Integration of Control Structure Synthesis & Plant Design: A *Novel* Plantwide Decomposition

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AIChE National Conference
Indianapolis, IN
Section 254 – Plantwide Control and Optimization

Nov. 5, 2002

Background

- **Age old problem**
  - **Process knowledge & heuristics**
  - **Design hierarchy**
  - **Optimization + Control Theoretic Methods**
- **Early pioneering work**
  - **Dupont: P. Buckley (1964), J. Shunta (1981)**
  - **A. Foss (1973)**
  - **Findeisen (1979)**
- ***Some* recent approaches**
  - **Luyben & co-workers: 9 systematic steps**
  - **Morari & co-workers: Decomposition, control: optimization + regulation**
  - **Shinnar & co-workers: Partial control economy**
  - **Stephanopoulos & co-workers: Hierarchical representation + MMC**
  - **Skogestad & co-workers: Self-Optimizing control methodology**
  - **Douglas & co-workers : Controllability index**
- ***And* many, many more valuable contributions**

- Tennessee Eastman Challenge Problem
  - ***At least* 10 different solutions**

"… researchers have chosen different control objectives.

Hence, it is not surprising that [these] studies … yielded different [plantwide] control structures. "

"The 'best' control structure for a plant depends on the design and control criteria established [for it]."

– Luyben et al 1999.

Hierarchical Structures

Increasing Model Complexity

- **Process Design Hierarchy**
  - **Level 1**
    - **Batch vs. Continuous**
  - **Level 2**
    - **Input-output structure**
  - **Level 3**
    - **Recycle Structure**
  - **Level 4**
    - **Separation System**
  - **Level 5**
    - **Heat Integration**

Steady State Models

Flowsheet the most economical

(Douglas 1988)

Increasing Model Complexity

weeks

secs

- **Control Structure Hierarchy**
  - **Level 0 (ss)**
    - **Site wide Optimization (wks)**
  - **Level 1 (ss)**
    - **Plant Optimization (days)**
  - **Level 2 (Dynamic)**
    - **Advanced Process Control (hours)**
  - **Level 3 (Dynamic)**
    - **Regulation (min. or sec.)**
      - **Controller type**
      - **Controller configuration**

Steady State & Dynamic models

(Morari 1980, Skogestad 2001)

Contribution

Yet Another **Approach**

- **Decision-Making Method**
  - ***Analytical Hierarchical Process (Saaty, 1982)***
    - **Select and assess a particular flowsheet decomposition (modules)**
      - **Basis: design objectives and operational constraints**
    - **Prioritize among the objectives systematically & consistently**
    - **Prioritize among control objectives consistently**
    - **Select among competing alternatives**

  - **Controller**
    - **Level 1: Active control constraints**
    - **Level 2: Advanced Process Control**
    - **Level 3: Regulatory Control**

Modified Analytic Hierarchical Process (AHP)

- **Decision making process**
  - **Ranks the relative importance of “inputs” and “states”**
  - **Accounts for interactions among the states**

- **Module “States”**
  - **Design/operations/control objectives: important/relevant**
  - **Both implicit and explicit**

- **Module “Inputs”**
  - **Expected disturbances**
  - **Crosses the boundary of the module**

Decomposition

- **Function of design objectives & operational constraints**
  - **Unit operations are candidate modules**
  - **Neighboring unit operations that relate to the objectives**
  - ***Similar* neighboring modules**
- **Steady state sensitivity assessment**
  - **Disturbance effects on the design objectives and operational constraints**
- **Evaluate the quality of the module**
  - **AHP**
    - **Achieves the relevant design objectives and operational constraints**
  - **Simulation**
    - **Attenuate disturbances, interactions**
  - **Compare alternative modules**

Development

Assume a Steady State Flowsheet has been provided for the plant.

