

Combined Strategic Design *and* Operative Planning in the Process Industry

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The Chemical Company

Introduction

Overview of the Talk



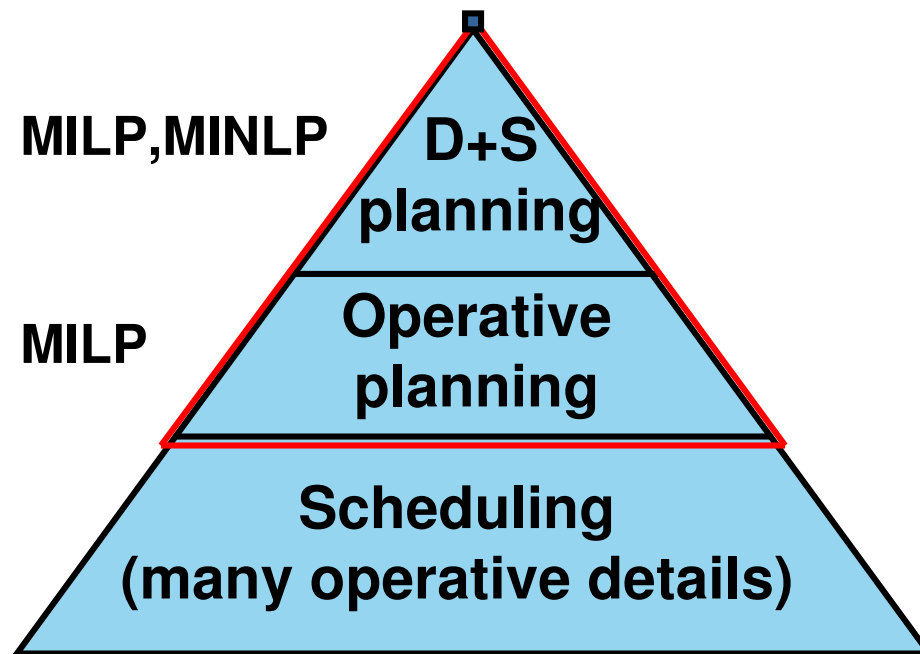
Conceptual issues in strategic, (multi-site) design and planning problems in the process industry

- Industries: chemical, pharmaceutical, food industry, metals
- Overview and examples of design models
- The need for combined design & operative planning models
- Operative + Design extensions & Design + Operative part
- Mathematical Complexity → tailor-made modeling and solution
- Appropriate and maintainable modeling and IT structures
- Discussion: Individual tailor-made solutions versus standard software

(Supply Chain) Planning Pyramid

Definitions and Facets

3 separate models



time horizon



several years



month...year



days, weeks

(can be a year
for long campaigns)

Yesterday: Christos Maravelias - *Integration of Production Planning And Scheduling*. **Today:** We want to encourage combined, integrated approaches for **D+S and operative planning** (1st and 2nd layer) !

Operative Planning

Definitions and Facets – Brief Overview

Operative planning : mid-term planning (a month to a year) involving various supply chain issues such as **production planning, sales planning,** and **shipment leading to MILP models.**

- **Advanced Planning System (APS):**

tactical planning or **master planning** with horizons of a few months, followed by production planning and scheduling [cf. Stadtler (2002), more precisely, short-term or detailed scheduling].

- **Our own definition (a functional definition):**

any kind of **planning producing plans and schedules used operatively** in production departments or by marketing forces of a company

- we assume that it applies to an **underlying production network topology**
- production should include, e.g., **sequence-dependent setup changes**
- purchase of raw materials, supplier selection, distribution decisions
- this definition could include **scheduling** as well

Design and Strategic Planning

Definitions and Examples

Design planning: (closer to hardware and physical reality)

- designing a production network
- structuring processes
- geometrical and physical layout and dimensioning of units
- sequencing
- topology

Strategic planning: (somewhat higher level, somewhat softer)

- designing product and customer portfolio
 - selecting markets
 - business models
 - co-operations with other companies
- elements of Game Theory

Design and Strategic Planning (1)

Flavors and Variants, Literature Examples



In the open literature we find many interesting design problems and models – here we list and mention a few of them :

- Goetschalckx (2002) calls it **strategic network planning** with a focus on the long-term, strategic planning and design of the supply chain
 - re-design a supply chain from time to time:
 - respond to market changes, or mergers and acquisitions producing a need to consolidate duplicated elements in the supply chain
- Kouvelis & Munson (2004) developed a design model to structure and to design the **global supply chains network structure**.
 - economics of scale
 - complexity costs, transportation costs with and without tariffs

Design and Strategic Planning (2)

Literature Examples with Process Industry Applications



Chemical and Process Industry:

- Shah (2005) calls it **supply chain infrastructure (network) design** or **redesign of the logistics network**
- Lasschuit&Thijssen (2004)'s MINLP model and software **GMOS** developed by Shell, at the **strategic and global planning** level for a network of production plants, represents decisions on
 - feedstock procurement and distribution,
 - utilization of production capacities,
 - utilization of modes of transport and demand allocation.

