makespan

Process Description

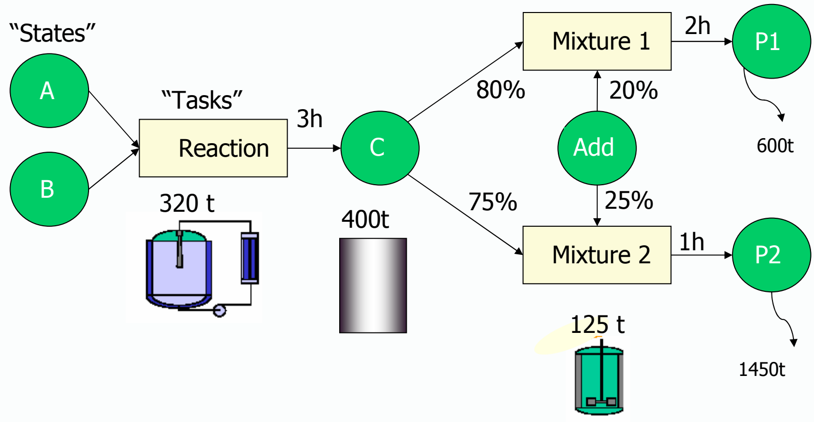
State-Task Network, STN (Kondili, Sargent & Pantelides, 1988, 1993)



Non ambiguities in the process description:

- ➢ Sharing of intermediate products;
- ➢ Different processing alternatives;
- ➢ Recycles.

Process + Resources + Production



How long it takes to produce ?

(adapted, Shah, 2004)

Global Model

(Kondili et al, 1988, Shah et al 1993)

Process	→ Tasks, States, STN
Multipurpose Resources	→ Capacity & Suitability
Time representation	Discrete, Fixed Times
Operating Costs	→ Batch linear function
Operating modes	→ Periodic e non periodic
Operating constraints	→ Cleaning, etc. …
Demand	→ Intervals, Fixed Values

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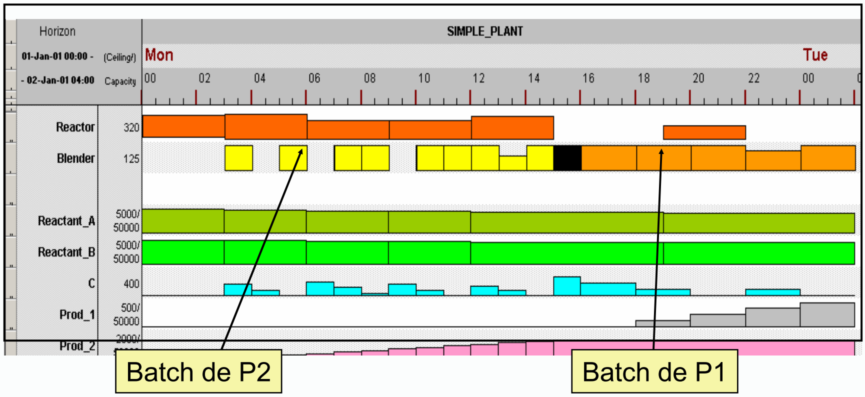
Constraints & Objective Function Linear → MILP Problem

Scheduling



Answer : 26 hours

(adapted, Shah, 2003)

STN Restrictions

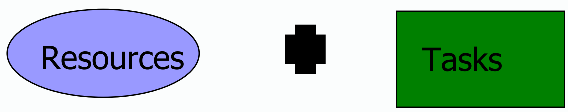
- ❑ Tasks are always associated to materials that suffer transformation.
- ❑ Tasks associated to a dingle equipment.
- ❑ Each resource is treated independently and non uniformly
- ❑ Generalizations implies the addition of constraints

Generic Models but with some complexity

Resource -Task Network, RTN

(Pantelides, 1994)

- Uniform treatment of all resources
  - Materials
  - Processing & Storage equipment
  - Utilities & Man-power
  - Connections
  - Transport resources …



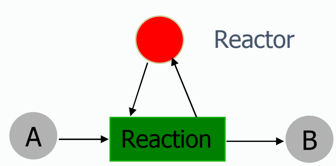
- Classified accordingly to its functionality
- All resources of the same class have the same functionality

- Abstract operation that consumes & produces resources

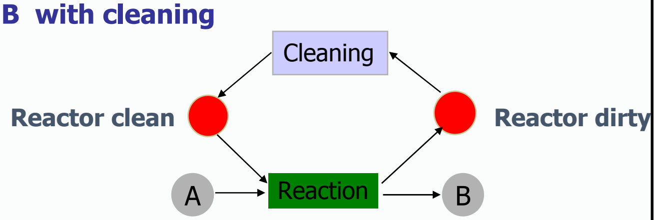
Resource-Task Network, RTN

(Pantelides, 1994)

