OPTIMAL DESIGN & OPERATION OF NATURAL GAS VALUE CHAINS

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Outline

- Natural gas: opportunities and key challenges
- Short-term operational planning: the Sarawak Gas Production System
- Design of a liquefied energy chain
- Global optimization of algorithms

Natural Gas Overview

- World natural gas demand expected to rise to 163 trillion cubic feet (tcf) by 2030 from 100 tcf in 2004[1]
- Expected to remain a key fuel in power generation and industrial sector over next two decades
  - Less CO_2 per unit energy produced
  - Massive reserves
  - Transition to "natural gas economy"
- Demands from new emerging technologies
  - Hydrogen economy
  - Hydrocarbon based fuel cells
  - Natural gas based chemical industry
  - Biofuels upgrading, oil sands mining and upgrading, etc.
  - Gas to liquid fuels

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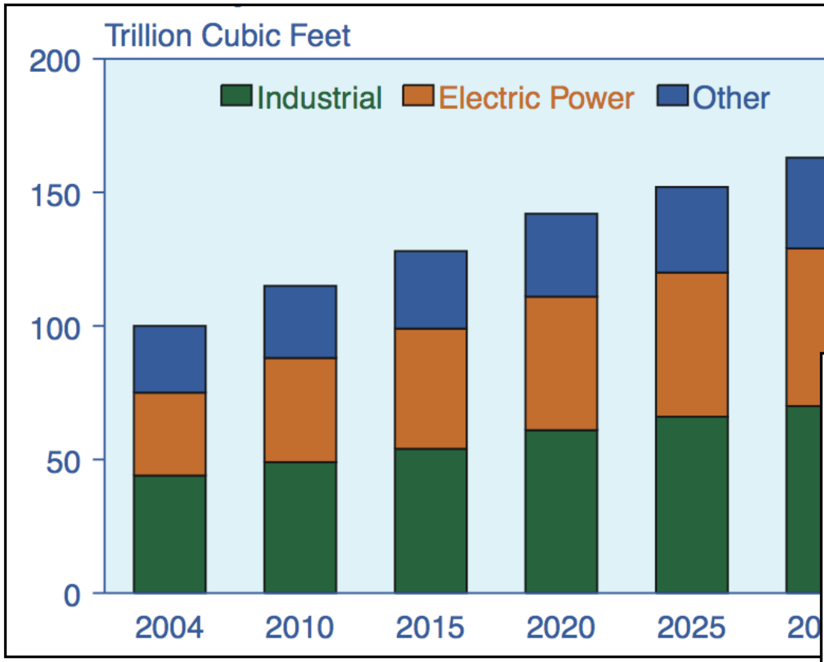
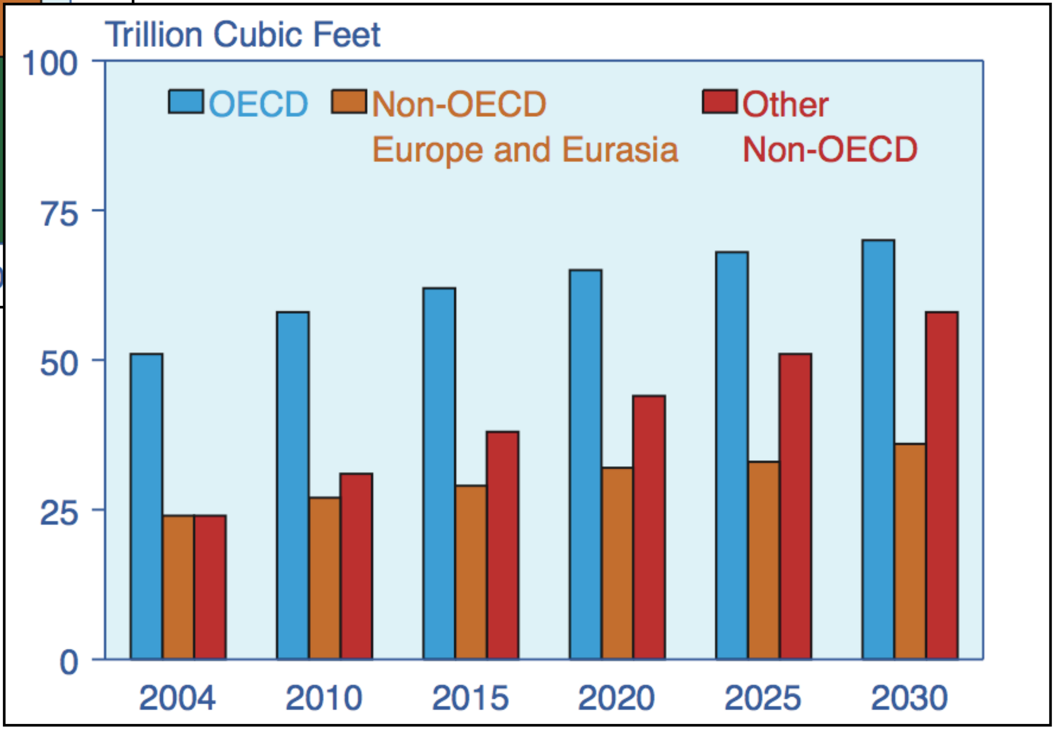
1. "International Energy Outlook 2007", Energy Information Administration, U.S. Department of Energy

Natural Gas Consumption



Consumption by Sector

Industrial sector accounted for 44% consumption in 2004



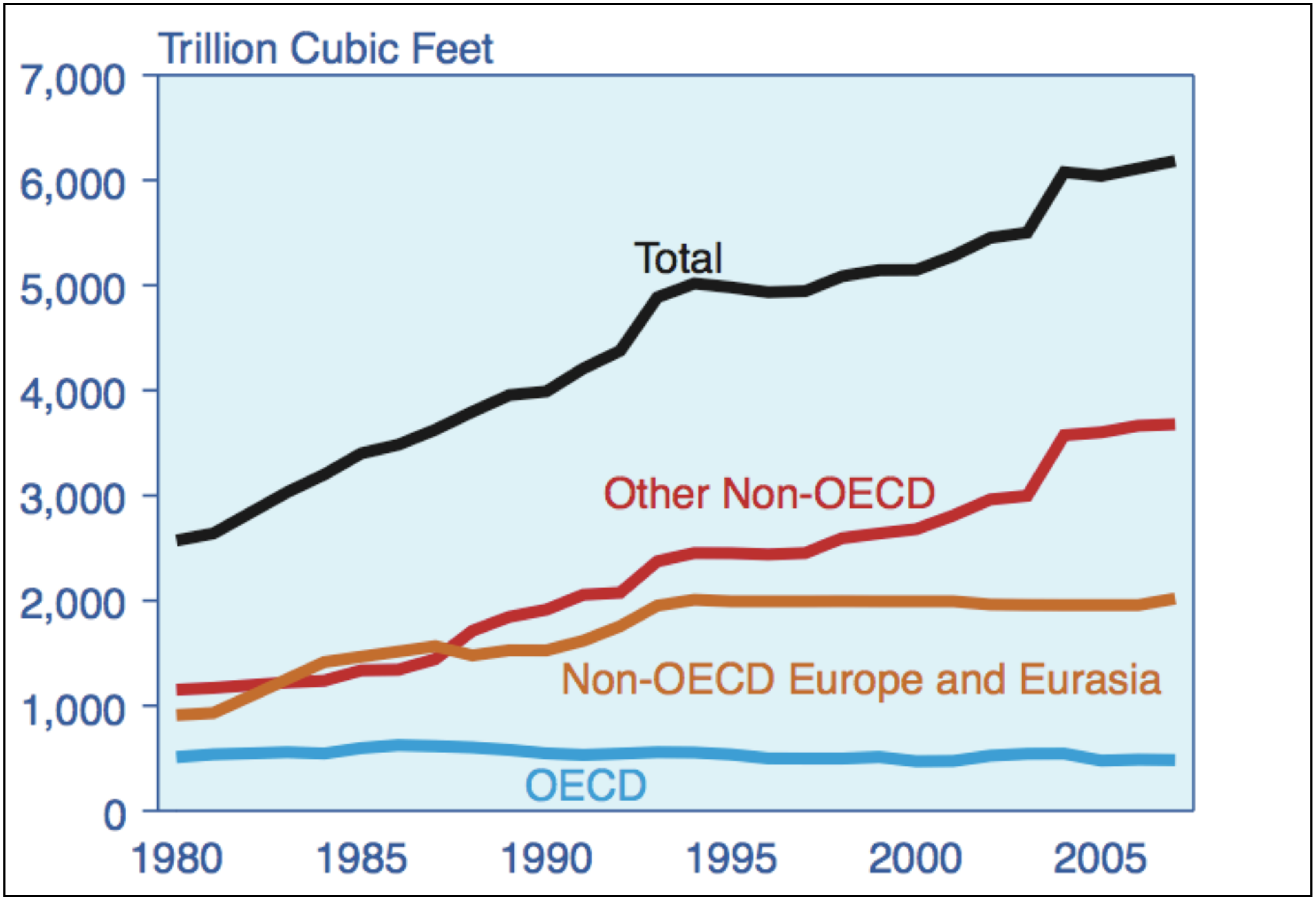
Rate of growth in non-OECD economies projected to be double of OECD growth rate

Consumption by Region

Reserves

- World natural gas reserves are estimated to be 6,183 tcf in 2007
  - Russia, Iran and Qatar account for 58% of total
- An estimated 4,000 tcf remain undiscovered
- Developed world will be increasingly relying on imports in future
- Reserve to production ratio estimated to be 65 years for world
  - >100 yrs for Middle East

Reserves



Trillion Cubic Feet
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
Total
Other Non-OECD
Non-OECD Europe and Eurasia
OECD
1980
1985
1990
1995
2000
2005

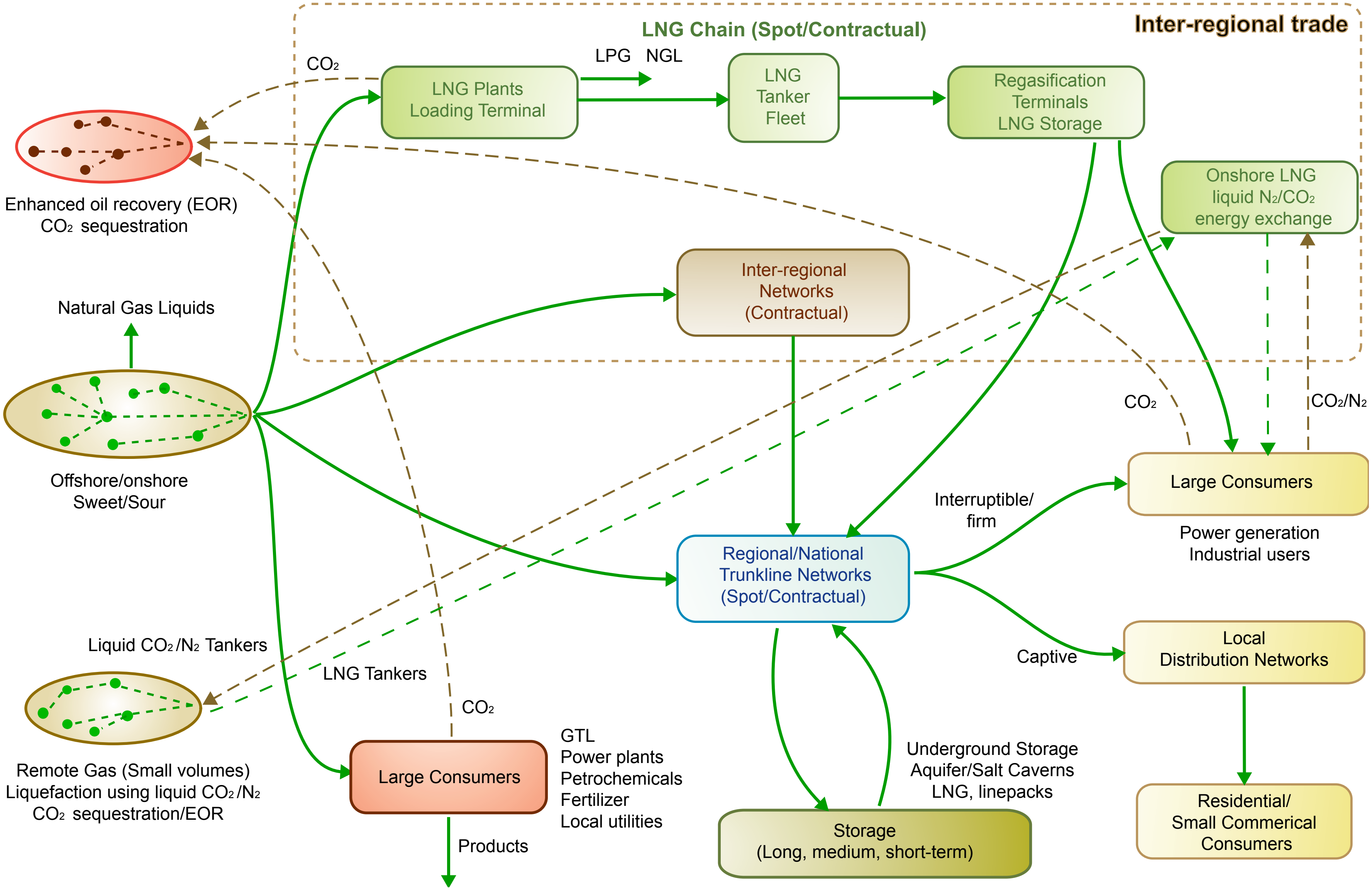
Key Challenges

- Of entire resource base, 3,000 tcf in *stranded* reserves
  - Too far from population centers or pipeline infrastructure
  - LNG expected to play a major role in exploiting these reserves (especially in Middle-East, Artic)
- Rise of global gas market
  - LNG may account for up to 16% of global gas demand by 2015
- More than 90% of growth in production during next two decades from non-OECD countries
  - Strained/unreliable supply chains to developed world
  - Increasing state involvement in upstream activities