- **Identify**
  - **design objectives (production rate, quality, etc.)**
  - **operational constraints (min reactor inlet temp, pressure, etc.)**
- **Decompose the process flowsheet into modules**
  - ***Horizontal* decomposition of the plant (Morari, 1980)**
  - **Module**
    - **Identify all potential alternatives**
    - **Determine the relevant design/operational objectives**
    - **Develop steady state models**
- **Identify "States" and "Inputs" of the module**
  - **States**
    - **Explicit objectives**
    - **Implicit objectives translated into process variables (Ng & Stephanopoulos, 2001)**
  - **Inputs: expected disturbances**

Development (*cont.*)

- **Identify the most promising modules**
  - **Constraints**
  - **Steady state sensitivity as a function of the expected disturbances**
  - **AHP**
    - **Select between alternative modules**
    - **Prioritize consistently among objectives (states and inputs)**
- **Develop the control structure for the individual modules**
  - **Identify control degrees of freedom (cDoF)**
  - **Address variables with no steady state effects**
    - **integrating modes**
  - **Determine active control constraints (*acc*)**
- **An *acc: state* in the AHP**
  - **Remove *acc***
  - **Redo the AHP**
  - **Repeat the analysis**

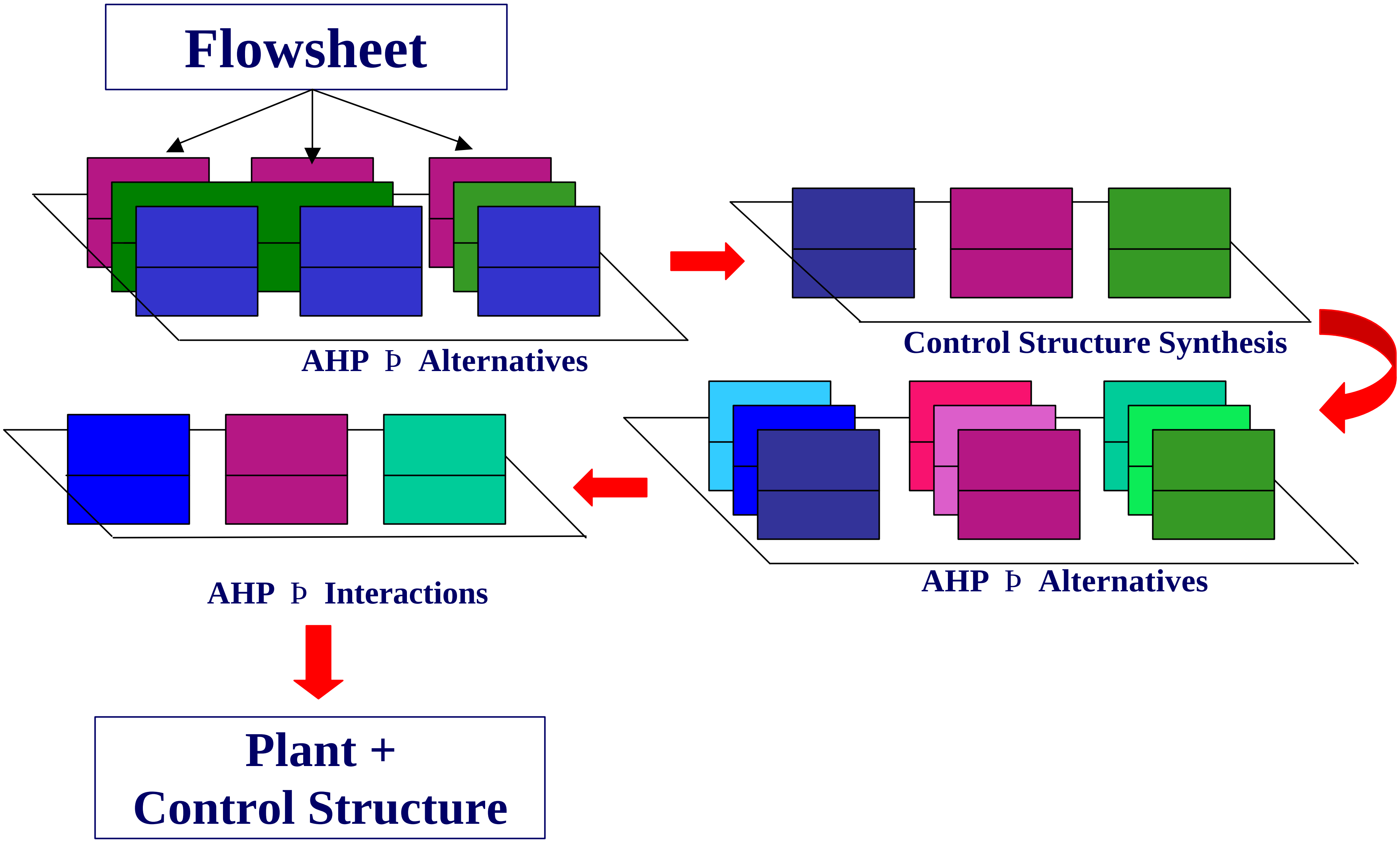
Development (*cont.*)