Reaction A → B



Reaction A → B with cleaning



GENERIC & SIMPLE MODELS

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Formulations: STN versus RTN

STN

$$MaxPR = \sum_{s \in SP} \left[\left(S_{s,H+1} - S_{s,0} \right) . v_s + \sum_t D_{s,t} . v_s \right]$$

s.t.

$$\sum_{i \in I_j} \sum_{t'=t-p_i+1 \geq 1}^{t} W_{i,j,t'} \leq 1 \quad \forall \ j, t = 1,...,H$$

$$0 \leq S_{st} \leq C_s \qquad \forall s, t = 1,...,H$$

$$V_{ij}^{\min} W_{ijt} \leq B_{ijt} \leq W_{ijt} \cdot V_{ij}^{\max} \qquad \forall i, j \in K_i, t = 1,...,H$$

$$0 \leq U_{ut} \leq U_u^{\max} \qquad \forall u, t = 1,...,H$$

$$U_{ut} = \sum_i \sum_{j \in k_i} \left(\alpha_{ui} W_{ijt} + \beta_{ui} B_{ijt} \right) \qquad \forall u, t = 1,...,H$$

$$S_{s,t} = S_{s,t-1} + \sum_{i \in \overline{T}_s} \overline{\rho}_{is} \sum_{j \in K_i} B_{i,j,t-\tau_i} + \sum_{i \in T_s} \rho_{is} \sum_{j \in K_i} B_{i,j,t} \Sigma - D_{s,t} + R_{s,t}$$
$$\forall \ s \ , t \ = 1,...,H+1$$

$$S_{st}, W_{ijt}, B_{ijt}, D_{st}, R_{st}$$

RTN

$$MaxPR = \sum_{r \in RP} \left[\left(R_{r,H+1} - R_{s,0} \right) . vr + \sum_t \Pi_{r,t} . v_r \right]$$

s.t.

$$0 \leq R_{rt} \leq R_{rt}^{\max} \qquad \forall r, t = 1,...,H$$

$$V_{kr}^{\min} N_{kt} \leq \xi_{kt} \leq N_{kt} \cdot V_{kr}^{\max} \qquad \forall k, r \in PE_k, t = 1,...,H$$

$$R_{r,t} = R_{s,t-1} + \sum_k \sum_{\theta=0}^{\tau_k} \left(\mu_{kr\theta} N_{k,t-\theta} + \upsilon_{kr\theta} \xi_{k,t-\theta} \right) + \Pi_{rt}$$
$$\forall \ r \ , t \ = 1,...,H+1$$

$$R_{rt}, N_{kt}, \xi_{kt}, \Pi_{rt}$$

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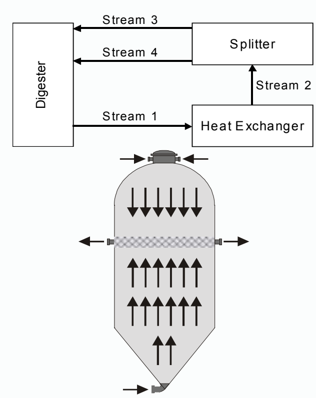
Scheduling: Caima Pulp Mill

(Castro, Barbosa-Póvoa e Matos, 2002)

- **Four Digesters operating in batch mode (D3, D4, D5 e D6)**
- **Vapor resource limitation**



What is the optimal digesters sequence that maximizes production while account for vapor limitations?

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Scheduling: Caima Pulp Mill

(Castro, Barbosa-Póvoa e Matos, 2002)

Process:

1 – Chip filling;
2 – Acid filling
3 – Heating (55ºC to 130ºC)
4 – Cooking
5 – Degasification (high & low pressure)
6 - Blowing

Cyclic Operation – sequence that is repeated

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Scheduling: Caima Pulp Mill

(Castro, Barbosa-Póvoa e Matos, 2002)

Detailed Model (gPROMS)
Cooking Operation modeling

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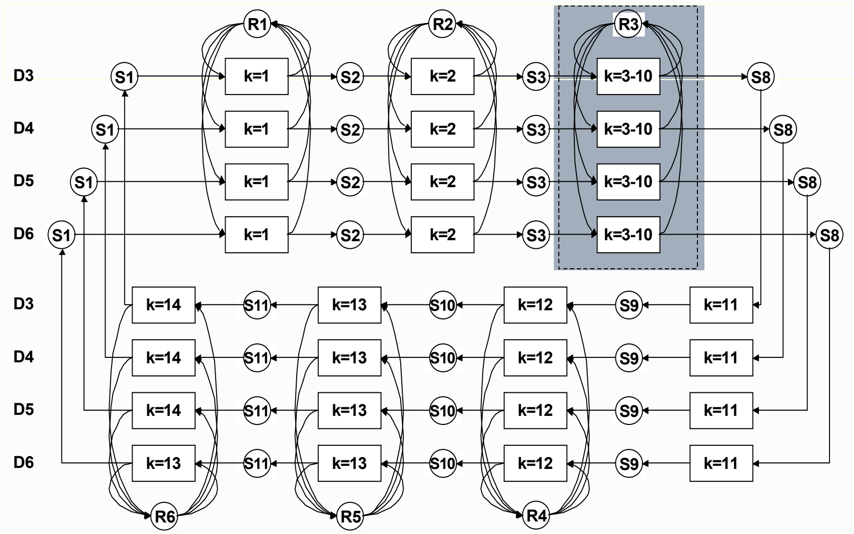
RTN Model – Scheduling
Time Discretisation