Key Challenges

- Hard to exploit conventional resources
    - High cost and uncertainty
    - New technology required
- Unconventional resources
    - Tight sands, shale and coalbed methane
- Environmental concerns
    - Managing carbon output of natural gas processes
    - Impact of unconventional production
- Long delays in infrastructure development with fluctuating demands and prices
    - High capital cost and specificity of infrastructure
    - Investment risk
    - Complex ownership and contractual agreements to manage risk

Natural Gas Supply Chain



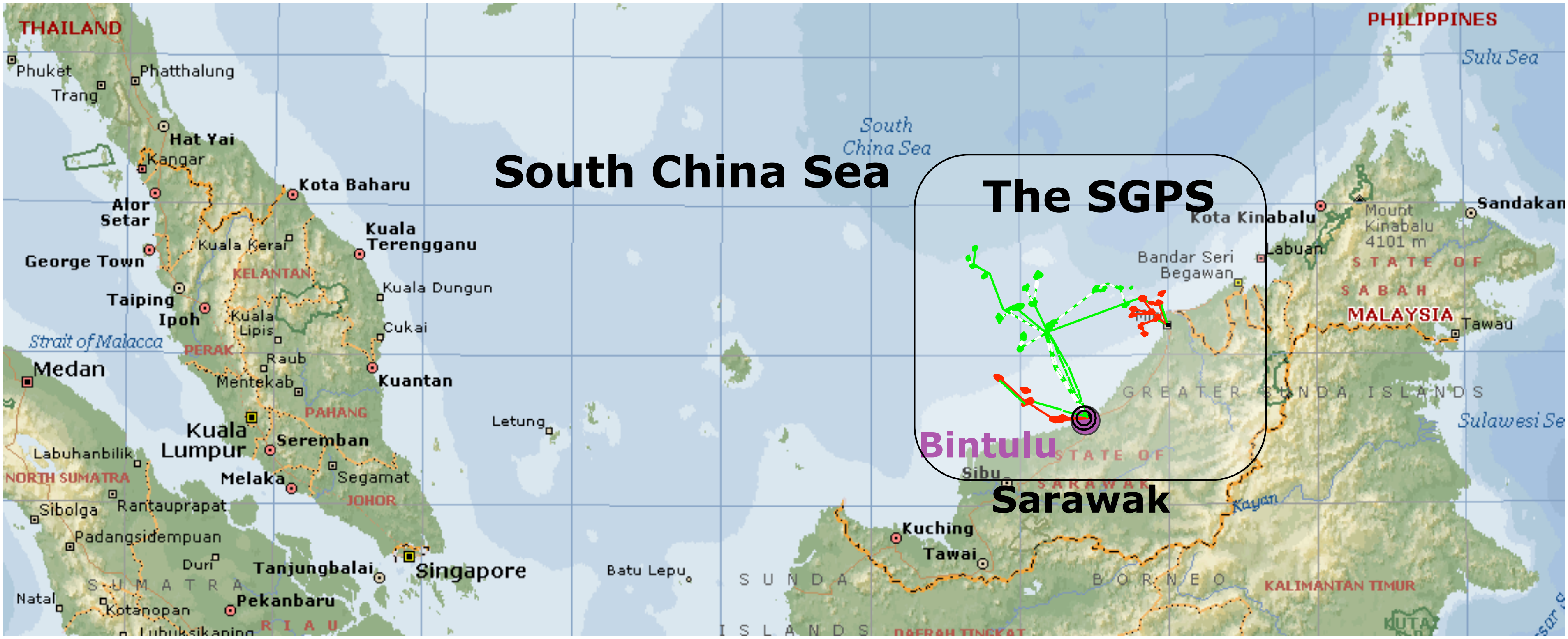
Short-term Operational Planning Sarawak Gas Production System

1. *Ajay Selot, L.K. Kuok, M. Robinson, T.L. Mason, Paul I. Barton. "A short-term operational planning model for natural gas production systems." AIChE Journal,54(2):495-515, 2008.*

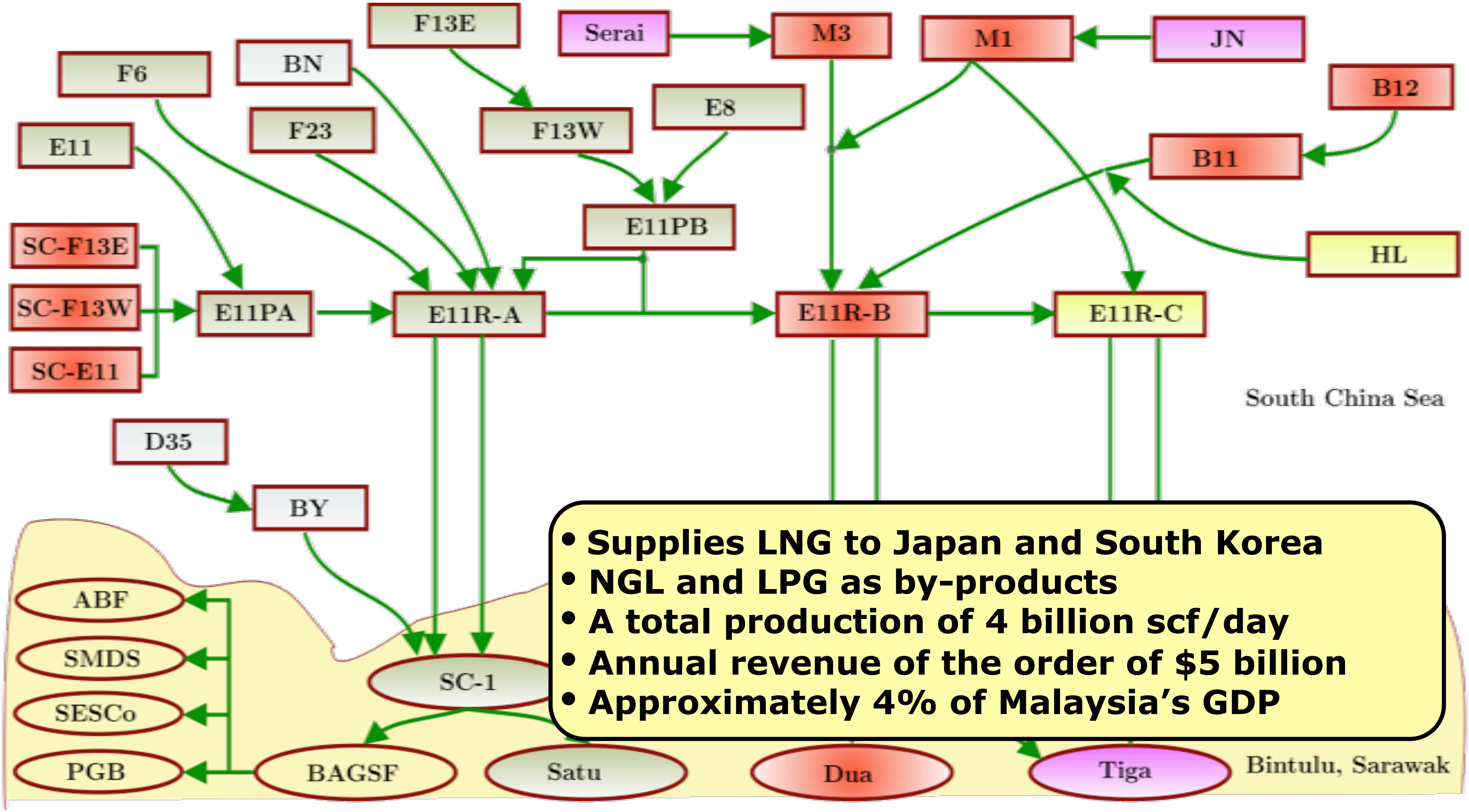
Operational Planning

- Short-term asset management
  - Optimize operation while obeying all constraints
  - Identify bottlenecks in network and facilities
  - Maintenance scheduling
  - Response to failures: real-time decision support
  - Couple with long-term asset management models
- Blending and intelligent routing
- Integrating upstream systems with LNG/LPG/GTL processing
- By-products optimization
- Commercial objectives and rules to enhance value from system operations

Sarawak Gas Production System



Sarawak Gas Production System



- Supplies LNG to Japan and South Korea
- NGL and LPG as by-products
- A total production of 4 billion scf/day
- Annual revenue of the order of $5 billion
- Approximately 4% of Malaysia’s GDP

System Features

- Multi-party ownership with a single operator
  - Complex *production-sharing contracts*
- Gas quality specifications - *gas sales agreement*
  - LNG customer requirements
  - LNG plant operations
  - Gas concentration must be tracked in network
- Nonlinear pressure-flowrate relationships
  - Actuators quite limited in the network
  - Must predict gas flow over 100+ km
- Multiple objectives
  - By-products are additional revenue generators