- **Develop dynamic models of the modules**
  - Employ necessary complexity
    - Behavioral, structural, logical, mathematical (ODE's or PDE's)
  - Identify dynamic "states" for the module
  - Disturbance sensitivity analysis
- **Apply control-theoretic measures**
  - Structural controllability
  - Structural observability, etc.
- **Engineering Principles & Heuristics**
- **Construct control structure**
  - Decide on controller tasks to meet the goals
  - Select control strategy
    - Type, configuration
- **Simulate dynamic module + control structure**

Development (*cont.*)

- **Combine modules and control structures**
  - **Plant and Control System (PCS)**
- **AHP**
  - **Assess PCS performance**
    - **Disturbances**
    - **Design objectives**
    - **Operational constraints**
- **PCS performance *not* satisfactory**
  - **Select alternative control structures and re-evaluate**
  - **If no alternative control structure is satisfactory**
    - **Iterate on selection of a “module”**

Illustration of the Development



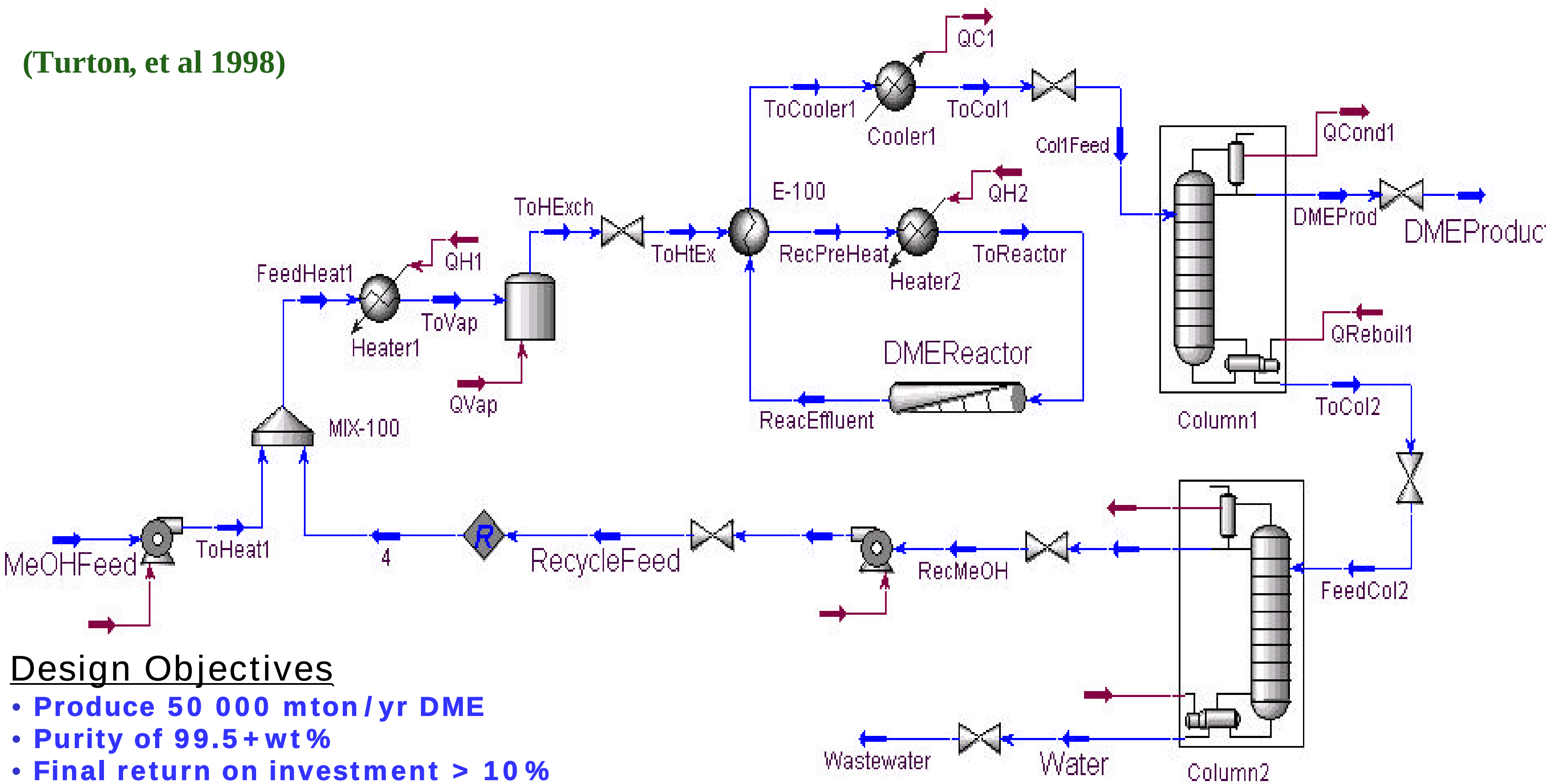
Remarks

- Systematic and hierarchical
- Iterative
  - Module decomposition can be revisited
  - Control structure can be revisited
  - Seeks the "best" performance of the integrated system
- Provides a prioritization
  - Objectives (control, operational, design)
  - Structures (control and decomposition)
  - Alternatives (process flowsheets)