⇒ **Optimal Sequence**

Cooking Process, RTN

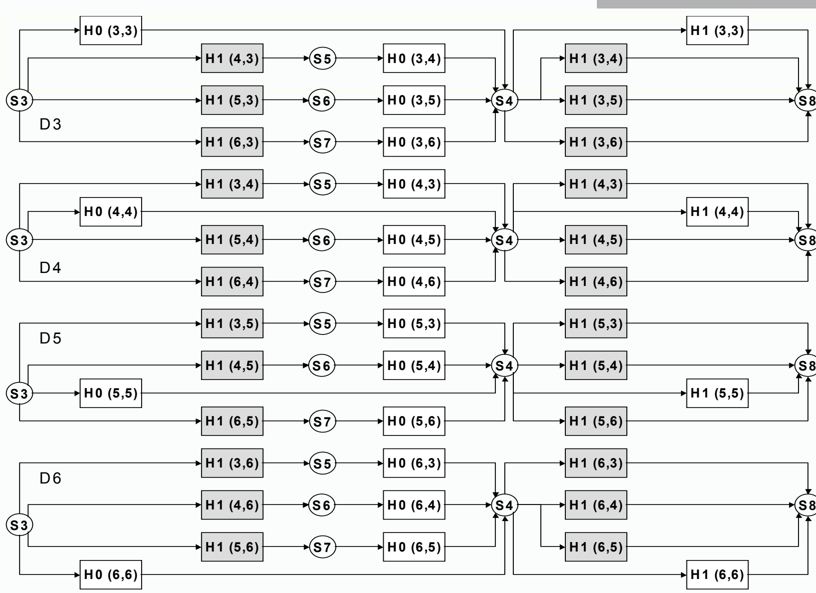
(Castro, Barbosa-Póvoa e Matos, 2002)



Heating phase simplification K=3-10

Heating Phase, RTN

(Castro, Barbosa-Póvoa e Matos, 2002)



Scheduling: Caima Pulp Mill

(Castro, Barbosa-Póvoa e Matos, 2002)

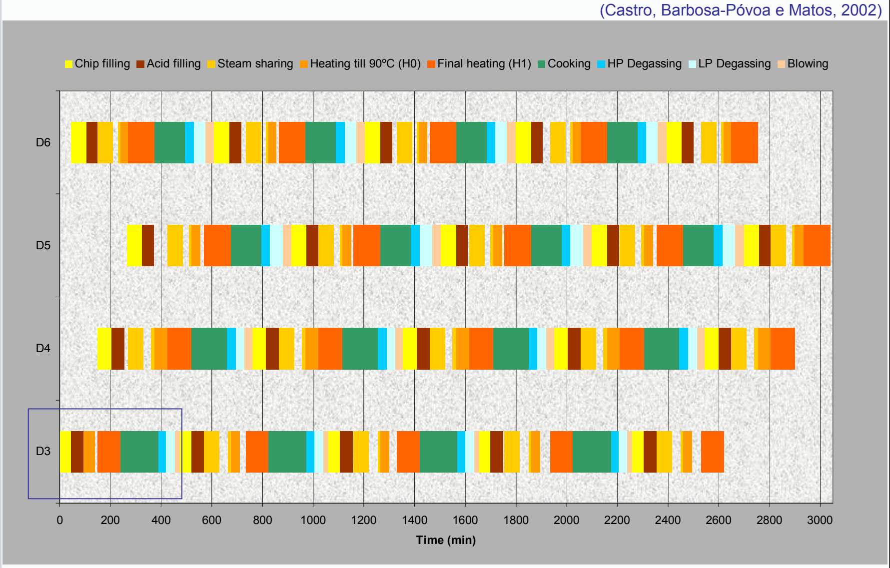
Optimal Sequence

	13 t/h	14 t/h
Optimal Sequence	D3-D4-D5-D6	D3-D6-D4-D5
Cycle Time (min.)	605	595

Scenarios Study

Optimal Scheduling for 14 ton/hr

(Castro, Barbosa-Póvoa e Matos, 2002)



Flexible Systems Scheduling

(Shah, 1998, Floudas & Lin, 2004, Mendez et al., 2005)

- Generic & Flexible Representations
- Detailed Models

BUT IS MISSING ….

