CACHE NEWS

NEWS ABOUT COMPUTERS IN CHEMICAL ENGINEERING EDUCATION.

No. 34

Spring 1992

The CACHE CORPORATION

WHAT IS CACHE?

CACHE is a not-for-profit organization whose purpose is to promote cooperation among universities, industry and government in the development and distribution of computer-related and/or technology-based educational aids for the chemical engineering profession.

CREATION OF THE CACHE CORPORATION

During the 1960s the rapid growth of computer technology challenged educators to develop new methods of meshing the computer with the teaching of chemical engineering. In spite of many significant contributions to program development, the transferability of computer codes, even those written in FORTRAN, was minimal. Because of the disorganized state of university-developed codes for chemical engineering, fourteen chemical engineering educators met in 1969 to form the CACHE (Computer Aids for Chemical Engineering) Committee. The CACHE Committee was initially sponsored by the Commission on Education of the National Academy of Engineering and funded by the National Science Foundation. In 1975, after several successful projects had been completed, CACHE was incorporated as a not-for-profit corporation in Massachusetts to serve as the administrative umbrella for the consortium activities.

CACHE ACTIVITIES

All CACHE activities are staffed by volunteers including both educators and industrial members and coordinated by the Board of Trustees through various Task Forces. CACHE actively solicits the participation of interested individuals in the work of its ongoing projects. Information on CACHE activities is regularly disseminated through CACHE News, published twice yearly. Individual inquiries should be addressed to:

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CACHE NEWS

The CACHE News is published twice a year and reports news of CACHE activities and other noteworthy developments of interest to chemical engineering educators. Persons who wish to be placed on the mailing list should notify CACHE at the aforementioned address. Contributions from CACHE representatives are welcome. This issue was editied by D. M. Himmelblau with contributions from a number of CACHE members and representatives.

CACHE NEWS

No. 34 **Spring 1992**

CACHE Task Forces and Committees

Chemical Engineering Optimization Models with GAMS

By Ignacio Grossmann, Carnegie Mellon University

Volume No. 6 of the CACHE Process Design Case Studies, "Chemical Engineering Optimization Models with GAMS" has recently been prepared by faculty and students from Carnegie Mellon University, Northwestern University and Princeton under the coordination of Ignacio E. Grossmann. The faculty involved are Larry Biegler from Carnegie Mellon, Chris Floudas from Princeton and Iftekhar Karimi from Northwestern University. GAMS Development Corporation, the licensing technology office at Stanford University, the XMP Optimization Software and the Engineering Design Research Center at Carnegie Mellon have donated the computer software for this case study.

Many problems in chemical engineering can be modelled as optimization problems. These include analysis, design and operations problems. Currently courses and textbooks in chemical engineering optimization emphasize mostly theory and methods, and are restricted to rather small problems and applications. Although it is of course important to cover basic methods and the theory of optimization, it is also important to take into account that a number of new developments have taken place in this area. One of the important developments has been new modelling systems, such as GAMS, that offer the possibility to quickly model and solve a variety of optimization problems. These modelling systems offer the advantage that students can concentrate mostly on problem formulation, without having to spend too much effort on how to use the software. The second important development in optimization over the last few years are new and improved algorithms that offer the possibility of solving much larger problems. Such is the case of linear programming where currently problems involving thousands of constraints and thousands of variables can be readily solved. Similar trends have taken place in mixed-integer linear programming. Another development is in the area of nonlinear programming where currently one can solve problems involving several hundreds of equations and variables. Finally, important developments have also taken place in the solution of differential-algebraic systems and in the solution of mixed-integer nonlinear programming problems which until recently have received very little attention. Therefore, given all of these developments there would seem to be an important educational need to reinforce the modelling skills of students so as to make use of both modern modelling systems, as well as modern optimization algorithms with which one can solve larger and more complex engineering problems.

The major objective of this case study is to provide a set of chemical engineering problems to supplement optimization courses at both the undergraduate and graduate level. This case study is of course not meant to replace textbooks, but rather to provide additional material that should be useful for both instructors and students. The major emphasis of this case study is on the formulation of optimization problems in a variety of different application areas. Also, the emphasis of the case study is to expose students to the GAMS modelling environment for optimization.