Dimethyl Ether Process Flowsheet

$2MeOH \rightarrow DME + H_2O$

(Turton, et al 1998)



Design Objectives

- **Produce 50 000 mton/yr DME**
- **Purity of 99.5+wt%**
- **Final return on investment > 10%**
- **Methanol single pass conversion of 80%**

DME Process

- **Design Objectives**
  - **50,000 mton/yr dimethyl ether (DME) (production)**
  - **DME product purity of 95 wt% (quality)**
  - **10% return on investment (economics)**
- **Operational Constraints**
  - **80% Methanol Conversion**
  - **Minimum reactor inlet temperature (250°C)**
  - **Maximum reactor outlet temperature (400 °C)**
  - **Methanol in the effluent water stream (200 ppm)**
- **Implicit objective**
  - **Flexibility**

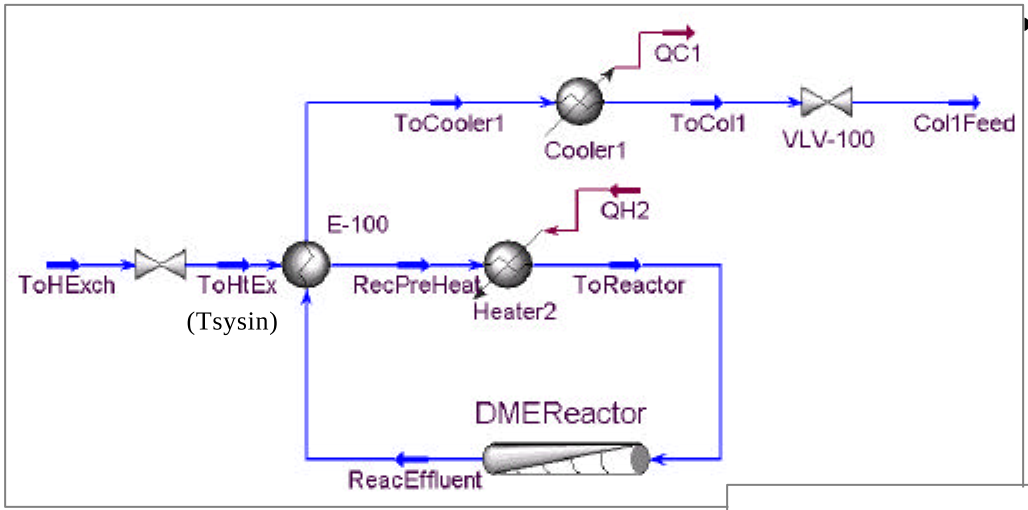
DME Process Flowsheet Decomposition

- **Objective and Constraint assignment**
  - **Process units**
    - **Reactor**
      - production, economics, flexibility, conversion,
      - minimum inlet temperature, maximum outlet temperature
    - **DME Column**
      - production, economics, flexibility, purity
    - **Recycle Column**
      - methanol in water effluent stream, economics, flexibility
  - **Neighboring units**
    - **Reactor**
      - furnace, cooler, process process heat exchanger, evaporator
    - **DME Column**
      - Recycle column, cooler
    - **Recycle Column**
      - DME column
  - **Unassociated units**
    - Recycle pump, Feed Pump, Recycle/Make-up mixer, Feed Pre-heater