- Dynamic Scheduling treatment
- Uncertainty study
- Explore more efficient solution methods – complex problems
- Real cases solution

Design / Retrofit

Given:

- ❑ Process Description
- ❑ Plant Superstructure : Equipment & Topology
- ❑ Equipment Suitability –Tasks/Materials
- ❑ Operational constraints
- ❑ Demands
- ❑ Operating & Investment Costs/Values
- ❑ Operation times

Determine:

- ❑ Plant design : Equipment & Topology
- ❑ Optimal Operation : scheduling

So as to:

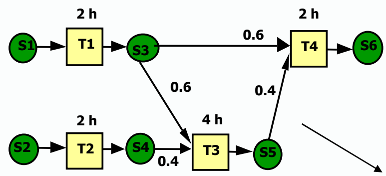
- ❑ Optimize and Objective Function

  Min. Costs / Max. Profit

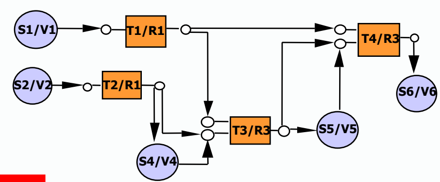
Design / Retrofit

(Barbosa-Póvoa e Macchietto, 1994)

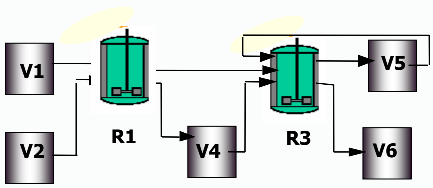
State-Task Network, STN



maximal State-Task Network, mSTN



Equipment Network, Flowsheet



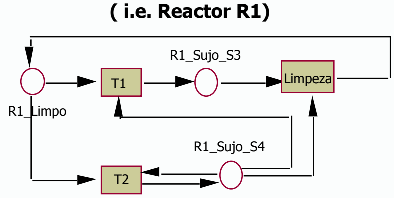
- **Only feasible configurations**
- **Precise representation of :**
  - **- all transfers**
  - **- all material locations**
  - **- any storage policies**

Equipment-Process Modeling

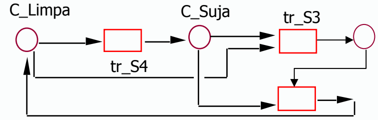
(Barbosa-Póvoa & Macchietto, 1997)

Equipment State- Task Network (eSTN)

(i.e. Reactor R1)



(i.e. Connection)



- eTask (process, storage, services & Transfers)

- eState (connections / units)

- **Define allowable states of each piece of equipment / connection (eStates)**
- **Define allowable transformations between equipment states caused by process, transfers, storage and cleaning tasks (eSTN Tasks)**

→

Representing:
-precedence constraints
-sequence dependencies
-cleaning requirements

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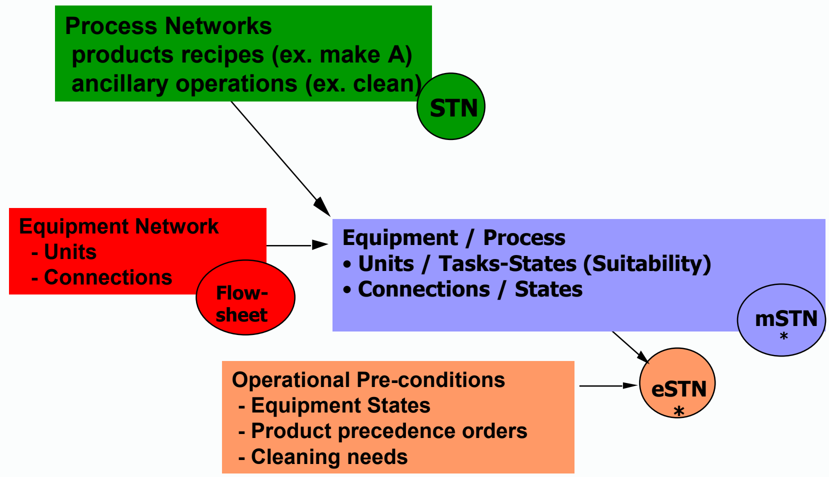
Design - Modeling

(Barbosa-Póvoa, 1994)



* - generated automatically

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Model Characteristics

(Barbosa-Póvoa and Machietto, 1994)

- Process Representation, STN;
- Resources with Discrete & Continuous Capacity;
- Plant Topology
- Time Discretisation;
- Short-term & Periodic Operation;
- Multipurpose Resources
- Fixed Processing Times;
- Non-preemptive Operations;
- Generic Storage Policies;
- Operating demands;
- Utility circuits;
- Multi-product operation.

\+

Objective Function

↓

MILP Problem

Retrofit: Example

(Barbosa-Póvoa, 1994)

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Expand Existence Capacity ???