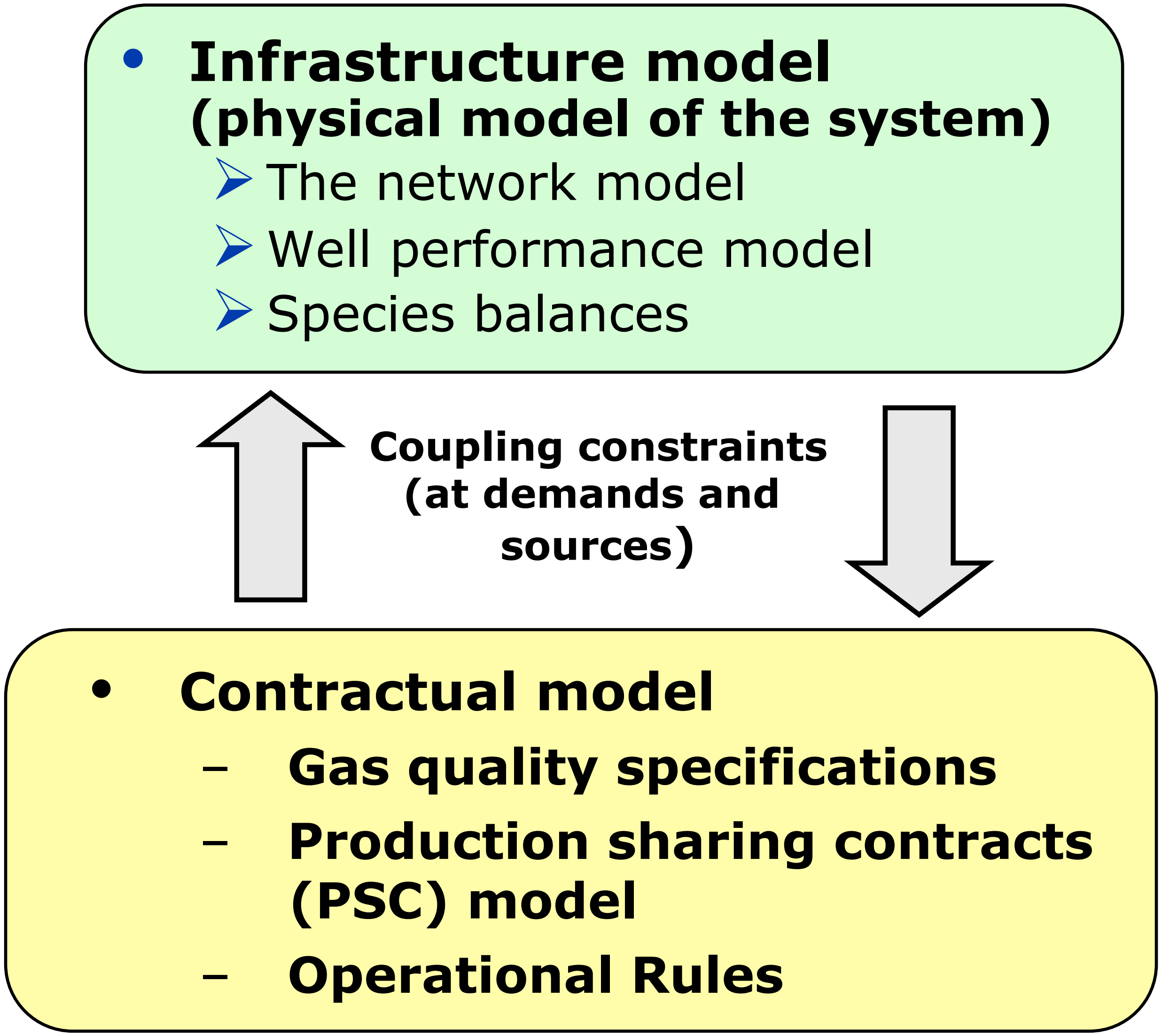
Challenges

- Upstream planning optimization problems are highly nonlinear (and nonconvex)
- Nonconvex optimization cannot be solved reliably by *local optimization methods (e.g., SQP)*
- Representation of complex Production-Sharing Contract (PSC) rules requires *logical constraints*
  - Cannot be handled by continuous optimization method: MINLP formulation
- Hence the opportunity requires state-of-the-art deterministic global optimization algorithms
  - Worst-case exponential run-time
  - Crucial interplay between model, problem structure and algorithms

Model Overview

- Model formulated from perspective of upstream system operator
- Decision support tool for system operators between events
- Plan and predict
  - Production rates from each well
  - Corresponding pressure-flowrate, composition distribution
  - State of production-sharing contracts
- Planning period: 2-10 weeks
- Operational objectives
  - Production rates: Gas, Natural Gas Liquids (NGL), Specified fields

Model Overview



- **Infrastructure model (physical model of the system)**
  - The network model
  - Well performance model
  - Species balances

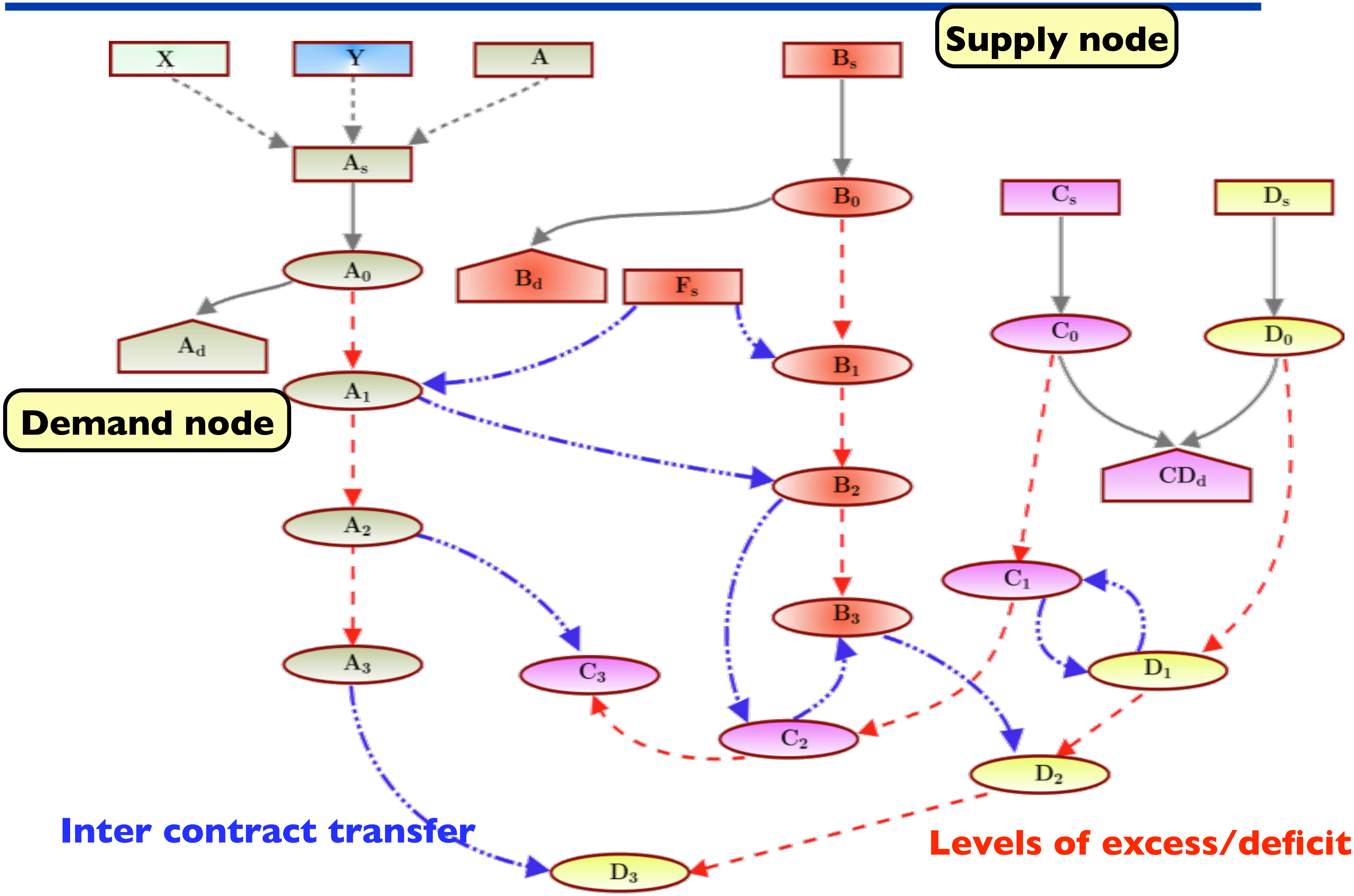
Coupling constraints (at demands and sources)

- **Contractual model**
  - **Gas quality specifications**
  - **Production sharing contracts (PSC) model**
  - **Operational Rules**

- **Blending/ Intelligent routing**
- **Nonlinear pressure-flowrate relationships**
- **Bilinear constraints at mixers or splitters**

- **An embedded framework for representing complicated PSC, commercial/ economic and operational rules and customer requirements**

PSC Network Representation



Supply node

Demand node

Inter contract transfer

Levels of excess/deficit

Hierarchical Multiobjective Case Study

- There are multiple objectives for system operation
- Moreover, a clear hierarchy of objectives
  - Maximize dry gas delivery
    - Contractual obligation
  - Maximize natural gas liquids (NGL)
    - Additional revenue generator
  - Prioritization of some fields (maximize production)
    - Link with long-term planning models
- Multiple solutions with same maximal dry gas delivery
  - Can be exploited to obtain a win-win situation without trade-offs

Hierarchical Multiobjective Case Study - BARON

Value

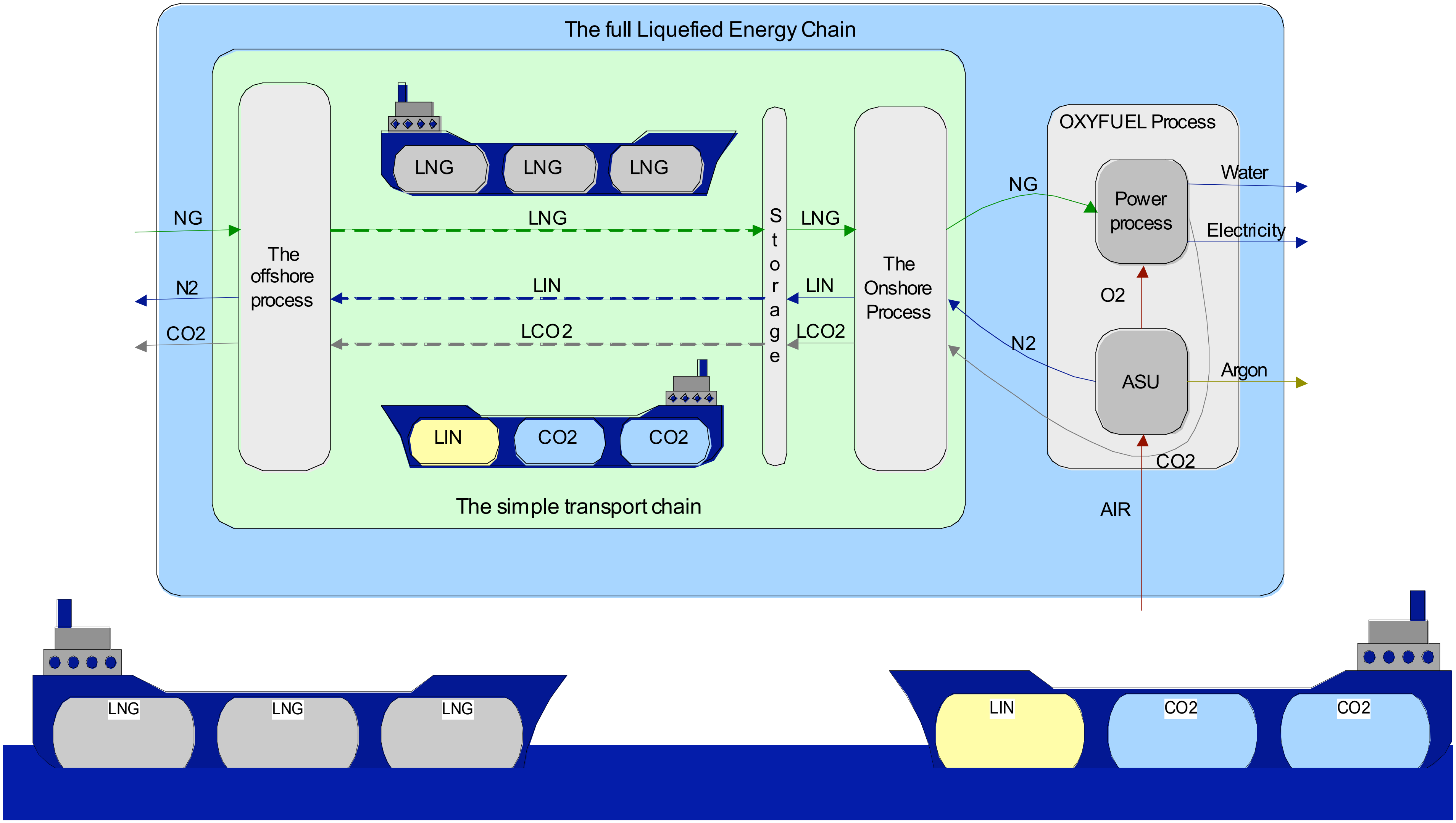
Objective	Dry gas production	NGL	Priority fields	Time
	MMscfd	bpd	MMscfd	s
Dry gas production	3,333	134,036	224	9363
NGL	3,333	137,433 (+2.5%)	224	75
Priority fields	3,333	137,433	224/294[1]	>705,379