Design and Strategic Planning (3)

Literature Examples with Process Industry Applications

- Ahmed & Sahinidis (2001) present a mixed integer programming (MIP) model for long range chemical process planning.
- **Kallrath (2002)** : a combined strategic and operative planning MILP model accounting for **chemical reactors of known capacity to be opened or shut down**, and it accounts for **sets of units belonging to a site subject to acquisition**.
- **Guillen et al. (2006)**: simultaneously **optimize process operations and financial decisions to enhance the integrated planning/scheduling of chemical supply chains** – they refer to the design or strategic part as financial or budget planning. They provide a mathematical formulation combining a scheduling/planning model with a cash flow and budgeting formulation
 - integrated planning/scheduling of chemical supply chains,
 - design or strategic part: financial or budget planning,
 - scheduling/planning model combined with a cash flow and budgeting formulation.

Examples in **red** are already **combined approaches** !

Multi-Site Design and Strategic Planning

Design Decisions: Problem Types & Decision Variables

problem type

capacity planning
facility location
financial design
functional design

portfolio optimization
supply chain structure
supply chain design
topology

unit selection
unit design
unit investment

degrees of freedom / decision variables

units, reactors, tanks, etc.
depots, warehouse, production sites
transfer prices, transport costs, total duties
production rates of reactors, process rates of filling stations
customers, products
location variables for warehouses, sales points
topological variables, location variables
connection of nodes in a network,
possible routes of material through nodes
reactor shutdown/opening
capacity and production rates of the units
new reactors, tanks, or filling stations

Design Planning under Uncertainty

Robustness and Sensitivity



- The time horizon easily could involve 5-10, or even 20 years.
 - Most strategic design problems exploit demand input data as the driving force. These data are based on demand forecast.
 - **Costs** for **raw material**, **energy** and **transport** as well as sales prices are also subject to **forecast** – a difficult task in itself !
 - Therefore, at least the amount of demand, costs and prices are subject to **uncertainty** leading to an **optimization problem under uncertainty**.
- **robustness** with respect to deviations from the predicted demand, costs or prices
 hedge against certain risks while taking a design decision
- **solution approaches**
 - **scenario based stochastic optimization**
 - **robust optimization** (Ben-Tal, Bertsimas, Floudas, ...)
 - **sensitivity analysis**

The Need for Exact Optimization in Design Optimization

Long term effects

- Safe separation of investment scenarios ...

scenario	description	alternatives	
		A	B
	net present value (NPV) in units of million US\$	110	120
	integrality gap, max. deviation from optimal solution	2.1%	1.8%
	Maximum possible NPV exact method → bounds	112.31	122.16

scenario	description	alternatives	
		A	B
	net present value (NPV) in units of million US\$	112	110
	integrality gap, max. deviation from optimal solution	n/a	n/a
	Maximum possible NPV meta-heuristic, no bounds	?	?

- Uncertainty of the input data and the model sensitivity determines what is a **reasonable gap** !
- Large horizon → the larger the impact, the larger the uncertainty ...

Integrated Design & Operation Planning

Motivation and key arguments for the combined approach



- Strategic or design features & the operative core are strongly connected by the capacity or other coupling quantities – the coupling quantity ...
 - ... to the investment decision to add larger or more reactors to the production network is the **production capacity**
 - ... in tank design problems is the **storage capacity**
- Design planning without the operative planning kernel bears the risk to work with the wrong effective capacity
 - operative planning model is used to explore the limits of the capacity
 - intelligent operative planning can increase the effective production capacity of the production network and can decrease the investment costs
 - pure operative planning can help to prepare design decisions or lead to design planning
- To really see the „correct“ effective capacity may involve **scheduling** !

Integrated Design & Operation Planning

The Choice of Objective Function



Objective functions in ...