This case study comprises a detailed description of 21 problems in chemical engineering. The description of each problem includes the problem statement, a detailed problem formulation, and presentation and discussion of results. In addition, exercises are also given by which students can modify the formulations and extend them to other types of problems. The case study also contains a number of appendices such as a tutorial introduction to GAMS. It also provides a user guide for the mixed-integer nonlinear program code DICOPT++, and for the solution of differential algebraic systems and implementation of decomposition methods. In addition, the case study also contains the GAMS user guide that provides a detailed description of the syntax and all the capabilities that are possible with GAMS. Finally, the case study also has a 31/2 in. diskette for IBM personal computers that contains both the GAMS software, the related algorithms for optimization and the input files for the 21 problems.

The main features of GAMS is that it is a modelling system in which the problems are described in terms of equations. The equations can be expressed in explicit form or through the use of indices. Data can be handled through the specification of sets, parameters and tables. Also with GAMS one can model a variety of different optimization problems; namely linear programming, mixed-integer linear programming, nonlinear programming and mixed-integer nonlinear programming problems. An important feature is that GAMS provides an automatic interface for the algorithms for each of these type of solvers. In addition, a very important capability is the fact that GAMS can perform automatic differentiation for nonlinear problems which removes the burden for the student to have to provide analytical derivatives for the objective function and of the constraint. The student version of GAMS is capable of handling problems with up to 1000 nonzero elements in the Jacobian matrix (300 nonlinear elements) and up to 20 discrete variables. The software can run on IBM PC's and compatibles

(1MByte recommended), and runs on the DOS operating system 2.11 or higher.

The type of models and algorithms that can be handled within GAMS are as follows. For linear programming the simplex method is used as implemented in 3 computer packages, BDMLP, ZOOM and MINOS. Mixed-integer linear programming problems are solved with the LP based branch and bound method as implemented in the program ZOOM. Nonlinear programming are solved with the reduced gradient method as implemented in MINOS. Mixed-integer nonlinear programming problems can also be handled, and this is done with the software package DICOPT++ which is based on the outer-approximation method. Finally, one can reformulate differential- algebraic optimization problems as nonlinear programming problems through the use of collocation. It is also possible to implement in the GAMS language decomposition algorithms such as the Generalized Benders algorithm for nonlinear programming and mixed-integer nonlinear programming.

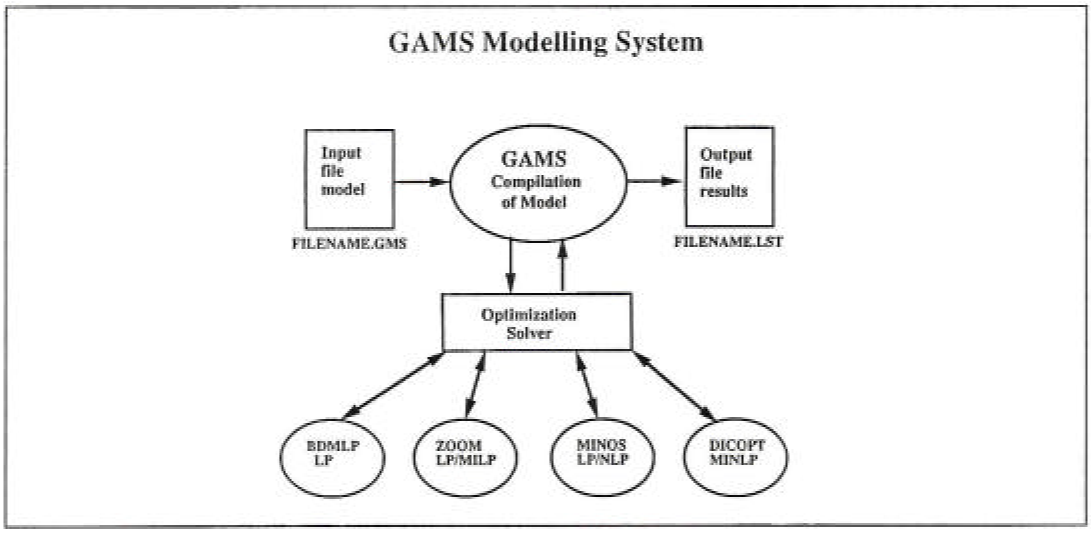


Figure 1
Structure of GAMS

As seen in Figure 1, the way the GAMS modelling system works is as follows. Firstly, the user prepares and input file in which the model to be solved is being specified in equation form. This input file is then compiled with the program GAMS which then automatically interfaces with any of the different optimization packages. The interface is done depending on the nature of the problem and depending on the option that has been specified by the user. Once the solution is obtained, GAMS creates an output file in which the results are reported for that model.