[1] Not Converged

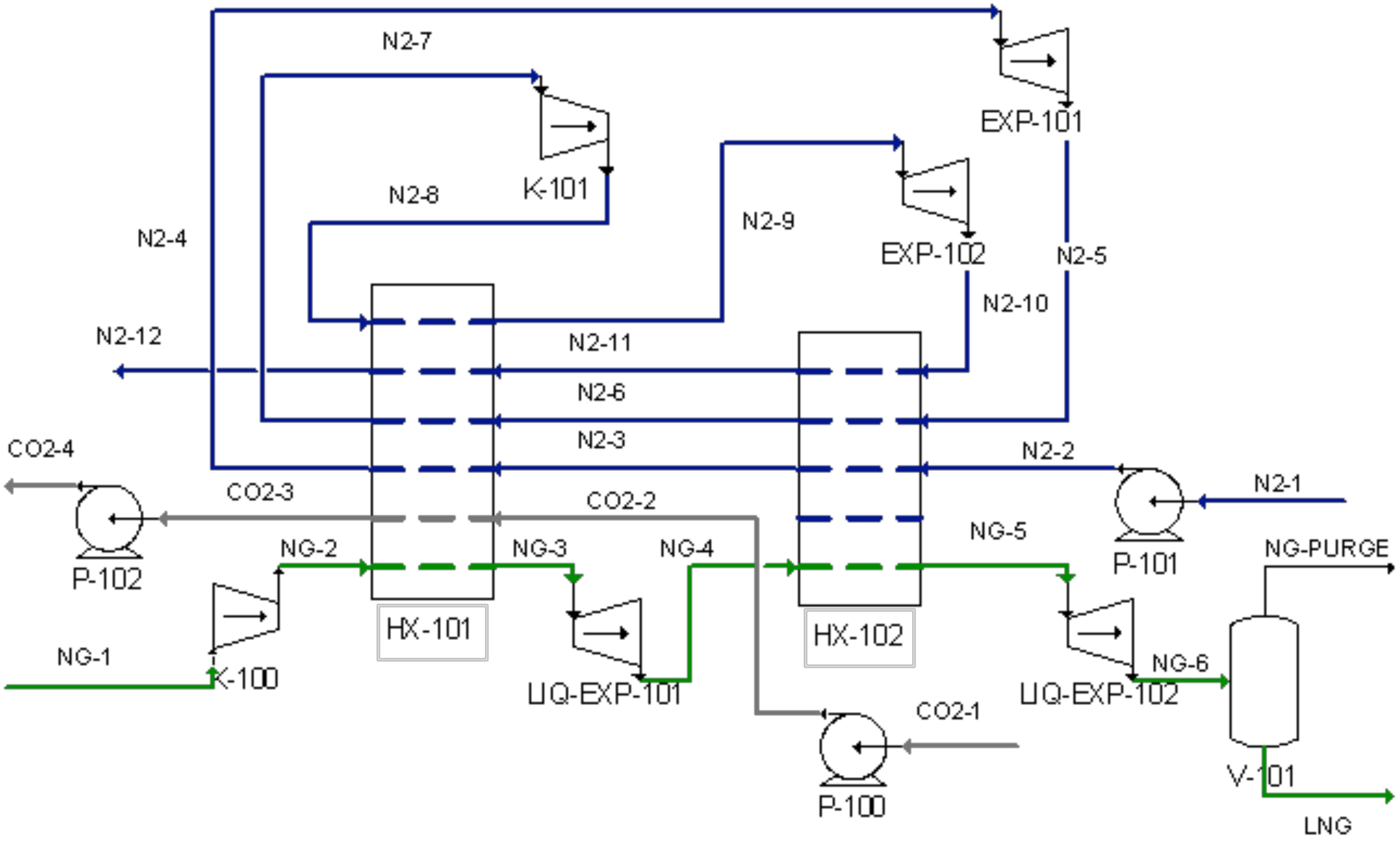
Design of a Liquefied Energy Chain

with Prof. Truls Gundersen (NTNU)

The Liquefied Energy Chain

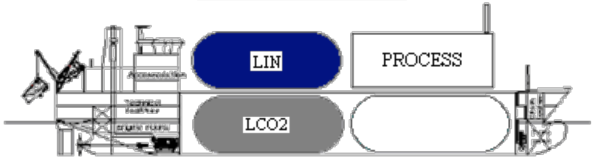


Offshore Process

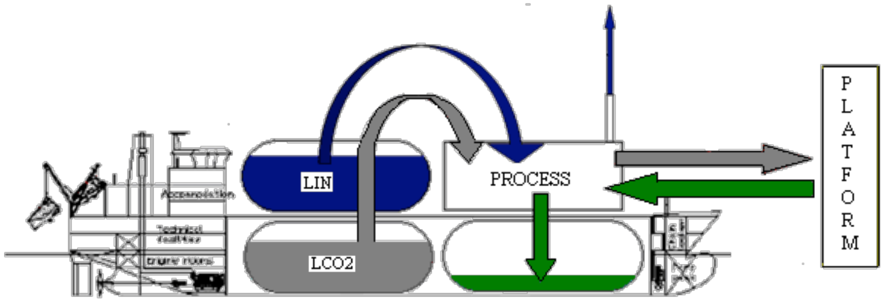


Ship

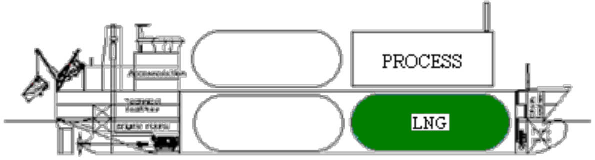
Outbound transport



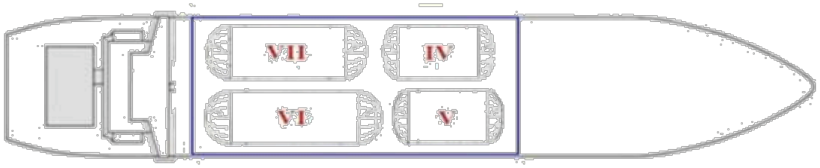
Production (loading/offloading)