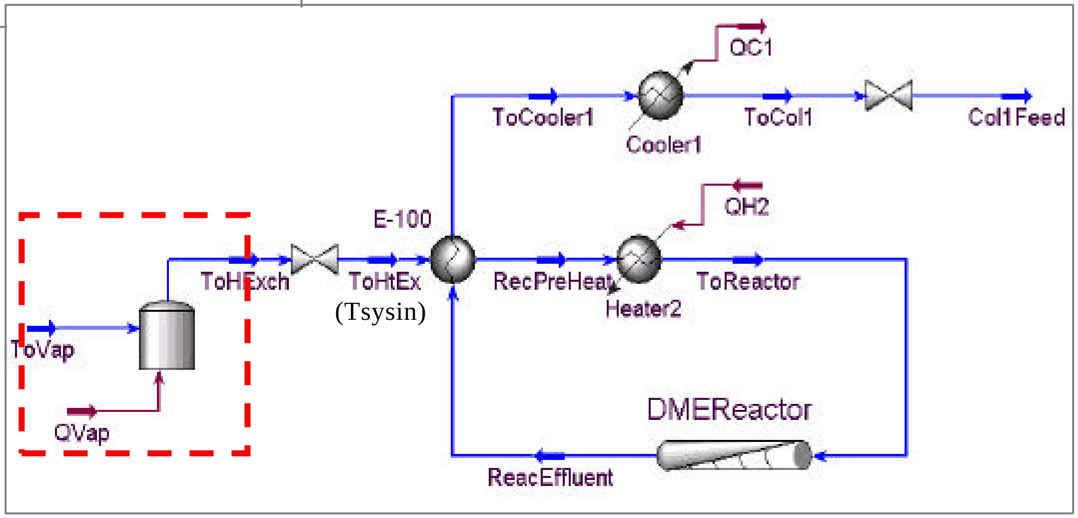
DME Modules

- *Potential* **Modules**
  - **Reactor, FEHE, furnace, cooler**
  - **Reactor, FEHE, evaporator, furnace, cooler**
  - **DME column**
  - **DME column, cooler**
  - **DME column and Recycle column**
  - **DME column, Recycle column, cooler**
  - **Recycle column**
- **Develop steady state models/module**
  - **HYSYS.Plant v2.2**

Reactor Module Selection



- Alternatives
  - AHP to select the best one



Reactor Module Selection by AHP

- Steady state sensitivity results to develop the AHP/module
  - The effect of an "input" on a "state"
    - Valuation scale: 1 £ x £ 9
    - 1 small effect
    - 9 large effect
  - Generate *scaling* matrices
    - For every "input" rank the states relative to one another
    - Scaling philosophy (consistency)
  - SVD (scaling matrices) and original matrix = final weighted AHP
- Compare alternative modules
  - Smallest *state sum* = best module
- Example: Reactor module w/o evaporator = best

Reactor Module Selection by AHP

State: Input Level 1	Flow Chng	Comp Chng	Inlet Temp
Flexibility	2	5	7
Economics	8	6	9
Production	5	5	5

Effect of an Input on a State:

On a scale from 1 to 9, where 9 is a large effect, rate the effect of each ***input*** on the ***state of the module.***

Relative Effect of States for an Input:

For the ***input*** in question, what is its effect on this ***state*** relative to the other ***states?***

Flow Chng Level 2	Flexibility	Economics	Production
Flexibility	1	5	7
Economics	1/5	1	5/7
Production	1/7	7/5	1

AHP Results: Alternative Module Selection

Reactor Mod w/o Evaporator

State: Input Level 0	Flow Chng	Comp Chng	Inlet Temp	CW Temp	Press Fuel
Flexibility (Tsysin)	2.28	4.68	6.55	2.61	0.90
Economics	3.78	2.34	0.23	0.35	1.51
Production	5.55	2.34	0.35	0.17	0.60
Reac. Tin	0.15	0.08	0.12	0.17	1.51
Conversion	0.92	1.25	0.35	0.17	0.30