To illustrate more clearly the capabilities of the GAMS program and its ease of use, let us consider the following simple analytical example which is given in the optimization textbook by Reklaitis et al (1983). The problems is as follows:

$$\min Z = x_1^2 + x_2^2 + x_3^2$$

$$\text{s.t. } x_2 - x_3 \geq 0$$

$$x_1 - x_3 \geq 0$$

$$x_1 - x_2^2 + x_2 x_3 - 4 = 0$$

$$0 \leq x_1 \leq 5$$

$$0 \leq x_2 \leq 3$$

$$0 \leq x_3 \leq 3$$

The above problem corresponds to a nonlinear programming model. As seen in Figure 2 the input file of GAMS for this problems lists the variables and equations that comprise this problem. One can also specify the upper bounds for the variables; the lower bounds are specified through the statement that three variables x_1, x_2, and x_3 are positive variables. One can also supply an initial guess, which in this case is $x_1 = 4$, $x_2 = 2$ and $x_3 = 2$. Finally, to invoke the solution of the

```
test.gms
  $TITLE Test Problem
  $OFFSYMXREF
  $OFFSYMLIST

  *  Example from Problem 8.26 in "Engineering Optimization" by
  *  Reklaitis, Ravindran and Ragsdell (1983)
  *

   VARIABLES  X1, X2, X3, Z;
   POSITIVE VARIABLES X1, X2, X3 ;

   EQUATIONS  CON1, CON2, CON3, OBJ;

   CON1..      X2 - X3 =G= 0;
   CON2..      X1-X3 =G= 0;
   CON3..      X1 - X2**2 + X1*X2 - 4 =E= 0;
   OBJ..       Z =E= SQR(X1) + SQR(X2) + SQR(X3);

  * Upper bounds
    X1.UP = 5;
    X2.UP = 3;
    X3.UP = 3;

  *  Initial point

   X1.L  = 4;
   X2.L  = 2;
   X3.L  = 2;

   MODEL TEST  / ALL / ;

   OPTION LIMROW = 0;
   OPTION LIMCOL = 0;

   SOLVE TEST USING NLP MINIMIZING Z;
```

Figure 2
GAMS Input File

nonlinear programming optimizer, which in this case is the program MINOS, the solve statement is included which specifies that we want to minimize the objective function z. As seen in Figure 3, the output file that is obtained indicates that the optimal value of the objective function for this problem is 7.2177. Also, as can be seen in this figure optimal the value of the variables, which are denoted as level values, is $= x_1 = 2.526$, $x_2 = 0.916$, $x_3 = 0$.

As an additional example, consider the problem of the optimal assignment of streams to heat exchangers as reported in the textbook by Edgar and Himmelblau (1988). The formulation for this problem corresponds to the following assignment problem:

$$\min Z = \sum_{i=1}^{n} \sum_{j=1}^{n} C_{ij} x_{ij}$$

$$\text{s.t.} \sum_{i=1}^{n} x_{ij} = 1 \qquad j = 1..n$$

$$\sum_{j=1}^{n} x_{ij} = 1 \qquad i = 1..n$$

$$x_{ij} = 0,1 \qquad i = 1, n \;\; j = 1, n$$

where $x_{ij} = 1$ if stream i is assigned to exchanger j, and 0 if it is not.

The coefficients C_{ij} are given as follows:

	Exchangers			
Streams	1	2	3	4
A	94	1	54	68
B	74	10	88	82
C	73	88	8	76
D	11	74	81	21

The above corresponds to an integer-programming problem that has 16 0-1 variables, and 8 constraints. This problem, being an assignment problem, is actually solvable as a linear programming problem.