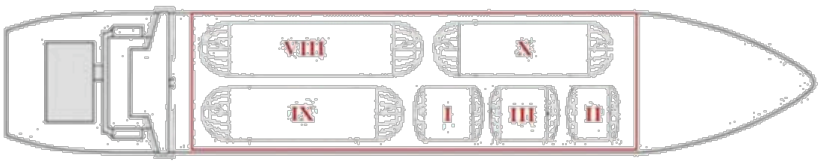
Inbound transport



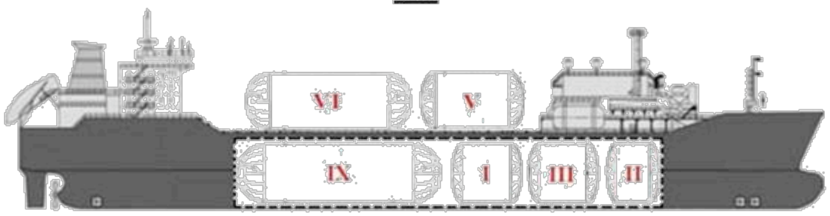
On Deck



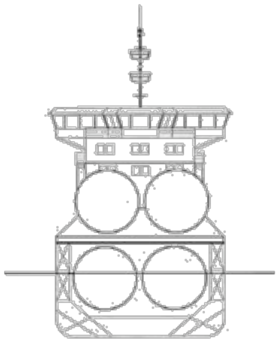
Below Deck



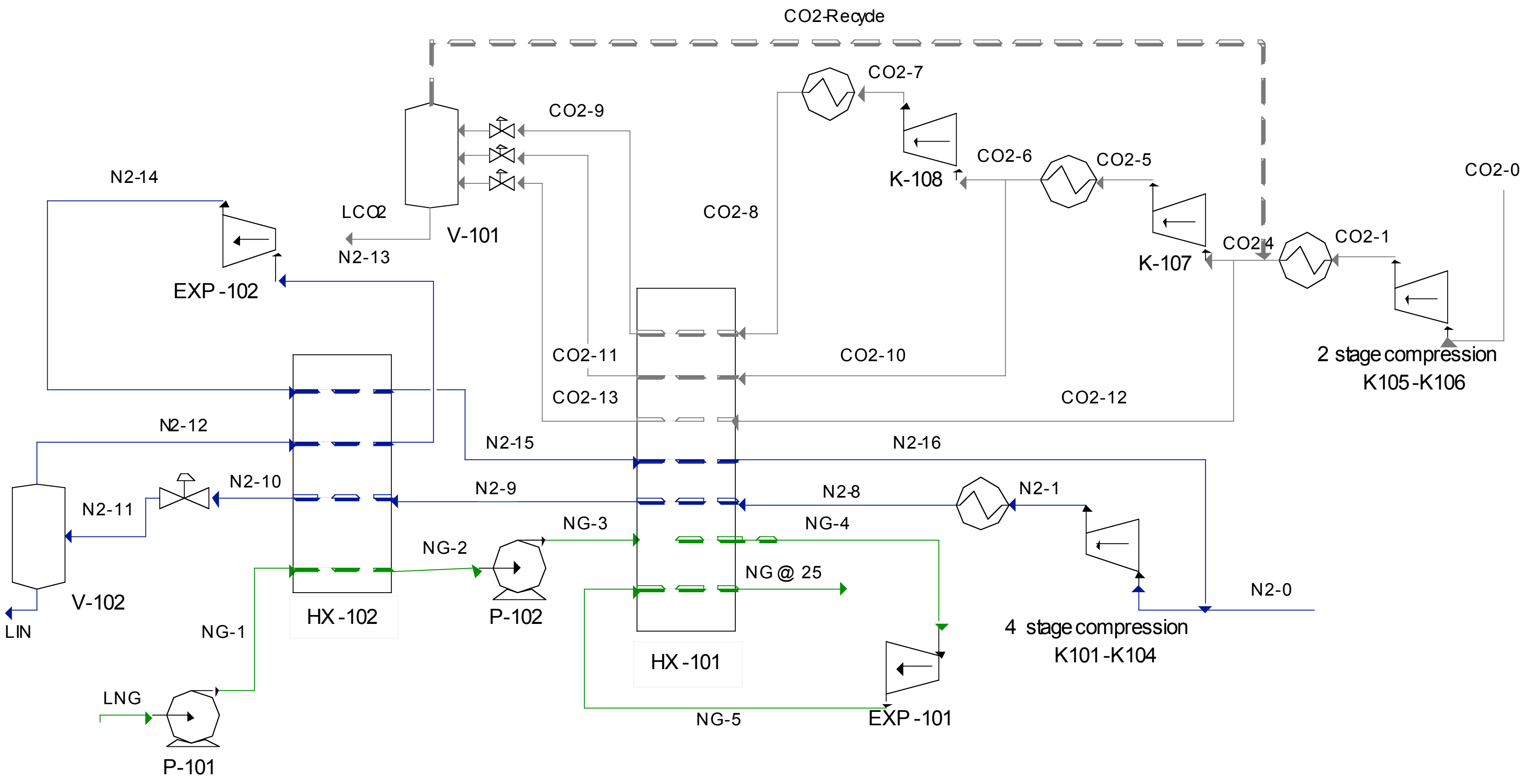
Side



Cross section



Onshore Process



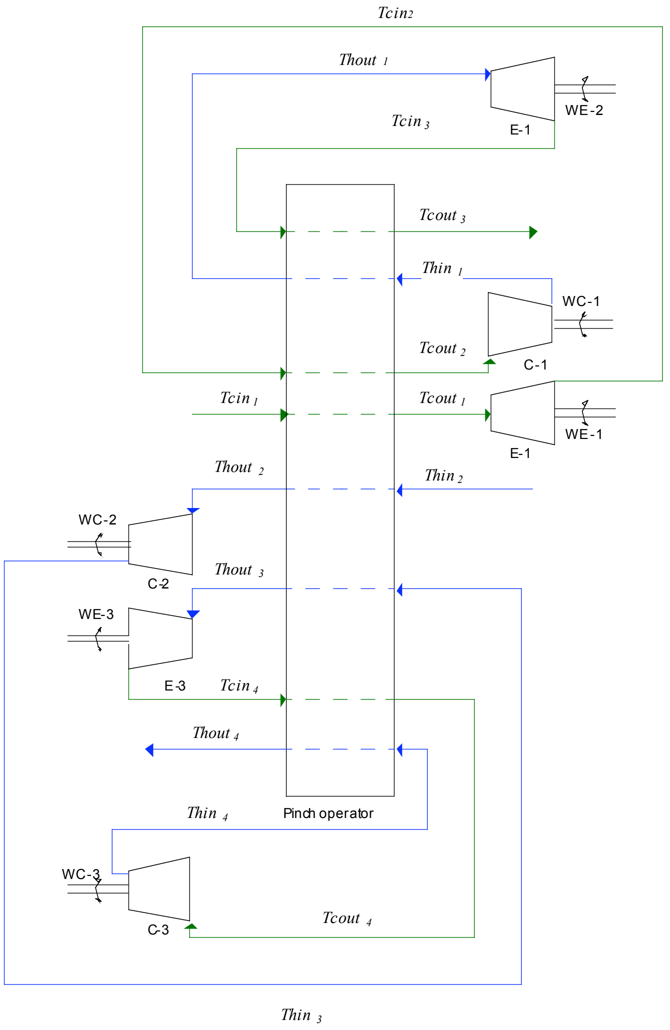
The ExPAnD Methodology

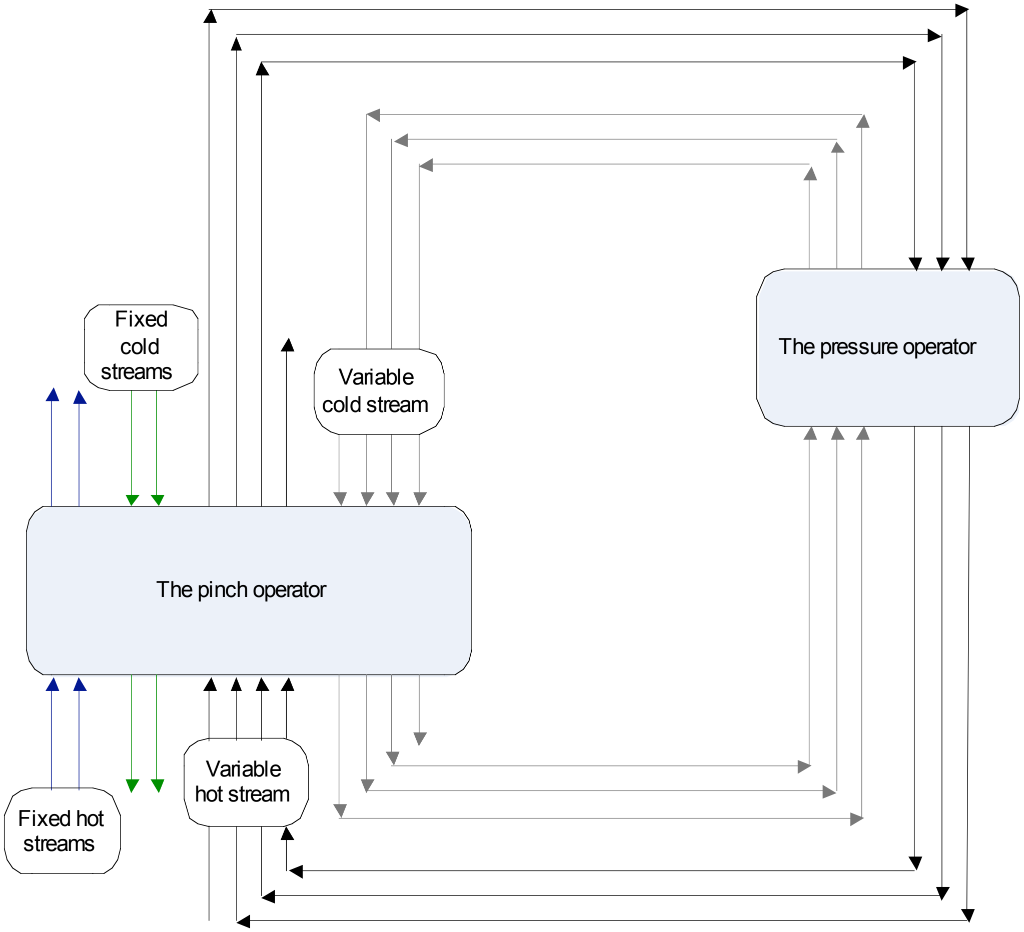
(Extended Pinch Analysis and Design)

- Combines Pinch Analysis (PA), Exergy Analysis (EA) and Optimization/ Math Programming (OP)
  - PA for minimizing external Heating and Cooling
  - EA for minimizing Irreversibilities (thermodynamic losses)
  - OP for minimizing Total Annual Cost

- Problem Definition
  - ***"Given a Set of Process Streams with Supply State (Temperature, Pressure and the resulting Phase) and a Target State, as well as Utilities for Heating and Cooling, Design a System of Heat Exchangers, Expanders and Compressors in such a way that the Irreversibilities (or alternatively, utility- or total annual costs) are minimized."***

The ExPAnD Methodology




Fixed cold streams

Variable cold stream

The pressure operator

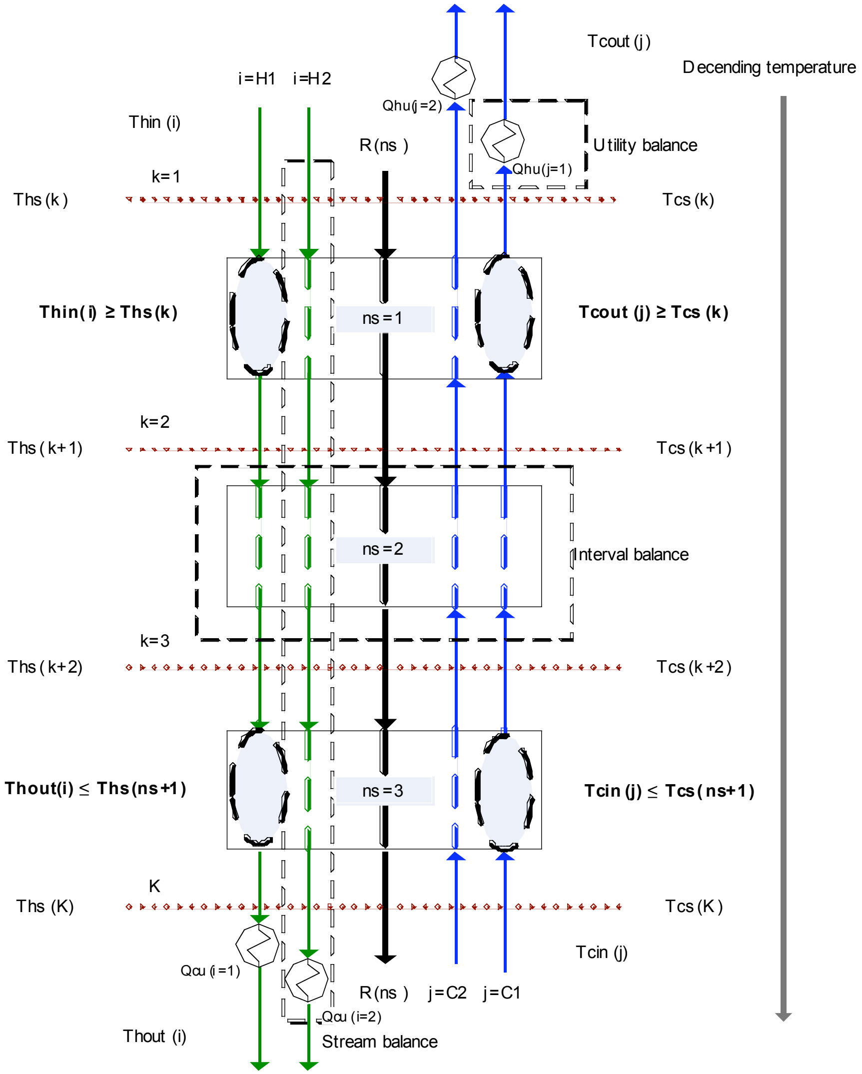
The pinch operator

Fixed hot streams

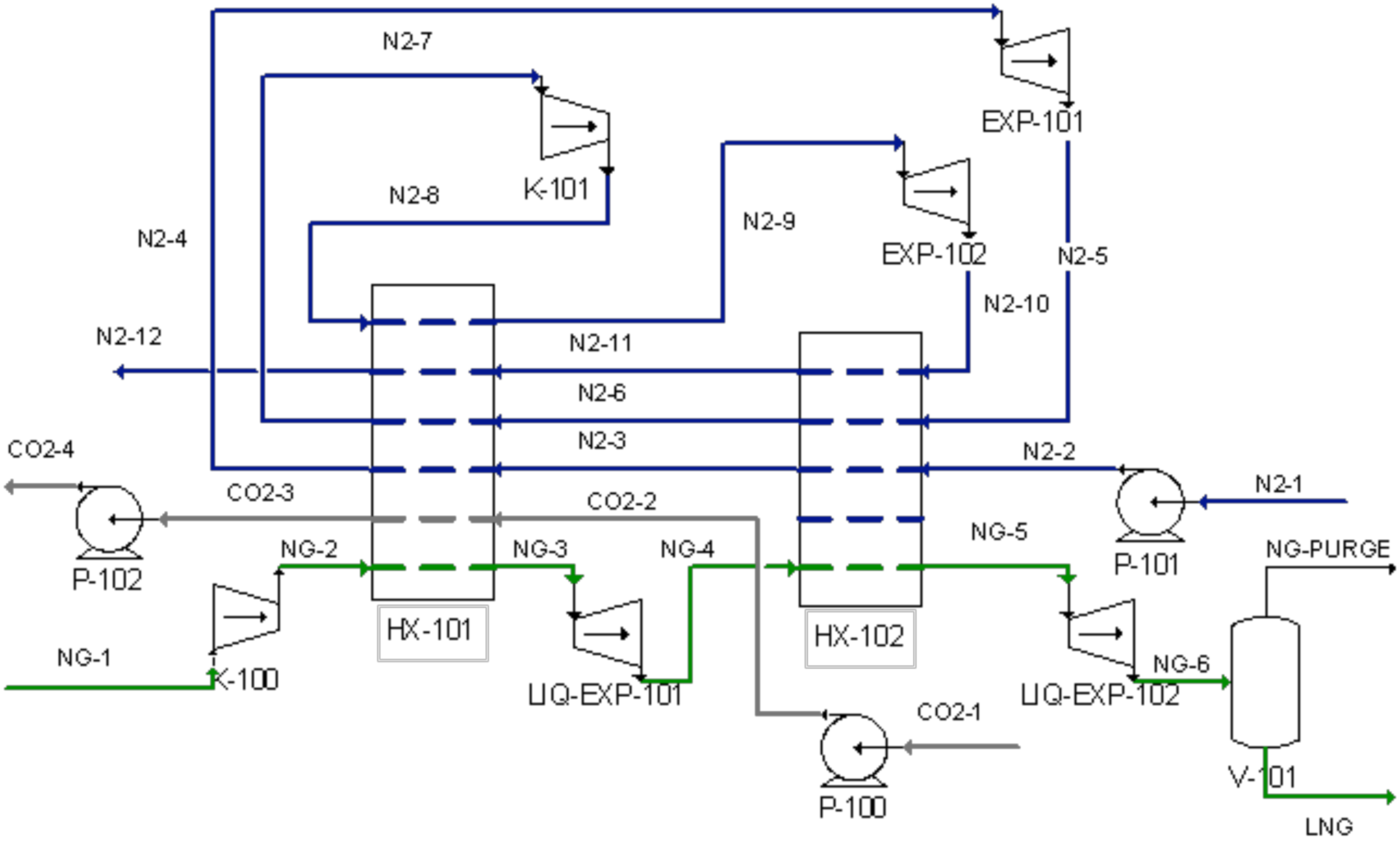
Variable hot stream

The ExPAnD Methodology

- Manipulation of the pressure for the process streams in a heat exchanger network may reduce the total irreversibilities
- The optimization formulation can suggest a reasonable initial design for realistic problems