Reactor Mod with Evaporator

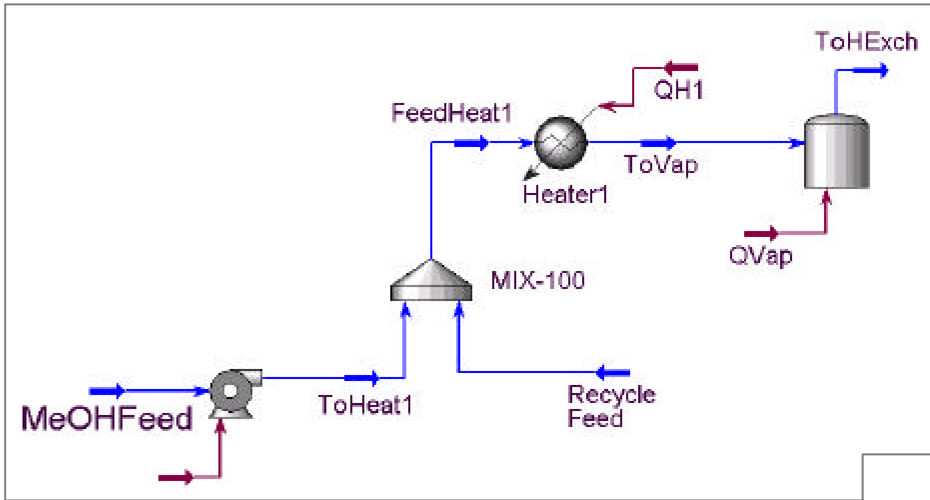
State: Input Level 0	Flow Chng	Comp Chng	Inlet Temp	CW Temp	Press Fuel	Steam Press
Flexibility (Tsysin)	0.17	1.34	4.68	1.18	2.57	0.12
Economics	6.17	4.85	5.35	4.64	0.43	3.47
Production	2.14	2.25	1.86	2.95	0.43	0.50
Reac. Tin	0.34	0.18	0.15	0.15	0.14	0.74
Conversion	1.37	0.72	1.11	1.11	0.14	0.74

Module Comparison	Flexibility	Economics	Production	Reac.Tin	Conversion
Module 1 *	17.0	8.21	9.01	2.03	3.00
Module 2	10.1	24.9	10.0	1.70	5.19