As seen in Figure 4, where the GAMS output file of this problem is presented, one can specify this problem through the use of sets for both the streams and exchangers, and also by specifying a table for the data of the cost coefficients. Also note, that the equations of the model, namely the assignment constraints and the objective function, can be written in terms of indices. As seen in Figure 4, the output file reports an optimal value of the objective function of 97, which has been obtained with the code ZOOM. Also, in this case we have used a display statement in order to report the variables in a different way as seen in this figure. The results indicate that stream A should be assigned to exchanger 4, stream B to exchanger 2, stream C to exchanger 3, and stream D to exchanger 1.

```
                              SOLVE SUMMARY

     MODEL     TEST                           OBJECTIVE  Z
     TYPE      NLP                            DIRECTION  MINIMIZE
     SOLVER    MINOS5                         FROM LINE  35

****  SOLVER STATUS                 1  NORMAL COMPLETION
****  MODEL STATUS                  2  LOCALLY OPTIMAL
****  OBJECTIVE VALUE                           7.2177

   RESOURCE USAGE,  LIMIT                 1.648       1000.000
   ITERATION COUNT,  LIMIT               15           1000
   EVALUATION ERRORS                      0              0

   EXIT - OPTIMAL SOLUTION FOUND
   MAJOR ITNS, LIMIT                      7            200
   FUNOBJ, FUNCON CALLS                  34             34
   SUPERBASICS                            1
   INTERPRETER USAGE                    .23
   NORM RG / NORM PI              9.678E-10

                                 LOWER     LEVEL     UPPER    MARGINAL

--- EQU CON1                       .       0.916     +INF        .
--- EQU CON2                       .       2.526     +INF        .
--- EQU CON3                     4.000     4.000     4.000     2.637
--- EQU OBJ                        .         .         .       1.000

                                 LOWER     LEVEL     UPPER    MARGINAL

--- VAR X1                         .       2.526     5.000       .
--- VAR X2                         .       0.916     3.000      EPS
--- VAR X3                         .         .       3.000      EPS
--- VAR Z                        -INF      7.218     +INF        .
```

Figure 3
GAMS Output File

```
*
*  Assignment problem for heat exchangers from pp.409-410 in
*  "Optimization of Chemical Processes" by Edgar and Himmelblau
*

SETS
     I   streams        / A, B, C, D /
     J   exchangers     / 1*4 / ;

TABLE  C(I,J)   Cost of assigning stream i to exchanger j

          1      2      3      4
   A     94      1     54     68
   B     74     10     88     82
   C     73     88      8     76
   D     11     74     81     21  ;


VARIABLES  X(I,J), Z ;
BINARY VARIABLES X(I,J);

EQUATIONS  ASSI(J), ASSJ(I), OBJ;

ASSI(J)..   SUM( I, X(I,J) ) =E= 1;
ASSJ(I)..   SUM( J, X(I,J) ) =E= 1;
OBJ..      Z =E= SUM( (I,J), C(I,J)*X(I,J) ) ;

MODEL HEAT / ALL / ;

OPTION LIMROW = 0;
OPTION LIMCOL = 0;
OPTION SOLPRINT = OFF;

SOLVE HEAT USING MIP MINIMIZING Z;

DISPLAY X.L, Z.L ;
```

```
                 S O L V E      S U M M A R Y

     MODEL   HEAT                  OBJECTIVE  Z
     TYPE    MIP                   DIRECTION  MINIMIZE
     SOLVER  ZOOM                  FROM LINE  37

**** SOLVER STATUS     1 NORMAL COMPLETION
**** MODEL STATUS      1 OPTIMAL
**** OBJECTIVE VALUE               97.0000

 RESOURCE USAGE, LIMIT          0.719     1000.000
 ITERATION COUNT, LIMIT        16         1000


                      Iterations     Time
 Initial LP                16         .22
 Heuristic                  0         .00
 Branch and bound           0         .00
 Final LP                   0         .00


**** REPORT SUMMARY :        0     NONOPT
                             0 INFEASIBLE
                             0  UNBOUNDED
GAMS 2.25  PC AT/XT
Test Problem
E x e c u t i o n


----     39 VARIABLE  X.L

             1           2           3           4

A                                             1.000
B                     1.000
C                                 1.000
D        1.000


----     39 VARIABLE  Z.L                 =       97.000
```

Figure 4
GAMS File for Assignment Problem

With the above examples, it should be clear that using GAMS provides a rather convenient and flexible environment with which one can easily pose and solve optimization problems.