If Profitable???

- **How to expand ???**
- **How much it costs ???**

Retrofit: Example

(Barbosa-Póvoa, 1994)

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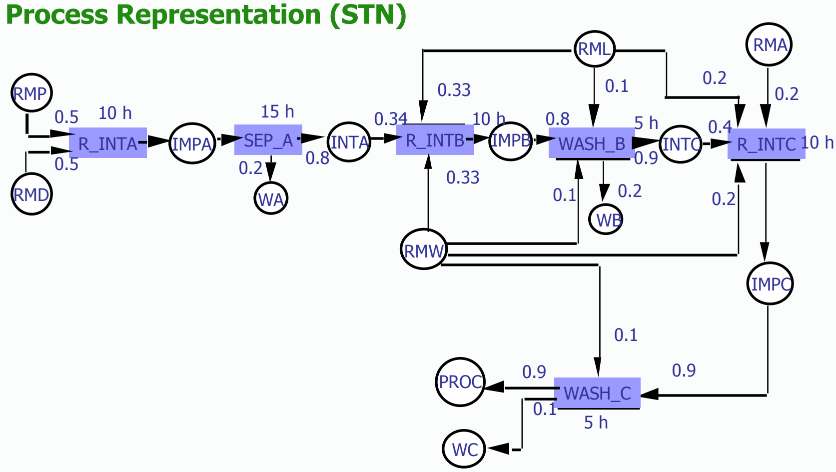
Process Representation (STN)



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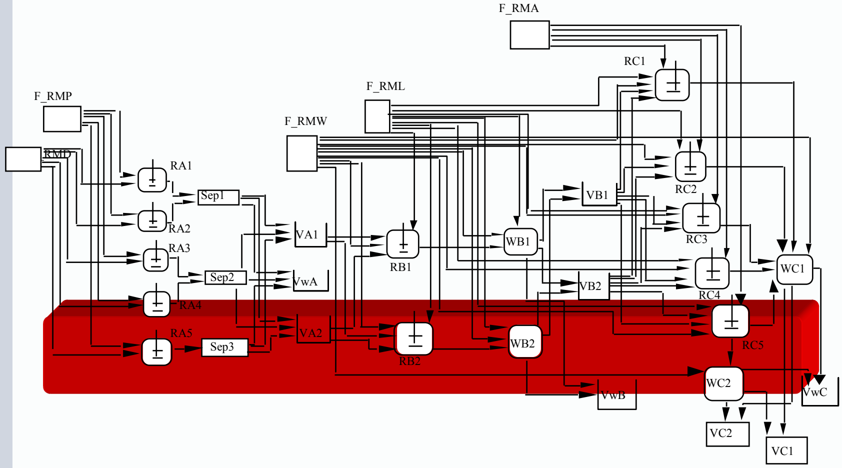
Retrofit: Example

(Barbosa-Póvoa, 1994)

Superstructure – Flowsheet

(in black existing plant – in red possible additions)



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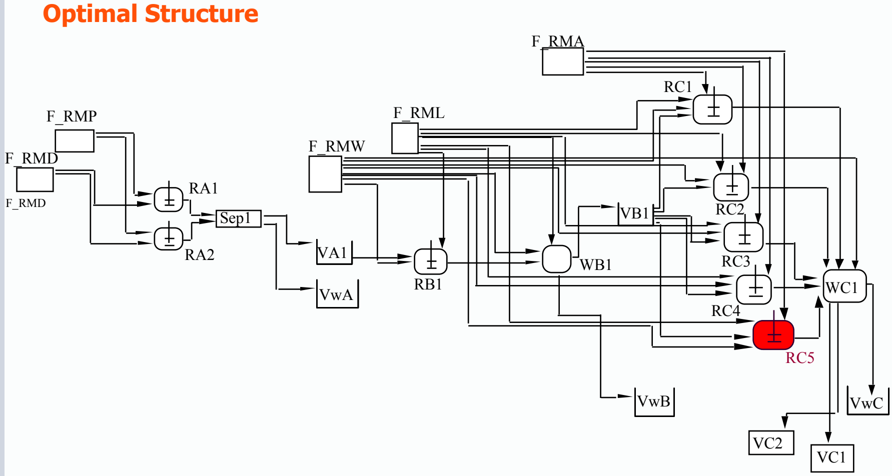
Retrofit: Example

(Barbosa-Póvoa, 1994)