- operative planning (usually, linear)
 - max. contribution margin incl. production & storage costs**
 - multi-criteria optimization (transport, stock, ...)**
- design and strategic planning (nonlinear ?, more subtle choice ..)
 - **net present value for investment decisions**
 - **complexity costs in portfolio problems (customers, products)**
 - **profit-after-tax**

Integrated Design & Operative Planning

Horizon and Time Resolution – Matching Time Scales

The integration requires us to represent different horizons & needs for time resolution **in one model ...**

- horizon
 - **strategic planning: several years**
 - **operative planning: month ... year**
- time resolution depends on the character of the decisions
 - **time discrete (month, quarters, years)**
 - **time continuous (e.g., installation of a new tank system)**
 - **the time resolution of the input data**
- heterogeneous time resolutions within the total horizon
 - **differently sized time buckets in time discrete models**
 - **co-existing time discrete and time continuous formulation**

Integrated Design & Operation Planning

Including Design/Strategic Decision into Operative Planning Models



- **Given:** an operative planning model – usually, a MILP model.
- **Methodology:** - certain given data → **variables**
 - the model → **MINLP with bilinear terms**
- **Example:** Unit investment problem: MILP
 - **existence of units and discrete capacities (MILP)**
 - **continuous capacities (MINLP)**
- **Example:** Profit after tax maximization:
 - **transfer prices and transport costs**
- **Many applications opportunities for adding design to operative model**

Example Problem Description

Strategic, Design and Operative Features

Kallrath (2002): OR Spectrum 24(3), 219-250

Strategic features

- reactor opening & shut-down
- buy whole plants
- 15 years horizon

Operative planning features

- production planning
- inventories
- distribution planning
- sales planning
- Transport
- raw material purchase

Design features

- **Purpose:** Analysis and optimal computation of investment decisions
- buy whole plants
- logical opening & shut-down implications
- all costs related data are discounted over time with a discount rate of $p\%$

Operative planning features

- Multi-period, multi-site, multi-product, multi-stage production
- multi-mode reactors, mode changes
- Nonlinear prices for raw material purchase

Example: Mathematical Model – (MILP)

Objects & Indices, Variables

Indices

- b : break points (non-linear prices) (4)
- c : sales categories (2)
- d : demand points (3 - 10)
- k : production periods at site s (30)
- m : modes at site s for reactor r
- p : products (15)
- r : reactors (56)
- s : production sites / plants (7)
- t : commercial time periods (10 - 20)

Variables

- δ_{srnk} : reactor state variables **bv**
- $\alpha\beta\gamma\chi$: mode changing variables
- m^D_{srnk} : time spend in mode m
- p^P_{srnpk} : production variables
- p^P_{srndk} : charge to other reactors
- p^P_{srntk} : charge to tanks
- σ_{sdpk} : transport
- s_{pt} : stock level
- s^L : sales of variables
- p^E : external purchase
- μ_{spbtk} : auxiliary variables non-linear product purchase

Example: Mathematical Model – (MILP)

Constraints & Objective Function, Special Features

Constraints

- reactor status → trace mode changes
- compute time spent in modes
- from time compute production
- distribute production to tanks & multi-site production network
- stock balance equations
- special transport treatment
- nonlinear purchase
- Sales
- Objective functions: contribution margin, net profit, multi-criteria aspects

Special Features

- raw material aspects
 - material requirement planning output; no constraints, no costs
 - take as much as needed at a fixed unit price
 - take as much as needed as using a nonlinear price scheme
 - take all available raw material (use or burn) at a fixed price
- probabilistic transport
- design reactor's opening & shut-down is modeled similar as mode-changing reactors

Example: Results

Computational and Commercial Results

Computational (XPressMP, Dash)

- 1st feasible integer solution within 1 min (300 notes), GAP < 3%
- **proof of optimality** in most cases within 3 minutes (3000 notes)

commercial:

- saving of **several millions US\$**
 - via reduction in transport costs by reduction of urgent shipments
- model-based investment plans helped to **convince senior management**
- **stability** of designs solutions up to 20% changes in demand forecast

■ *Validation:*

- comparison with non-model based plans
- discussions with people in finance departments

■ *Long - reaching implications*

- good **forecast** for economic data & demand
- **global optimality**, safe bounds

■ *Modeling aspects* : realistic balance for details

■ *Applicable to many situations*

- large companies
- companies in restructuring process
- merging companies

Integrated Design & Operation Planning

Adding Operative Planning Features to Design Models

Motivating Example



- **Example 1:** In a chemical or food company the target is to compute **cost minimal production sequences of a set of products for given demand** in a time period. (sequence design problem)
 - In the design problem only the production sequence matters.
 - In the DOEP the demands per time period can be satisfied by actual production or by what has been produced and stored in tanks in previous time slices.
 - **New basic decision:** produce just-in-time, or earlier & store.
 - **New objective function:** setup change versus storage costs
 - **Shelf-life time** brings in complexity in addition to the sequencing problem which is still inherent in each time period.