In this case study the chemical engineering problems that have been considered are as follows. Firstly, a number of analysis problems are provided that deal with chemical and phase equilibrium, with the minimum utility calculation for heat exchanger networks, and for parameter estimation in batch reactors. There are also a number of design applications that deal with heat exchanger networks, with the design of distillation columns (optimal feed tray location), the optimal design of batch processes, and the design of catalytic reactors. The case study also covers a number of applications in process synthesis such as reaction paths, heat exchanger networks and distillation sequences. Finally, planning and scheduling problems are also given for refineries, power systems, multiproduct batch plants, and for process selection and capacity expansion. It is important to note that the 21 problems that have been provided range from rather simple problems that are especially suitable for the undergraduate level, to problems that are more complex in nature and are better suited for a graduate course. All the problems have been extensively documented in the GAMS input files. Figures 5 to 8 present some of the problems included in this case study that deal with refinery scheduling, Gibbs energy minimization, heat exchanger network synthesis and parameter estimation for batch reactions.

Problem Type: LP   Input File: REFINERY.GMS

1. Problem Statement

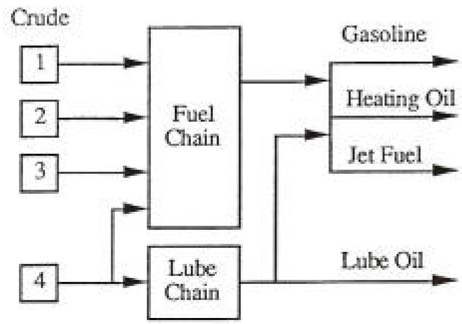


Figure 1. Processing Operation

Table 1. Problem Data

Products/Crudes	Product Yields bbl/bbl crude: Fuel Process 1	Fuel Process 2	Fuel Process 3	Fuel Process 4	Lube 4	Product Value $/bbl	Maximum Demand kbbl/wk
Gasoline	0.6	0.5	0.3	0.4	0.4	45.00	170
Heating Oil	0.2	0.2	0.3	0.3	0.1	30.00	85
Jet Fuel	0.1	0.2	0.3	0.2	0.2	15.00	85
Lube Oil	0.0	0.0	0.0	0.0	0.2	60.00	20
Operating Losses	0.1	0.1	0.1	0.1	0.1	-	-
Crude Cost $/bbl	15.00	15.00	15.00	25.00	25.00		
Operating Cost $/bbl	5.00	8.50	7.50	3.00	2.50		
Crude Supply kbbl/wk	100	100	100	200			

Find production schedule to maximize profit

Figure 5
Refinery Scheduling Problem by Karimi

Problem type : NLP

Input File : EQUIL.GMS

1 Problem Statement

Benzene-Acetonitrile-Water Vapor-Liq-Liq Equilibria @333K 0.769atm				
Component	Vapor Phase (mol fraction)	Liquid Phase 1 (mol fraction)	Liquid Phase 2 (mol fraction)	Feed (mol fraction)
C_6H_6 :	0.4785	0.0026	0.4788	0.3436
CH_3CN :	0.2818	0.0762	0.4539	0.3092
H_2O :	0.2397	0.9212	0.0673	0.3472
Total Moles	28.478	50.015	21.867	100.36

Table 1: Data and solution for Phase Equilibria Example - VLL solution.

Benzene-Acetonitrile-Water Liquid-Liquid Equilibria @333K 1atm				
Component	Vapor Phase (mol fraction)	Liquid Phase 1 (mol fraction)	Liquid Phase 2 (mol fraction)	Feed (mol fraction)
C_6H_6 :	—	0.0024	0.5147	0.3436
CH_3CN :	—	0.0711	0.4287	0.3092
H_2O :	—	0.9265	0.0566	0.3472
Total Moles	—	33.522	66.838	100.36

Table 2: Data and solution for Phase Equilibria Example - LL solution.