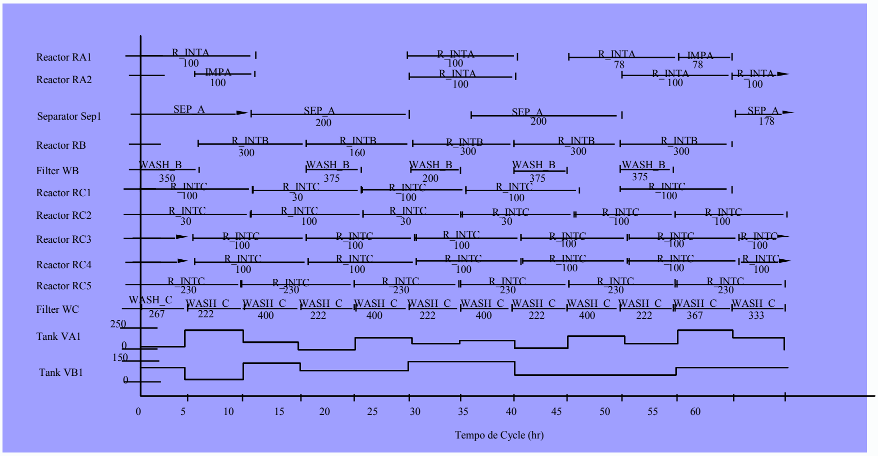
Optimal Structure



Profit = (> 20%)

Retrofit: Example

(Barbosa-Póvoa, 1994)



Design & Retrofit - RTN

- Generic Models
  - Plants Topology
  - Multipurpose Resources
  - Operating Constraints
  - Discrete & Continuous Capacities
  - Cyclic & Short Term Operation

  - Time
    - Discrete (Pinto, Barbosa-Póvoa e Novais, 2005)
    - Continuous (Castro, Barbosa-Póvoa e Novais, 2005)

Investment in the models applications

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Design of Flexible Systems

(Barbosa-Póvoa, 2006)

- Details models but exists space for much more :
  - Multi-level models (design, planning & scheduling)
  - Multi-objective models
  - Uncertainty modeling
  - Explore more efficient solution methods
- Explore the solutions of real cases

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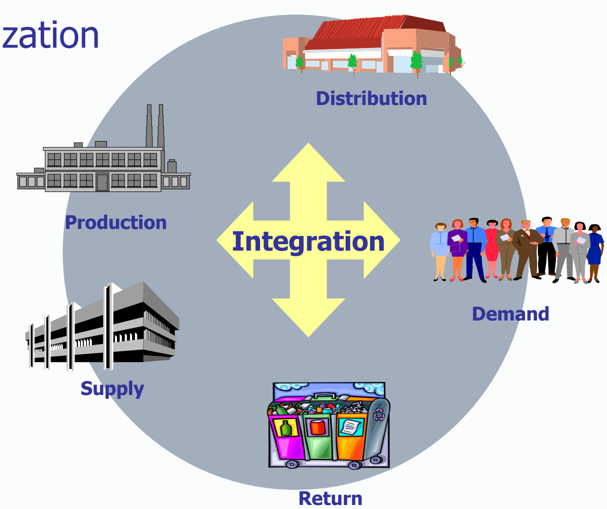
Supply Chain

Optimization



Optimization Opportunities

- The supply chains are difficult to understand
- Decisions are frequently based on common sense

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- Optimization tools allow the possibility of looking in an integrated form to:
  - Design & Operational decisions

Supply Chains

- Previous representations can be extended to the supply chain
- Knowledge obtained within the design and scheduling problems should be used.

↓

- Models
  - Detailed and able to capture interactions
  - Deal with uncertainty
  - Dynamic & Flexible
  - Extensible

Supply Chains Operation

(Amaro e Barbosa-Póvoa, 2004, 2006)

TOPOLOGY

Chain Structure
Transportation Network

➕

OPERATION

Tasks
Materials flows

➕

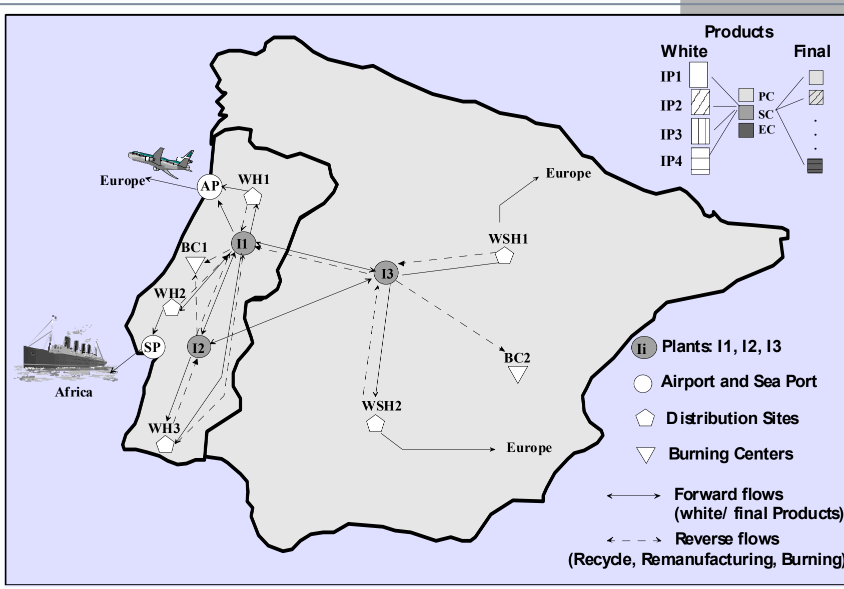
MARKET ASPECTS

Supply/Demand
Constraints

→ *ChainSTN* → **Model (MILP)**

Closed Loop Supply Chain with return of non-conform products: Pharmaceutical Industry