Integrated Design & Operation Planning

Adding Operative Planning Features to Design Models
Motivating Example from the Paper & Metals Industry



- **Example 2:** Paper and metals industry - compute minimal waste cutting patterns to satisfy a fixed demand for a set of items.
 - **Paper industry: Production of rolls from master rolls** – famous Gilmore & Gomory (1961) algorithm – (pattern design problem).
 - **Steel industry: Complicated patterns involving circles and polygons** - Kallrath (2008) – (pattern design problem)
 - The design-operative extended problems (DOEP) allow to store the items cut in an earlier period and to satisfy demand in a given period from actual production *and* stock.
 - **Basic decision:** cut an item in a certain period in a pattern or not.
 - **Objective function:** pattern cutting/changing vs. storage costs.

Integrated Design & Operation Planning

Adding Operative Planning Features to Design Models



- **Given: A Design/Strategic Model (DP) and a Tailor-Made Solution Algorithm**
- **Goal: Add Operative Features and get a design-operative extended problem**

(DOEP)

- DP is time-independent.
- DP involves known demand to be satisfied from production.
- DOEP is time-dependent; it contains a time index.
- DOEP involves **production and inventory units** with finite capacities.
- DOEP adds inventory costs and possibly delay costs to the original objective function.
- DOEP contains a **material balance equation** coupling the material flow results of

Integrated Design & Operation Planning

What Makes Optimization Problem Difficult ?

When do we call a Problem Difficult ?



- requiring a lot of CPU time
 - difficult to find a feasible solution
 - difficult to close the gap (integrality gap, NLP: upper – lower bound)
- lack of numerical stability
- in NLP or MINLP the existence of many local minima

What makes optimization problems difficult ?

- structure (combinatorial aspects, symmetry, degeneration, ...)
- size (# variables, # constraints, # nonlinear terms, # non-zeros)

Integrated Design & Operation Planning

Mathematical Solution Approaches



Tailor-Made Exact Algorithms to master size & complexity

- model implementation: use an **algebraic modeling language**
- for monolithic models: standard MILP or MINLP solver
 - **bound generating auxiliary models**
- decomposition techniques (exact and approximate)
 - **column enumeration**
 - **column generation (Gilmore & Gomory, ...)**
 - **time-constructive decomposition approaches (Floudas)**
- hybrid methods (with bounds)

Decision Tracks

Combined/Integrated Approach ↔ Separate Models
Tailor-Made Solutions ↔ Commercial Standard Software



- Case 1: Standard software solves the decision problem at hand. Great !
- Case 2: Not Case 1, but the **commercial software** is **open enough** to understand precisely the embedded model and to **modify it to own needs**. Probably a good choice – go for it !
- Case 3: Neither 1 nor 2 – Reasons:
 - Strategic planning is related to the **business history** (customers, products, markets) – and is very relevant to **future success: creativity, new ideas** and **exploiting new degrees of freedom** matter ! Can a standard software be so rich in features ?
 - Design planning also reflects the **company's development over time** (physical structure) – again: any new degrees of freedom are thinkable ! It would be a surprise if any standard software is ready for this.
 - Combined/Integrated **D+S** and **operative planning** is **difficult** !

Combined/Integrated Approach

Arguments for an Integrated Tailor-Made Approach



Arguments for and benefits of a tailor-made combined approach

- combine and integrate strategic and operative planning precisely as wanted (e.g., **appropriate capacity coupling**)
- get optimal (or bound-proven) design and strategic decisions in the context of an underlying operative planning problem
- be **fully open to new strategic or design decision problems**
- include uncertainty → **optimization under uncertainty**
- let **mathematics master the complexity** and **exploit the problem structure**
- **keep flexibility** and react promptly on new requests
- **control the implementation speed** (adding new aspects to a vendor-controlled standard package may take longer).

Combined Approach

Software Design Issues

The combined model should ...