Determine phases and composition at equilibrium minimizing Gibbs energy

Figure 6
Multiphase Equilibria Problem by Paules and Floudas

Problem type: MINLP **Input file: SYNHEAT.GMS**

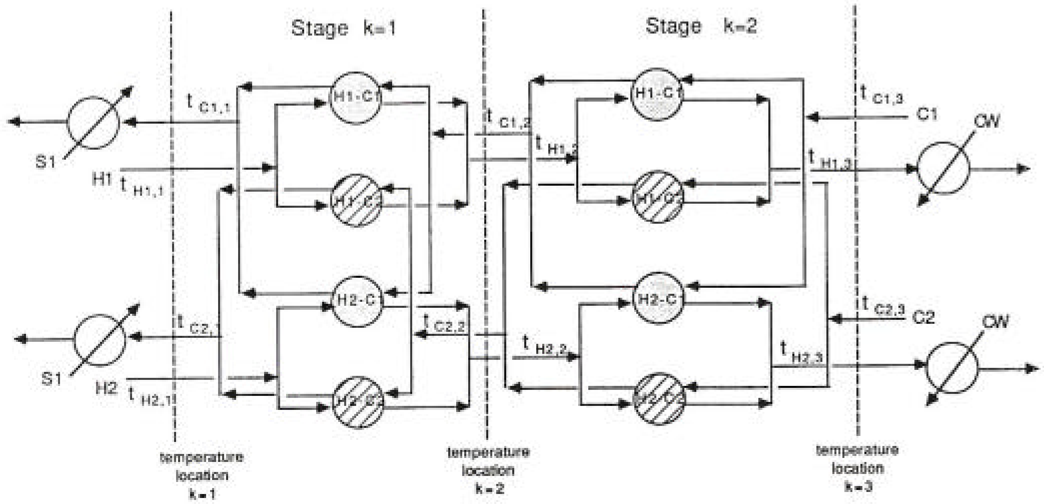


Figure 1 Two stage superstructure

Synthesize network structure with minimum total cost

Figure 7
Superstructure Optimization for Heat Exchanger Network Synthesis by Yee and Grossmann

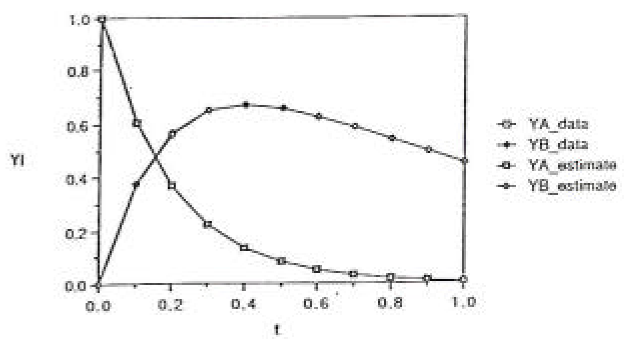
Problem type: NLP

Input File: PARAM.GMS

1. Problem Statement

$$A \xrightarrow{k_1} B \xrightarrow{k_2} C$$

t	.10	.20	.30	.40	.50	.60	.70	.80	.90	1.00
$\hat{y}^a$	.606	.368	.223	.135	.082	.050	.030	.018	.011	.007
$\hat{y}^b$	.373	.564	.647	.669	.656	.624	.583	.539	.494	.451



Find rate constants to minimize square errors from mesured values and ODE model

Figure 8
Parameter Estimation for a Batch Reactor by Biegler and Tjoa

The cost of this case study is $55 for CACHE supporting departments and $80 for non-supporting departments or for industry. Additional information and an order form for this case study can be found at the end of this newsletter.

References

Edgar, T.F. and D.M. Himmelblau, "Optimization of Chemical Processes", McGraw Hill (1988).

Reklaitis, G.V., A. Ravindran and K. M. Ragsdell, "Engineering Optimization", John Wiley (1983).

Microcomputer Chemical Engineering Programs (develped by Professors)

Edited by Bruce A. Finlayson, University of Washington

Have you wondered what microcomputer programs are being used in other chemical engineering curricula? This column provides a mechanism for University professors to let others know about the programs they've developed and are willing to share on some basis.

The program should be described by a 250 word description, machine requirements, and ordering information. These programs should be ready to be shipped out the door, and should have been tested by students at more than one University. It would be helpful if the specific Chemical Engineering course were identified in which the program is useful. The programs will not be reviewed by Professor Finlayson, nor will they be certified by CACHE.