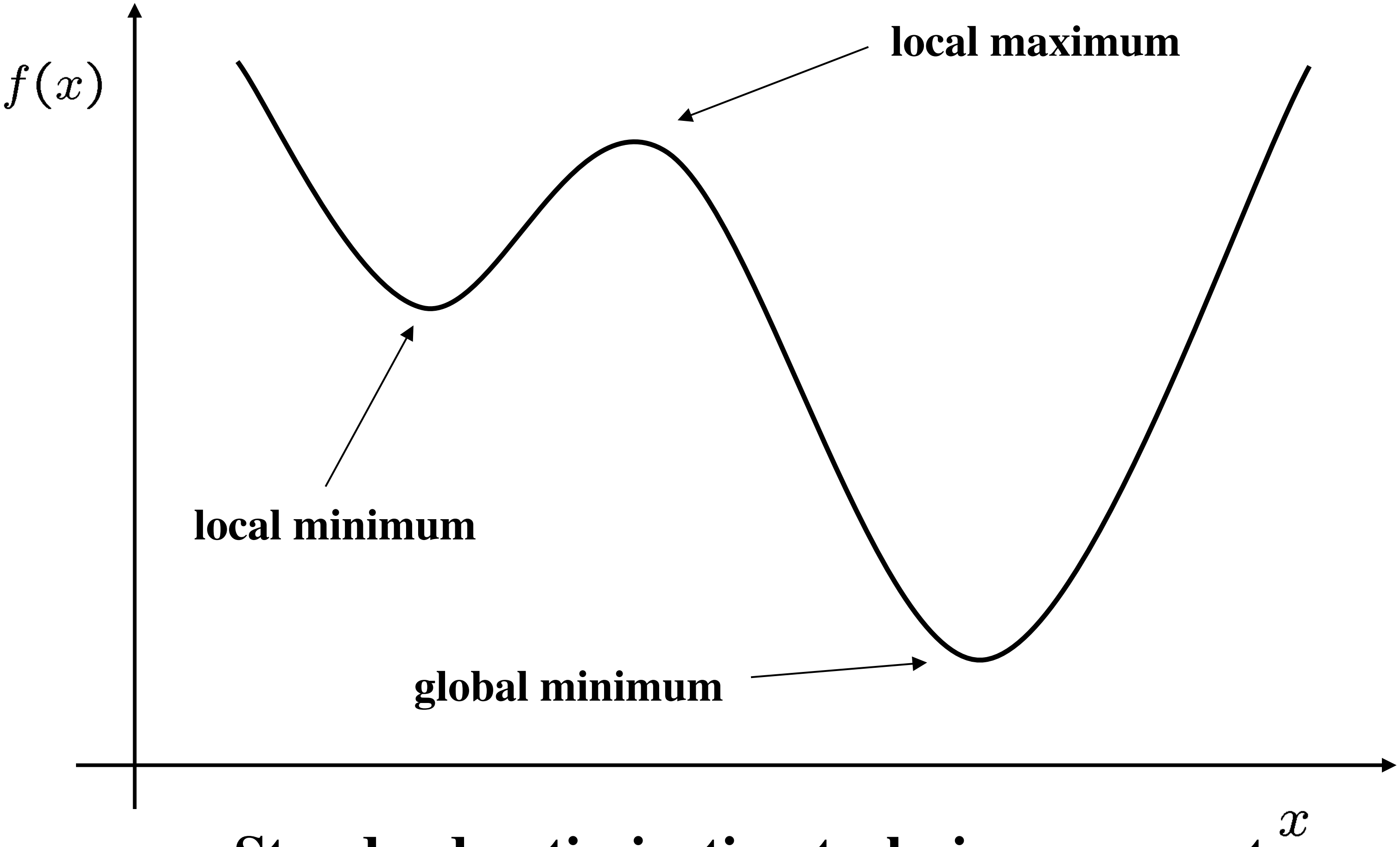


Offshore Process



Global Optimization of Algorithms

Nonconvex Optimization



Standard optimization techniques cannot distinguish between suboptimal local minima

Motivation

- Global optimization of large nonconvex NLPs (MINLPs) with special structure:

$$\min_{(\mathbf{x},\mathbf{y})\in\mathbb{R}^n} \quad f(\mathbf{x},\mathbf{y})$$

$$\mathbf{g}(\mathbf{x},\mathbf{y})\leq\mathbf{0}$$

$$h_i(\mathbf{x},\mathbf{y})=0,\ \ i=1\ldots m$$

$$\mathbf{x}\in\mathbb{X}\subset\mathbb{R}^{n-m},\ \ \mathbf{y}\in\mathbb{Y}\subset\mathbb{R}^m$$

- Consider a partition of decision variables **w** as (**x**,**y**)
- The system of equations in **y** given a $\hat{\mathbf{x}}\in\mathbb{X}$

$$h_i(\hat{\mathbf{x}},\mathbf{y})=0,\ \ i=1\ldots m$$

Motivation

- Assume that system of equations has special features
  - System can be solved for $\forall \hat{\mathbf{x}} \in \mathbb{X}$
  - A non-iterative algorithm for solution is possible
- Mathematical programs where objective function and constraints are *algorithms*

$$\min_{\mathbf{x} \in \mathbb{R}^{n-m}} \quad f(\mathbf{x}, \mathbf{y}(\mathbf{x}))$$

$$\mathbf{g}(\mathbf{x}, \mathbf{y}(\mathbf{x})) \leq \mathbf{0}$$

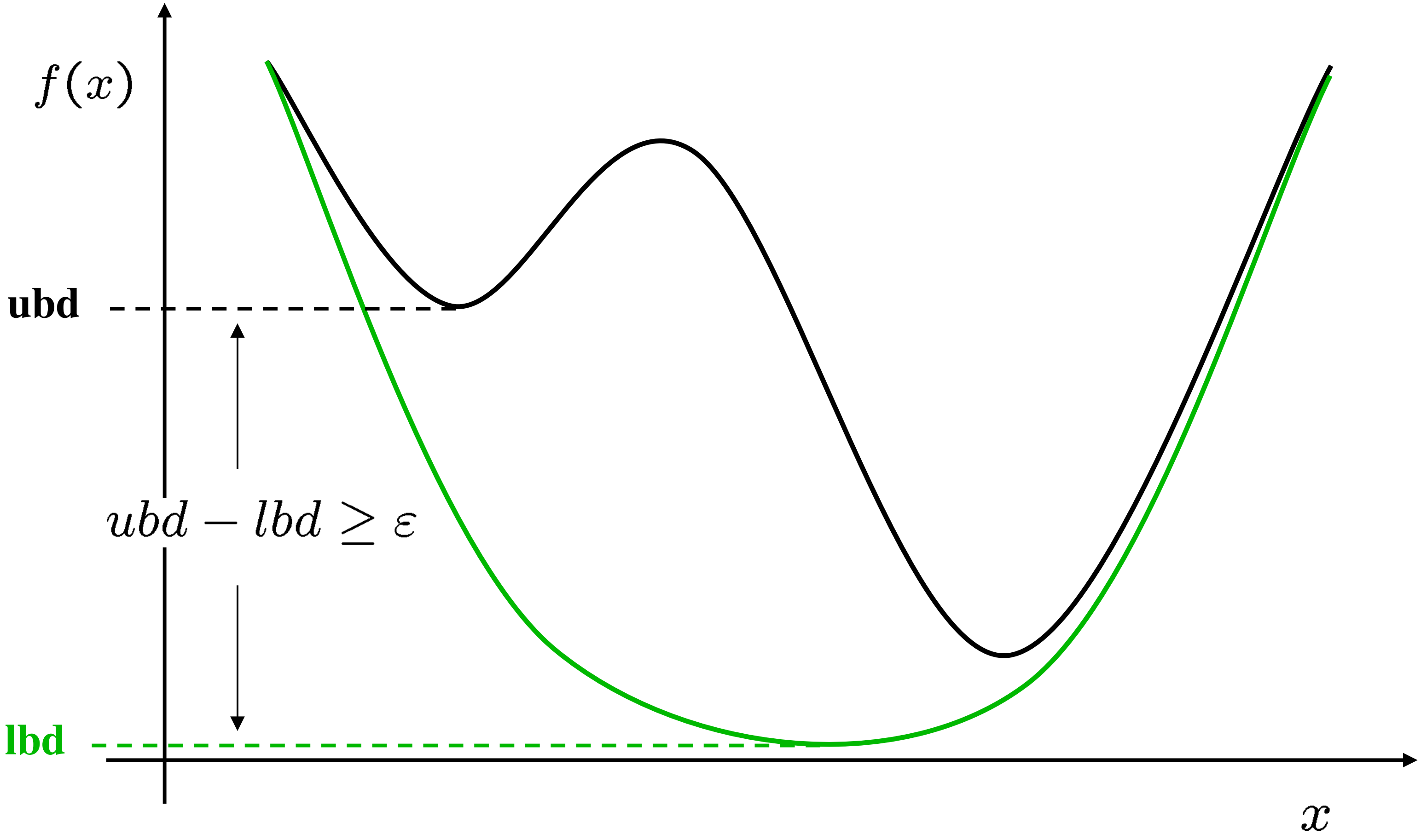
$$\mathbf{x} \in \mathbb{X} \subset \mathbb{R}^{n-m}$$

- Advantageous when *n* and *m* are large but *n-m* is small
  - Global optimization algorithms have worse-case exponential run-time in number of variables
  - Systems which have few inputs and outputs but a large number of internal states
    - » Chemical unit operations, biological systems, networks

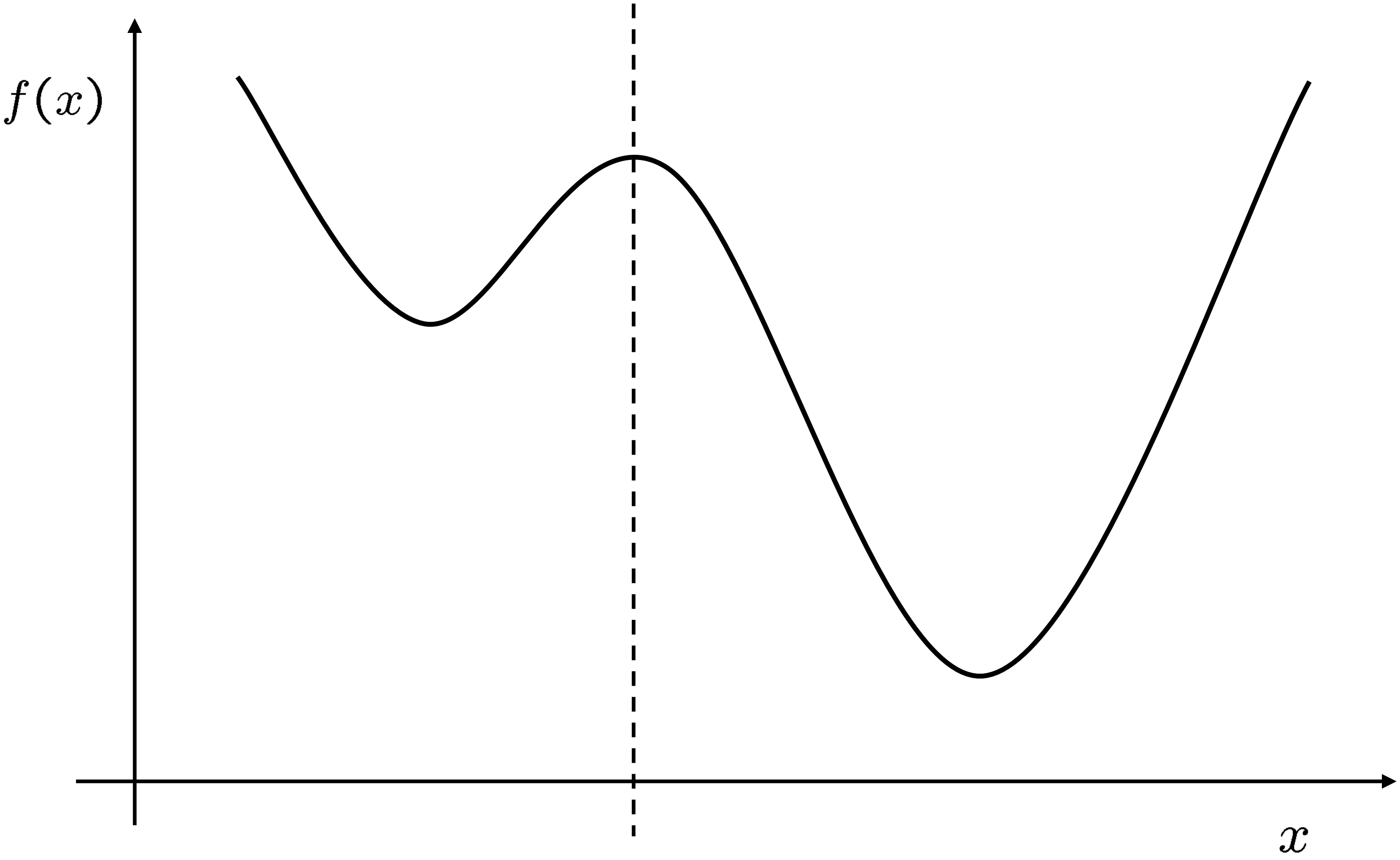
Motivation

- *Algorithms* in this context:
  - Arbitrary complex calculation sequences as long as each step is factorable and relaxations/subgradients/derivatives are available
  - Non-iterative procedures: NO if-then-else statements and conditional loops (at present)
  - Computer evaluated functions
- Global optimization of NLPs/MINLPs using Branch & Bound – solve a sequence of subproblems to bound the solution value
  - Need a lower bounding procedure to bound such computer evaluated functions
  - An upper bounding approach
- A *reduced-space global optimization method*