- ... be coded in an algebraic modeling language (GAMS, Mosel, AIMMS)
- ... have a core operative model
 - **production**
 - **storage**
 - **transport**
- ... have additional design modules, which
 - **can easily be activated**
 - **can easily be connected**

Combined Approach

Limiting factors

- **data availability** (probably the hardest one !)
 - **design object data** (consistent with the operative approach)
e.g., capacities, production rates, transport, connections, customer, products
 - **forecast data** (demand, price, costs) and their **uncertainties**
- model complexity (when satellite design modules are added)
 - **design units, design customers, design products**
- the **numerical complexity** to solve the resulting model
- model character & structure (MILP, NLP, MINLP,
convex ↔ non-convex),
- **maintaining the model** (**special difficulty**: the design extension is used less frequently than the operative part of the model)

IT Aspects

Commercial Software for Operative & Design Planning Survey Date: 2007

name	founded	web address	type	product	P	SD
Adv. Proc. Comb	1993	combination.com	PS	VirtECS	+	
AI Systems		aisystems.be	PS	SteelPlanner	+	
AspenTech	1981	aspentech.com	PE, APS	MiMi	+	
ASPROVA	1994	asprova.com	PS		?	
AXXOM	2001	axxom.com	P	ORion-Pi	+	+
Delta Software	1980	deltasw.com	CP	DeltaPlan	+	
Haverly Systems	1962	haverly.com	PS	GRTMPS	+	
Honeywell Process S.		see footnote	R, PS		+	
ILOG	1987	ilog.com	PS	PowerOPS	+	
Ingenious		ingenious.cc	PS	ProPlan, ProSched	+	
Insight	1978	insight-mss.com	ND	SAILS	+	+
i2 Technologies	1988	i2.com	APS		+	
Logic Tools	1995	logic-tools.com	APS, P	SupplyPlanner	+	
OM Partners		ompartners.com	PS	OMPDesigner,Planner	+	+
Optience	2003	optience.com	PS	SMartSuite	+	
OR Soft	1990	orsoft.net	PS	Schedule++	+	+
PSE	1997	psenterprise.com	PS	OSS Scheduler	+	
Quintiq	1997	quintiq.nl	PS		+	
River Logic	2000	riverlogic.com	P	Enterprise Opt	?	+
SAP	1972	sap.com	APS	SAP APO	+	(+)
Shell Global Solutions	2001	shell.com		GMOS	+	+
Supply Chain C.	1993	supplychain.com	P	Zemeter	+	
Technologix Inc	1993	technologix.ca	P	OptiNet	+	
VisOpt Inc		visopt.com	APS		+	
Wam Systems	1987	wamsystems.com	P	Picaso	+	

IT Aspects

Role of Individual Software and Advanced Planning Systems (APS)

- The combined approach (CA) can
 - **C1: completely exist on its own** (individual approach), or
 - **C2: simultaneously with tight connections** to an **APS** providing the operative data base.
- However, for the CA we need all data also for design units, plus long-term forecast and their uncertainties.
- These are usually not available in an APS. Therefore, in C2 a separate GUI and a local database for the CA approach interfaced to an APS is recommended.

Cost Aspects

Developing & Maintenance Costs of In-House Models



Development effort and costs scale with the complexity and richness of the operative core planning, or planning-scheduling model.

- If the model is properly built, strategic design aspects can be added module per module at project based costs.
- For maintaining, supporting and further developments this in-house model one needs one or two skilled people.
- Running cost of 5-to 20 % of the development cost, should be compared to the purchasing and customization cost and maintenance fees to be paid to a commercial provider .

Dependencies

Dependencies on Software Providers or In-House Specialists

With any piece of software to be used over a longer time horizon dependencies are established.

- Commercial software providers often also operate as consulting firms.
- Large commercial software providers may not have strong competitors and thus strongly influence the price.
- The dependence on in-house specialists can at least be better controlled. However, the number of in-house specialists should not be too small (risk to lose the know-how due to personal fluctuation).
- A well functioning in-house optimization group is also very helpful to obtain appropriate external software and/or consulting.

Conclusions

- **key motivation for the combination:** **strategic/design and operative planning problems are strongly connected by capacity**
 - **proper operative planning provides extra capacity**
 - **design decisions have great effect on the plant's capacity**
- **facets, examples, opportunities** and **limits** of the combined approach
- Future: add **detailed scheduling** to the pictures (3rd layer of the pyramid)
- **individual tailor-made solution** versus **standard tools**
 - **strategic and design problem can be very rich in their degrees of freedom (standard software most likely cannot cope with this)**
 - **co-existing combined model connected to an APS for master planning**
- **ideal case: commercial software generic**
 - **generic** enough to serve as a real standard
 - **sufficiently open** to map the client's reality in the desired details
 - and to **include tailor-made solution techniques** if necessary