In order to edit the column efficiently, the submissions must be made to Finlayson via BITNET, address FINLAYSON@MAX or on a diskette in ASCII. He will acknowledge receipt of the submission via BITNET and will send the edited column to the CACHE office via BITNET. Letters cannot be accepted.

The column can only be successful if professors submit their writeups. Let us hear from you!

WILSON - A non-ideal vapour-liquid equilibrium tool

By Dr. R. E. Hayes
University of Alberta

WILSON is a software package which performs non-ideal vapour liquid equilibrium calculations and plots phase diagrams. Operations include bubble point, dew point and flash calculations. Plotting options include X vs. Y at constant temperature or pressure with azeotrope prediction, and X and Y vs. pressure or temperature. The program uses the Wilson model for the liquid phase and the virial equation of state for the vapour. The data base provided contains 33 pure components and may be easily expanded by the user. The program is menu driven and has online help available.

This package runs on an IBM PC or compatable equiped with CGA or EGA graphics. WILSON has been used for three years in Chemical Engineering Thermodynamics courses at the University of Alberta.

More information my be obtained from:

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FAX 403 492 2881

BIODESIGNER

By Demetri Petrides
New Jersey Institute of Technology

BioDesigner is a software tool designed to enhance the effectiveness and productivity of engineers and scientists engaged in design and development of individual or integrated biochemical processes. For a given flowsheet, BioDesigner calculates the material and energy balances, estimates the size and cost of equipment, and carries out a detailed economic evaluation. The program has scheduling capabilies and has the ability to handle batch and semicontinuous processes. A design case in BioDesigner can have any number of unit operations, material streams, and chemical components because memory for those objects is allocated dynamically at runtime. BioDesigner is intended to be used at the early stages of process development and during scale-up. It enables chemical and biochemical engineers to quickly carry out a conceptual design for a new project idea and evaluate it from an economic point of view.

BioDesigner makes use of advanced graphics to facilitate the human/computer interaction and minimize the learning period. It is equipped with an advanced "Help" facility that minimizes the need for manuals.

The current version of BioDesigner runs on any Apple Macintosh computer with at least 1 MB of RAM (more memory is required for large flowsheets). It is written in THINK C and is distributed in object code and parts of source code if desired.

BioDesigner was developed as a part of the Ph.D. thesis of D. Petrides at the Biotechnology Process Engineering Center (BPEC) of the Massachusetts Institute of Technology. Peter Klenk, an undergraduate computer science student, contributed significantly in the development of the interface and a number of other features.

BioDesigner has been used in biochemical engineering courses at MIT during the last two years.

More information may be obtained from:

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Internet: dxp6129@tesla.njit.edu

The following programs have been listed in prior editions of the CACHE News.

1. Vapor compression refrigeration cycle, No. 24 and 25 Stanley Sandler, University of Delaware

2. Compression of an ideal gas, No. 24 and 25, Stanley Sandler, University of Delaware

3. Computer Aided Analysis for Process Systems, No.24 and 25, Ted Cadman, University of Maryland

4. Discounted Cash Flow Analysis (and Present Worth), No. 24 and 25, Bruce A. Finlayson, University of Washington

5. Short-cut Distillation and Flash Calculations, No. 24 and 25, Bruce A. Finlayson, University of Washington

6. Convective Diffusion Equation (CDEQN), No. 25 and 26, Bruce A. Finlayson, University of Washington

7. Engineering Plot (ENGNPLOT), No. 25 and 26, Bruce A. Finlayson, University of Washington

8. Educational Software for Teaching Process Dynamics and Control, No. 26 and 27, Patrick Richard and Jules Thibault, Laval University

9. MIDAS - Microcomputer Integrated Distillation Sequences, No. 26 and 27, Andrew Hrymak, McMaster University

10. A Rigorous Multicomponent Multistage Steady-State Distillation Rating Program, No. 27 and 28, E.C. Roche, Jr., New Jersey Institute of Technology

11. RESIM. A Reactor Design Teaching Tool, No. 27 and 28, B.W. Wojciechowski, Queen's University

12. Real-time Multiloop Computer Control Program, UC ONLINE , No. 27 and 28, by Alan Foss, University of California at Berkeley

13. Real-time Dynamic Distillation Simulation and Relative Gain Program , No. 27 and 28, by Alan Foss , University of California, Berkeley

14. The Kinetics and Selectivity of Consecutive Reactions, No. 29 and 30, by Alvin H. Weiss and Reynold Dodson, Worcester Polytechnic Institute.