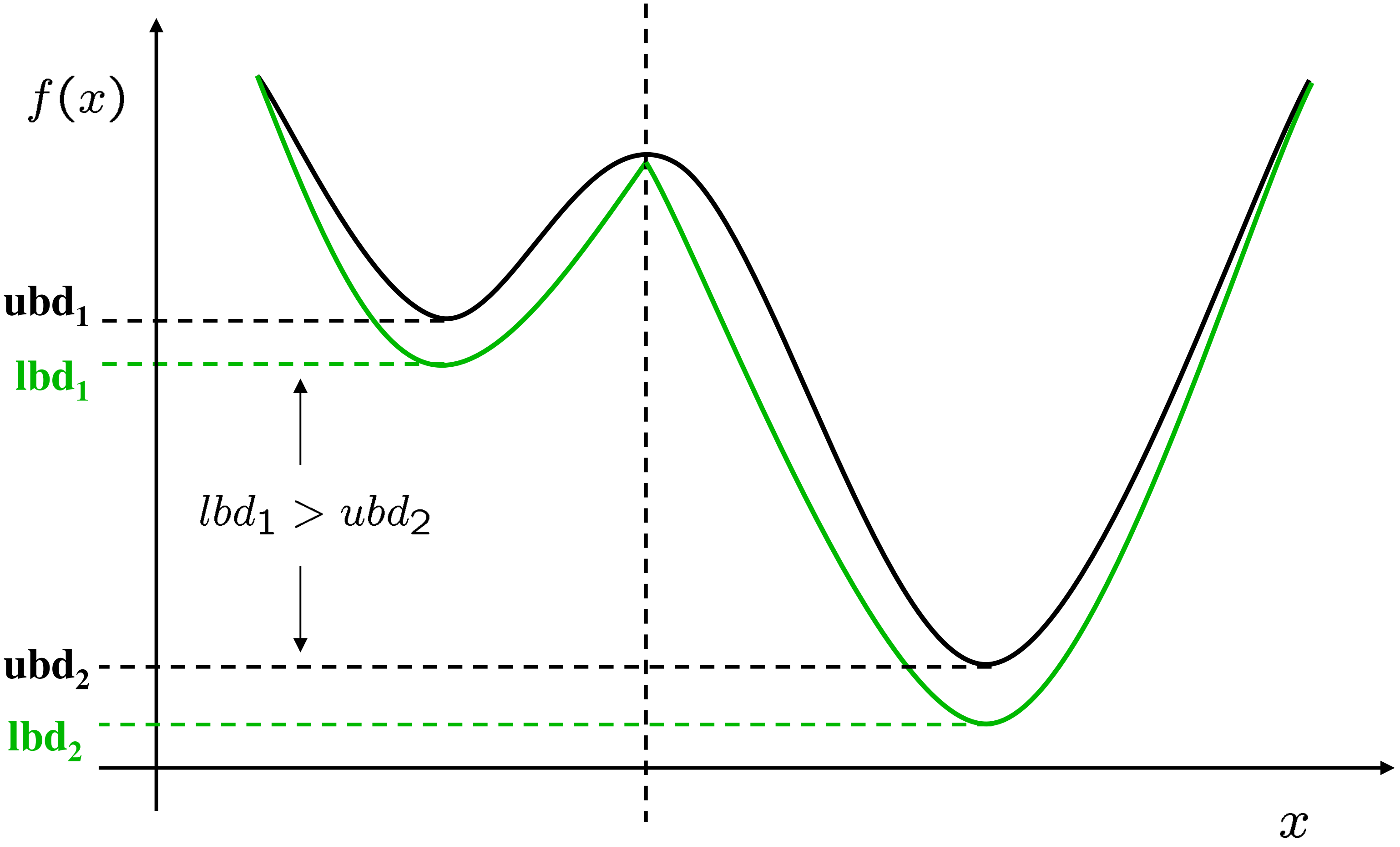
Convex Relaxation



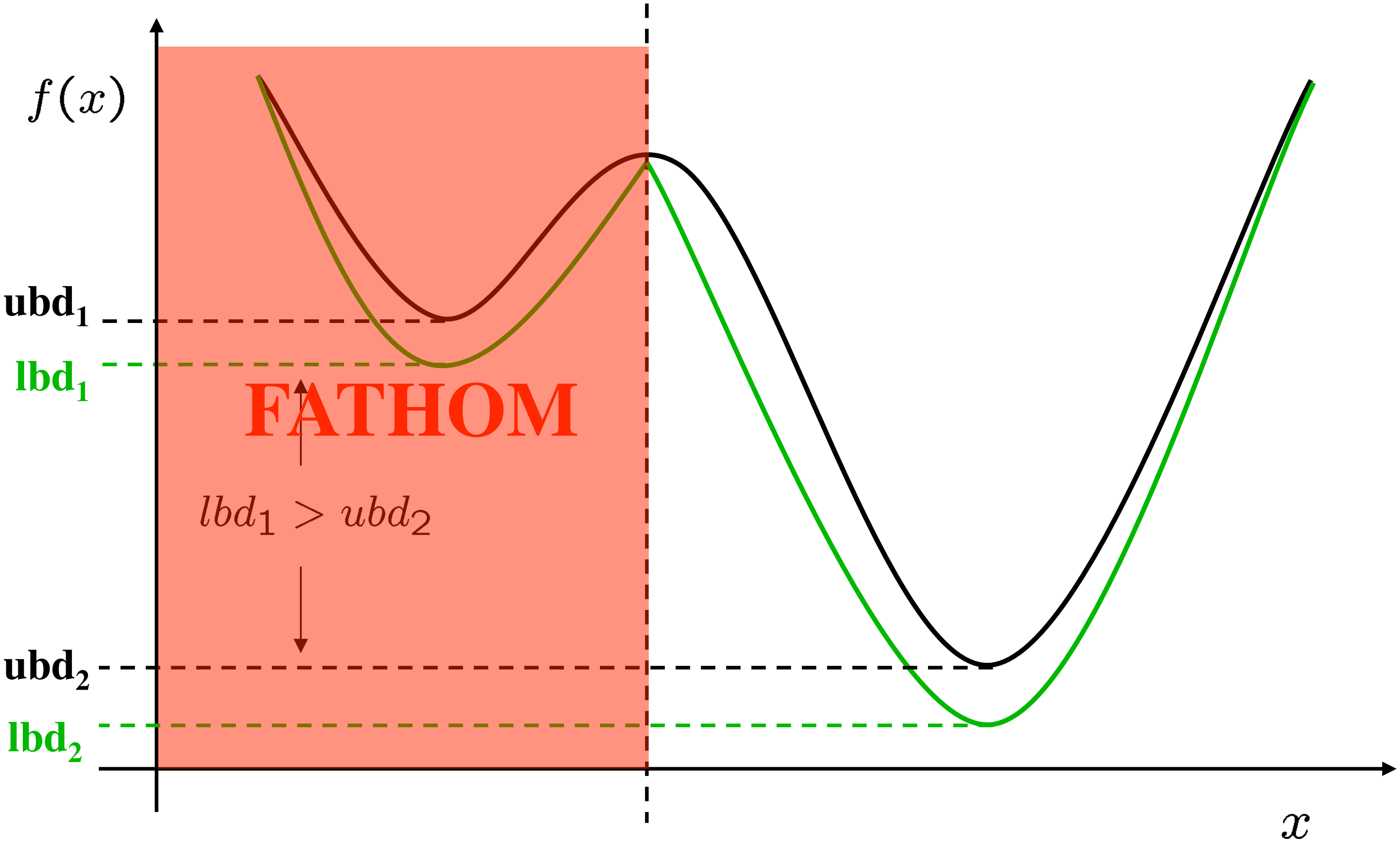
Branch



Branch, Bound



Branch, Bound, and Fathom



McCormick Relaxation of Algorithms

- Computer procedure for evaluating factorable functions
  - Each step is an elementary operation
  - Propagate convex underestimators, concave overestimators and corresponding subgradients for each elementary operation
    - Known intrinsic convex/concave envelopes
    - McCormick composition theorem
    - Rules for binary and unary operations
- Combine with ideas from automatic differentiation (AD)[1]
  - Operator overloading (simpler but slower)
  - Source code transformation (quite complicated but faster)
- Implemented in libMC[2]
  - Using operator and function overloading in C++
  - Use an object having fields to store necessary values: over- and under- estimators, corresponding subgradients
  - Overload intrinsic functions - known envelopes
  - Propagate bounds using interval arithmetic
  - Propagate convex/concave relaxations and subgradients

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[1] *Alexander Mitsos, Benoit Chachuat, Paul I. Barton. "McCormick-Based Relaxation of Algorithms." In press: SIAM Journal on Optimization, 2008*

[2] *Benoit Chachuat. "libMC: A numeric library for McCormick relaxation of factorable functions." http://yoric.mit.edu/libMC, 2008.*

Lower Bounding Approach

- Use libMC to generate relaxations
- Relaxations produced by McCormick theory may be not be differentiable
  - Nonsmooth convex lower bounding program
- Nonsmooth bundle method can be used directly
  - However, slow convergence and non-robust implementations
- Instead use bundle method as a linearization heuristic to generate LP relaxations
  - LP methods are reliable and guarantee an “answer”

Application to Gas Networks

- Production infrastructure model[1] - nonconvex NLP
    - 759 variables with 663 equality constraints
    - Only 96 variables in the reduced problem in the most optimistic scenario
- Hide internal network variables from the optimizer
    - Internal node pressures, arc volumetric and species molar flowrates, facility states
- Fast calculation in sequential mode while traversing the network
    - Source to sink calculation
    - Non-iterative
- Incorporate all equality constraints into calculation procedure

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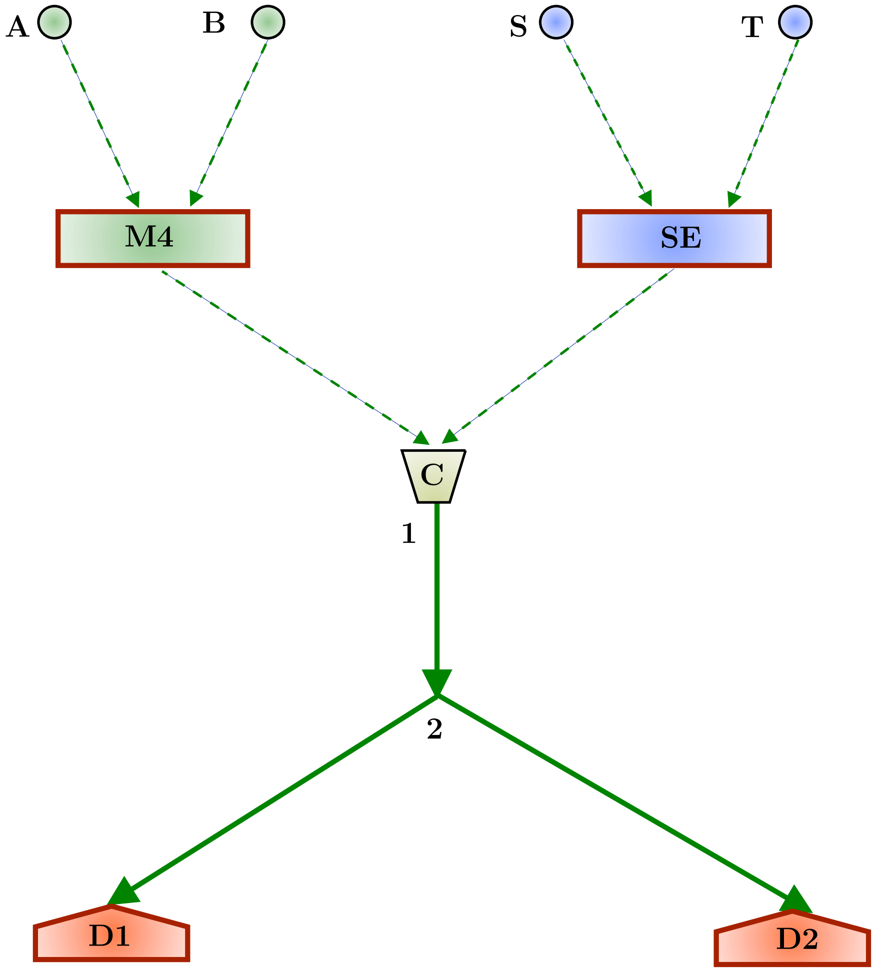
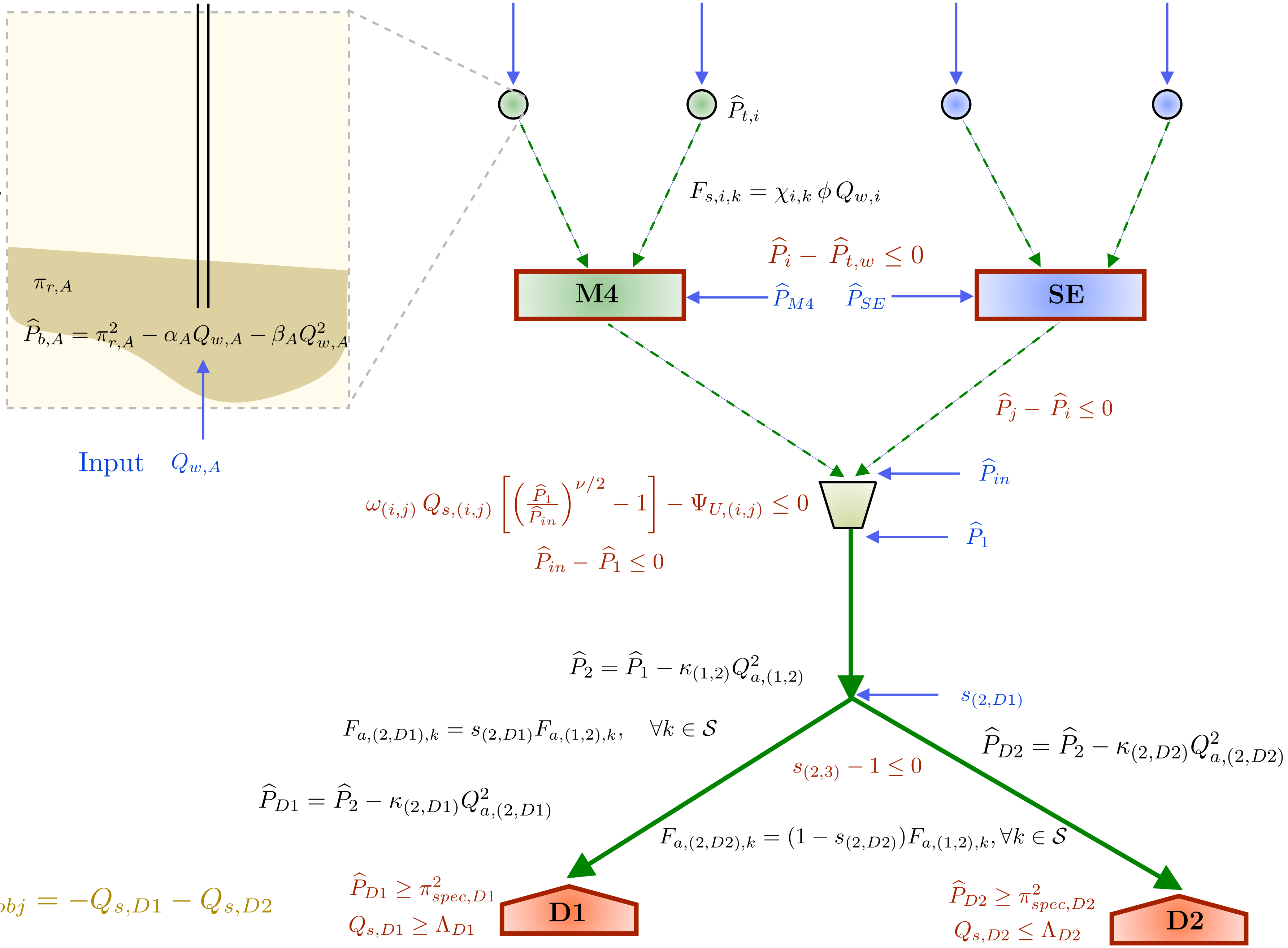
1. Ajay Selot, L.K. Kuok, M. Robinson, T.L. Mason, Paul I. Barton. "A short-term operational planning model for natural gas production systems." AIChE Journal,54(2):495-515, 2008.