(Amaro e Barbosa-Póvoa, 2006)



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Closed Loop Supply Chain with return of non-conform products: Pharmaceutical Industry

(Amaro e Barbosa-Póvoa, 2006)

Main Operations

Production – intermediate medicines production (not for sale) involves essentially operations like:
- sterilization,
- components calibration,
- mixing, etc.

Customization – considers operations as:
- filling,
- blistering,
- packing, etc.

Distribution and Supply – considers operations as:
- storing,
- distribution.

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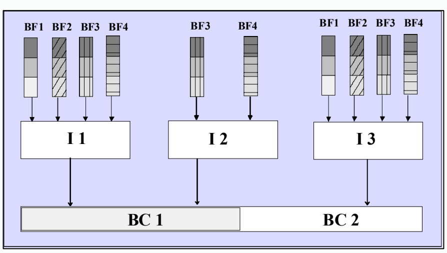
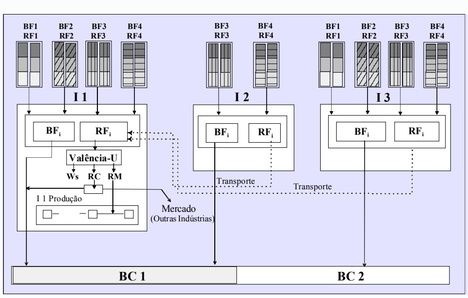
Closed Loop Supply Chain with return of non-conform products: Pharmaceutical Industry

(Amaro e Barbosa-Póvoa, 2006)

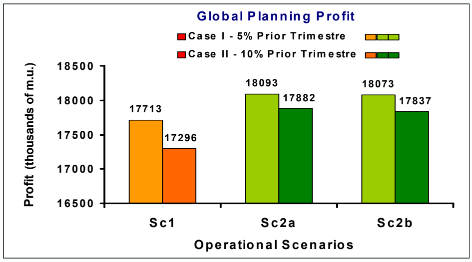


Scenario 1 – no recover, Burning (SC1)



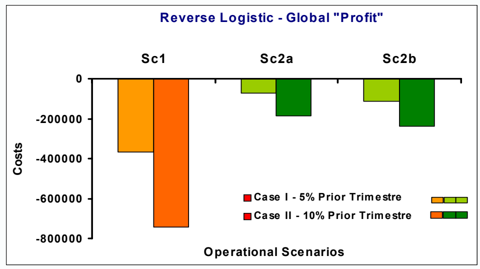
Scenario 2 – recover,
- without minimums (SC2)
- with minimums (SC3)

Return with and without Recover (Amaro e Barbosa-Póvoa, 2006)



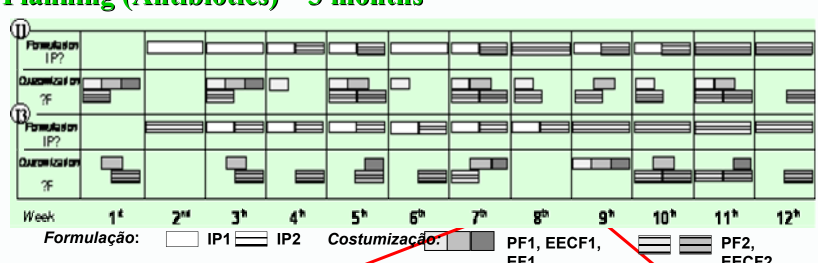
Recovery of medicines is more favourable than the non-recovery situation.

The increase of non conform products recovery reduces the chain "profit".

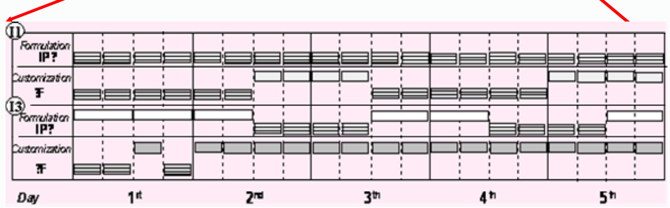


Planning & Scheduling (Amaro e Barbosa-Póvoa, 2006)