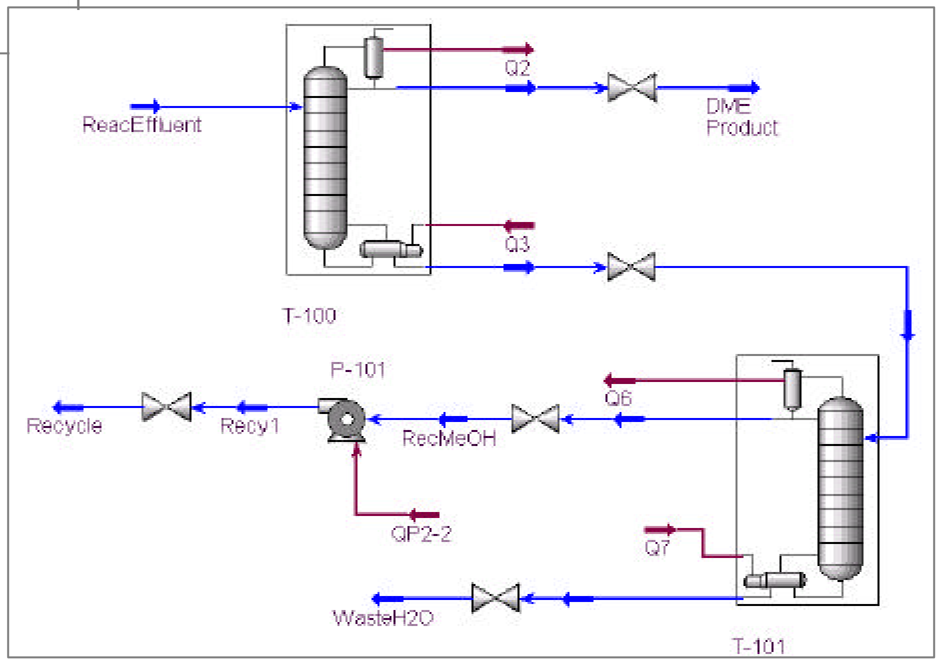
State Sum
39.25
51.89

DME Modular Decomposition

Feed Preparation Module



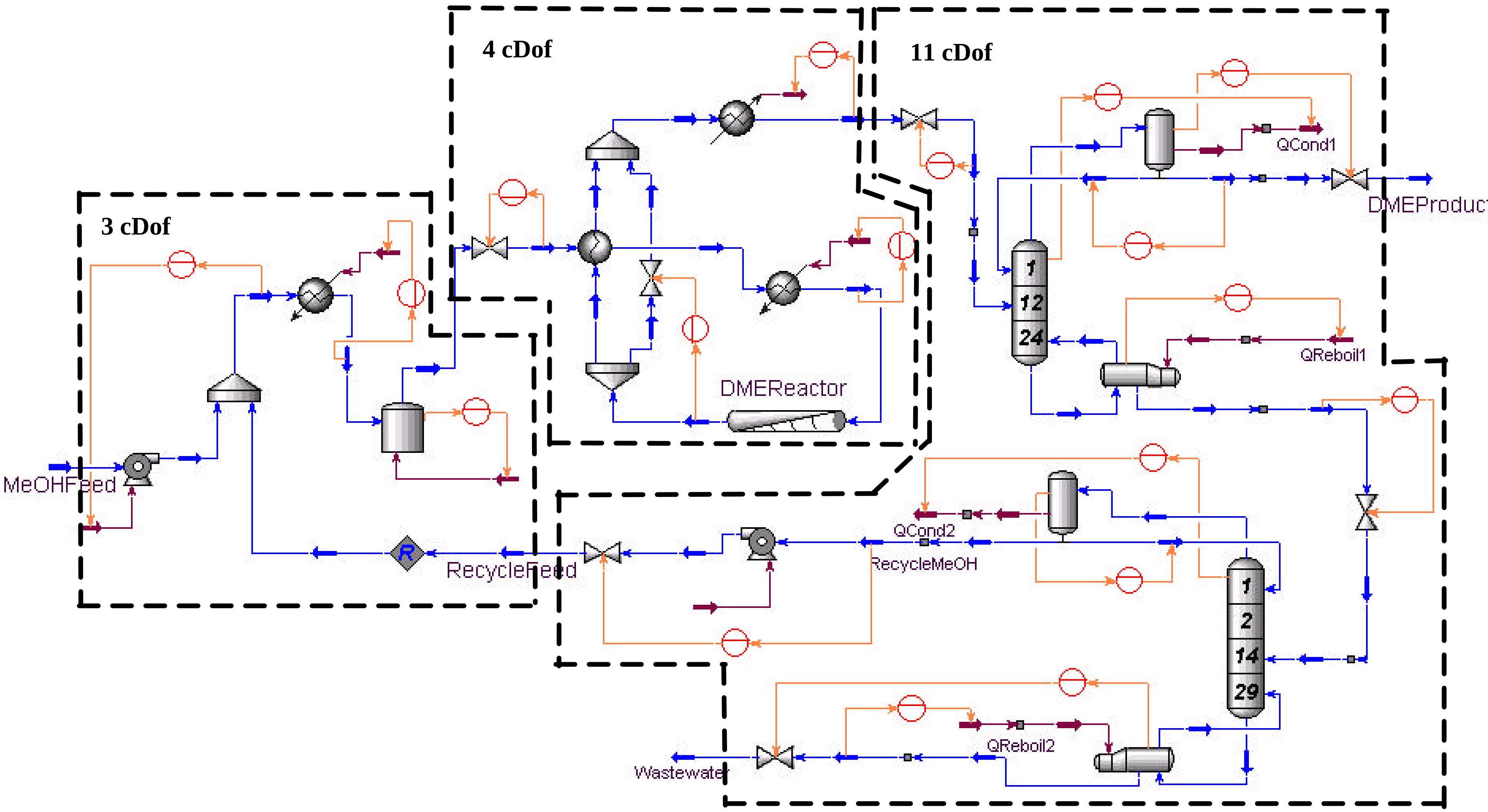
Column Module



Control Structure

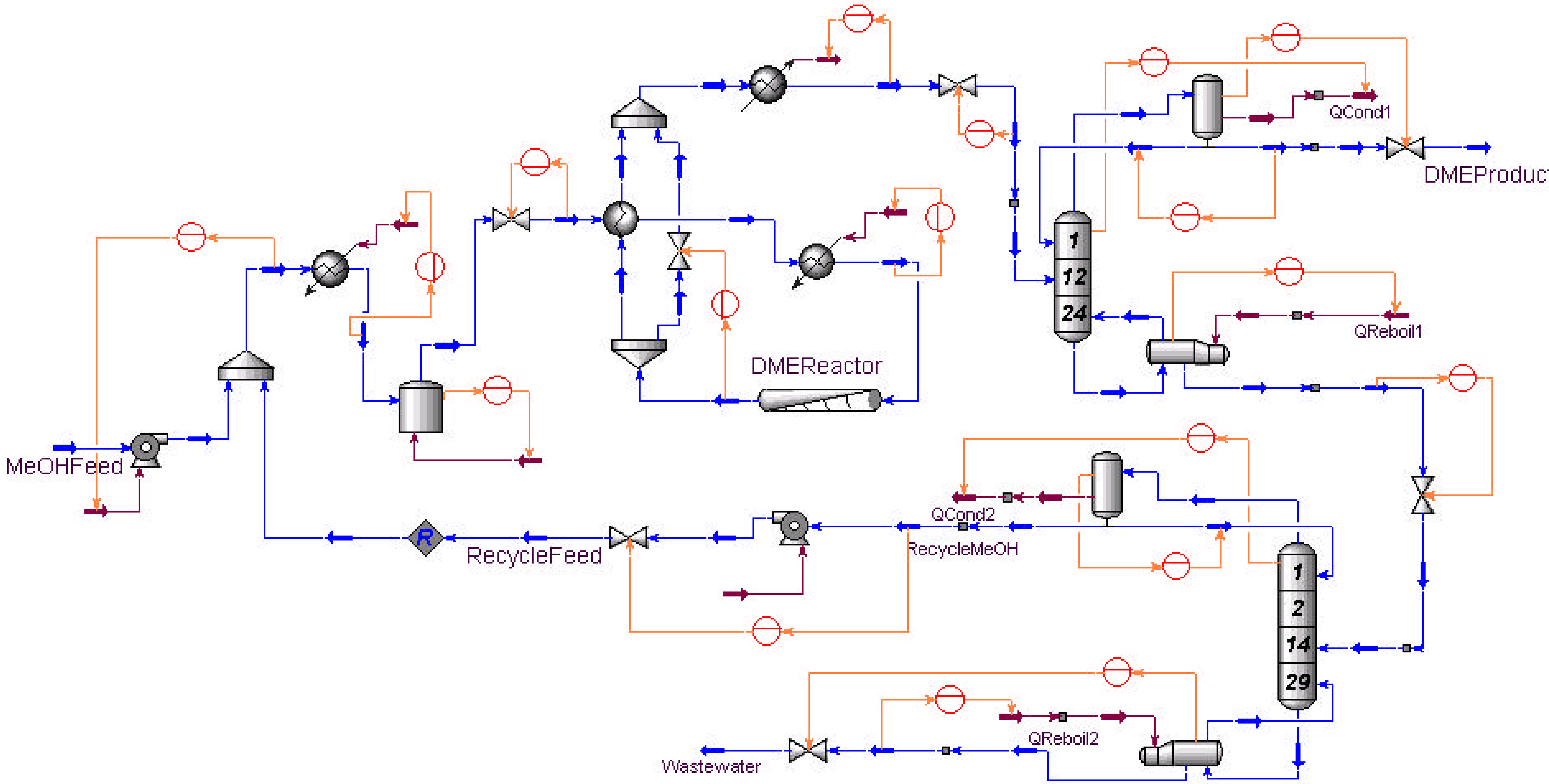
- **Module**
  - **Define Control tasks**
    - **Example: Reactor Module**
      - **Minimum Reactor Inlet Temperature**
      - **Methanol Conversion**
      - **Maximum Reactor Outlet Temperature**
      - **Condensed effluent stream from the module**
  - **Control strategy**
    - **S. Skogestad & coworkers: (2000): Self-optimizing control variables**
      - **2 cDoFs**
    - **W. Luyben & coworkers (1997) : 9 steps (control structure)**
- **Plant**
  - **Luyben: control system**
  - **Skogestad: strategy**

Modular Plantwide Control Structure



Luyben's 9 steps/module

Plantwide Control Structure (Luyben)



18 cDoF Þ 18 control loops

(no pairing assessment completed)

Summary

- **A novel plantwide decomposition approach has been presented - AHP**
  - **Systematic and consistent prioritization**
    - **Design objectives**
    - **Operability constraints**
    - **Alternative decomposition**
- **Demonstrated on DME process**
  - **Plant+Control Structure**
    - **Modular approach**
    - **Full plant**
    - **Same PCS – Luyben's 9 step approach**

Acknowledgments: Dow Chemical Co., TTU Montford Matching Funds, TTU Chancellors Fellowship