Calculation Sequence

- Three types of variables:
  - *Input variables* – Production-rate at wells, selected pressures, split fractions
    - Manipulated by optimizer
  - *Internal Variables* - Network state variables
  - *Output variables* – Objective function and constraints, e.g., delivery amount and pressure, qualities
- Apply a transformation on pressure variables:

$$\hat{P} = P^2$$





$\widehat{P}_{t,A} = \frac{1}{\lambda_A}(\widehat{P}_{b,A} - \vartheta_A Q^2_{w,A})$

$Q_{w,A}$ $Q_{w,B}$ $Q_{w,S}$ $Q_{w,T}$

$\widehat{P}_{t,i}$

$F_{s,i,k} = \chi_{i,k}\,\phi\,Q_{w,i}$

$\pi_{r,A}$

$\widehat{P}_{b,A} = \pi^2_{r,A} - \alpha_A Q_{w,A} - \beta_A Q^2_{w,A}$

Input $Q_{w,A}$

$\widehat{P}_i - \widehat{P}_{t,w} \leq 0$

M4 $\widehat{P}_{M4}$ $\widehat{P}_{SE}$ **SE**

$\widehat{P}_j - \widehat{P}_i \leq 0$

$\widehat{P}_{in}$

$\omega_{(i,j)}\,Q_{s,(i,j)}\left[\left(\frac{\widehat{P}_1}{\widehat{P}_{in}}\right)^{\nu/2} - 1\right] - \Psi_{U,(i,j)} \leq 0$

$\widehat{P}_1$

$\widehat{P}_{in} - \widehat{P}_1 \leq 0$

$\widehat{P}_2 = \widehat{P}_1 - \kappa_{(1,2)} Q^2_{a,(1,2)}$

$s_{(2,D1)}$

$F_{a,(2,D1),k} = s_{(2,D1)} F_{a,(1,2),k}, \quad \forall k \in \mathcal{S}$

$\widehat{P}_{D2} = \widehat{P}_2 - \kappa_{(2,D2)} Q^2_{a,(2,D2)}$

$s_{(2,3)} - 1 \leq 0$

$\widehat{P}_{D1} = \widehat{P}_2 - \kappa_{(2,D1)} Q^2_{a,(2,D1)}$

$F_{a,(2,D2),k} = (1 - s_{(2,D2)}) F_{a,(1,2),k}, \forall k \in \mathcal{S}$

$f_{obj} = -Q_{s,D1} - Q_{s,D2}$

$\widehat{P}_{D1} \geq \pi^2_{spec,D1}$

$Q_{s,D1} \geq \Lambda_{D1}$

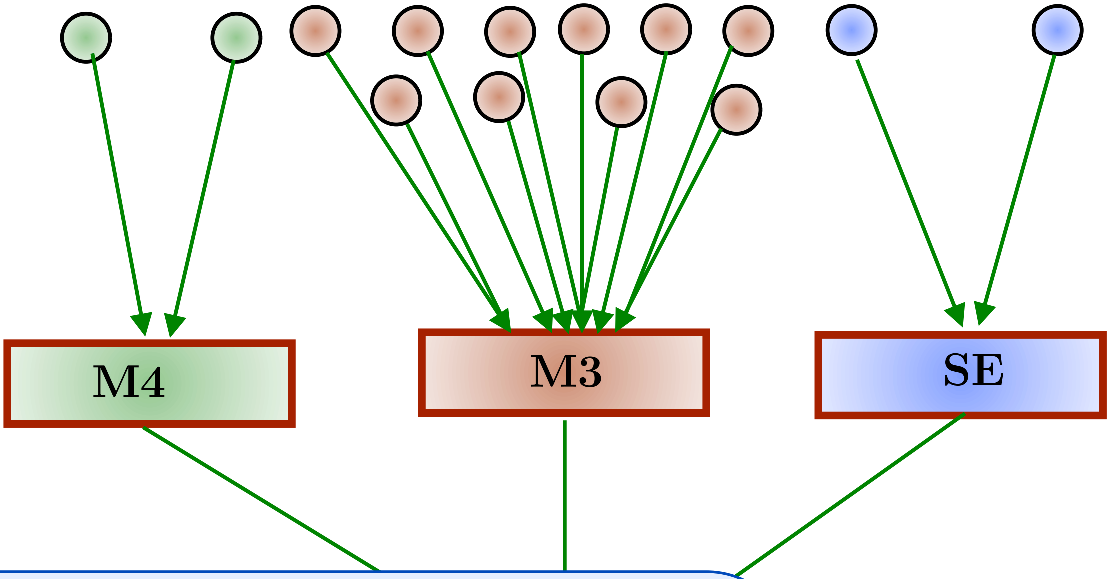
D1

$\widehat{P}_{D2} \geq \pi^2_{spec,D2}$

$Q_{s,D2} \leq \Lambda_{D2}$

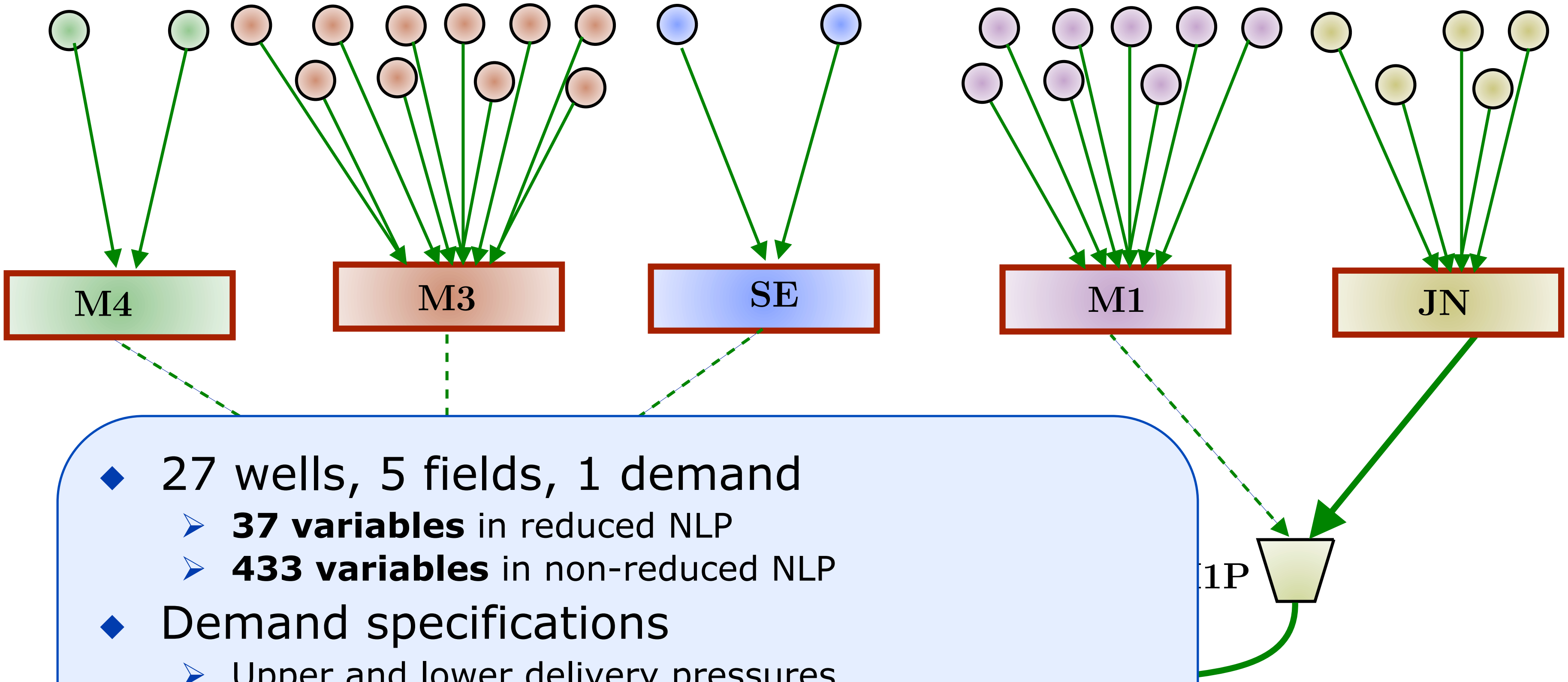
D2

Case Study A



- 14 wells, 3 fields, 1 demand
  - **19 variables** in reduced NLP
  - **~219 variables** in non-reduced NLP
- Demand specifications
  - Upper and lower delivery pressures
- Solved to 2% relative gap in **12 CPUs**
- 30.42 million m^3 per day of delivery

Case Study B



- 27 wells, 5 fields, 1 demand
  - **37 variables** in reduced NLP
  - **433 variables** in non-reduced NLP
- Demand specifications
  - Upper and lower delivery pressures
  - H_2S, CO_2 quality
- Solved to 3% relative gap in **3,208 CPUs**
- 73.83 million m^3 per day of delivery

Concluding Thoughts

- Natural gas will continue to grow in importance in the future
- Optimization-based planning and design tools can lead to systematic decision-making for investors, asset developers and operators
  - Short-term and long-term
- Novel natural gas based processes and value chains will be important for managing carbon outputs in industrial, transportation and power sectors

Acknowledgments

- Dr. Ajay Selot, Audun Aspelund
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- Sarawak Shell Berhad (Malaysia)
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