Planning (Antibiotics) – 3 months



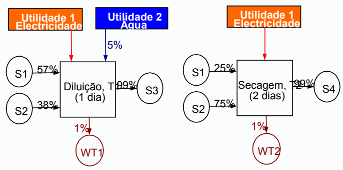
Scheduling – 5 days



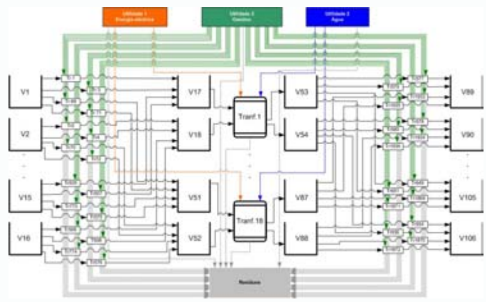
Design of a recovery network of an industrial polluted waste

(Duque, Barbosa-Póvoa e Novais, 2005, 2006)

Process



Super-estructure



+ Environmental data

Optimize the network maximizing the profit accounting for :

- **Demands within intervals**
- **Environmental Impacts (CTAM, CTWM, SMD…)**

Design of a recovery network of an industrial polluted waste

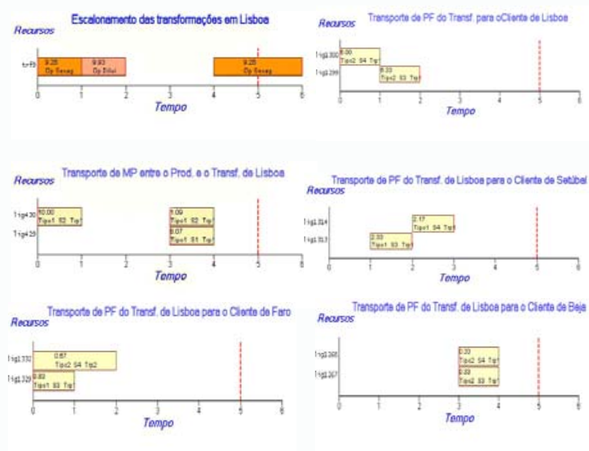
(Duque, Barbosa-Póvoa e Novais, 2005, 2006)

Simplified super-structure | **Optimal Network**

Design of a recovery network of an industrial polluted waste

(Duque, Barbosa-Póvoa e Novais, 2005, 2006)

Operation



Supply Chains

(Goetschalckx et al. 2002, Shah, 2004)

Area with a great potential.
There is some work done but there is space for much more:

- Improve existing structures
- Integrated different decision levels
- Explore environmental impacts
- Economic details
- Uncertainty
- Deal with complexity & different scales
- ….

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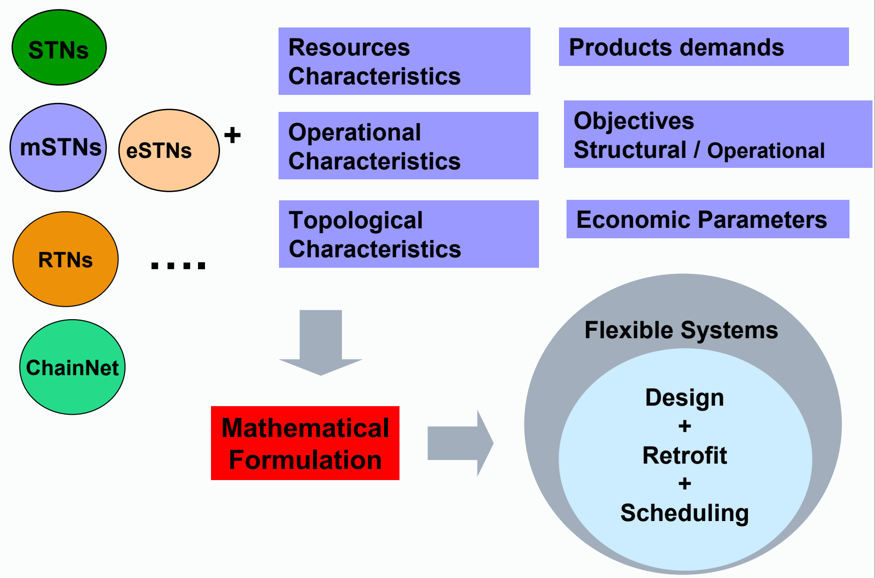
Optimization is a possible Solution



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Conclusions

- Design & Scheduling
  - Detailed models
  - Solutions of some real cases
  - There is space for more …
- Supply Chains
  - Detail models are appearing
  - Great complexity in the modeling & solution
  - There is space for more …

Optimization ➡ Possible Solution

Future

- Fill the "GAP" between research & its application
- Explore solution methods more efficiently :
  - Hybrid methods
    - Heuristics + MILPs
    - Meta-Heuristics + MILPS
    - Constraint Programming + MILPs
- Integrated different decision levels
- Explore environmental impacts
- Uncertainty

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Design and Scheduling of Flexible Processing Systems: An Optimization Approach

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