15. Equations of State, No. 30 and 31, by Kenneth R. Jolls, Iowa State University.

16. Thermal Design of Shell and Tube Heat Exchangers, No. 31 and 32, by Nurcan Bac and Ilker Ozal, Worcester Polytechnic.

17. Optimum Series Bioreactor Design, No. 31 and 32, by Gordon Hill, University of Saskatchewan.

18. REACT! A Chemical Equilibrium Calculator, No. 32 and 33, by James A. O'Brien, Yale University

Modern Authoring Systems for Computer Based Educational Materials

An authoring system is designed to to be a highly formatted application development tool. It is supposed to generate materials to "help your students learn faster, retain more, and perform better." In order for an authoring system to work, however, it is important to first build an "authoring environment." The tools involved, the personnel, and the interactive training development process are all a part of the authoring environment.

Some of the activities involved in preparing instructional modules on the computer are:

- Analysis
- Standards definition
- Design specification
- Development
- Production
- Programming
- Integration
- Validation

It is best to work with a team including media specialists, and use a variety of computer based tools that function to record or edit the educational materials. Basic skills this team should have are:

- Job task analysis
- Instructional design
- Storyboard and script development
- Graphic arts
- Systems engineering
- Software engineering and programming

Instructional design and development, graphics, and programming represent the major functions involved in authoring. Following is a brief list of specific activities.

Instructional Design

Tools

- Methodology
- Techniques and instruments
- Information management software

Personnel

- Instructional designers
- Storyboard writers
- Script writers

Flow of Activities

- Analysis
- Design
- Development
- Review and Edit

Graphics

Tools

- Paint packages
- Draw packages
- Animation packages
- Desktop publishing packages
- Scanning and digitizing devices

Personnel

- Artists with knowledge of computer systems

Flow of Activities

- Narrative treatment
- Scope of work
- Events definition
- Prototype
- Standards
- Working treatment
- Development
- Production
- Program

Programming

Tools

- Authoring system
- Authoring language
- Programming language
- Computer-managed instruction (CMI)

Personnel

- Systems engineers
- Software engineers
- Programmers
- Authors

Flow of Activities

- Systems architecture
- Module specification
- Events definition
- Prototype
- Standards
- Integrating system
- Program
- Integration
- Review cycle

The next pages comprise a list of authoring systems, taken from the article by Dr. Robert S. Becker entitled "How to Build an Authoring Environment in the March/April 1991 issue of *Instruction Delivery Systems*, pp 12-23, with permission of the Communicative Technology Corporation.

Directory of Authoring Systems

Company/System	Cost	Demo/Eval Available	Hardware Requirements	System Type	Special Notes
Accord 4.2 Global Info. Sys. Tech. 1800 Woodfield Dr. Savoy, IL 61874 (217) 352-1165	$10,300		386, VGA, 4MB Multi-User Unix	MENU	A,B,C,E
ACT III Multimedia Informatics Group, Inc. West Hartford, CT 06110 (203) 953-4040	$495	BOTH	PC, XT/AT PS-2 or comp.	MENU	A,B,C,D,E
Adroit Computer Associates 711 Stewart Ave. Garden City, NY 11530 (516) 227-3300	$10,000	BOTH	PC, XT/AT PS-2 or comp.	MENU	B,C,D,E
AIS-II Mc Donnell Douglas CBT Sys. 2450 S. Peoria, #400 Aurora, CO 80014 (303) 671-4800	$3,900	DEMO	PC comp. EGA, 640K Color monitor	MENU	B,C,E
ASAP! Ashton Interactive Trng PO Box 830 Dandridge, TN 37725 (615) 397-0742	$795	BOTH	PC, XT/AT PS-2 or comp.	MENU	B
ASAP! Plus Ashton Interactive Trng PO Box 830 Dandridge, TN 37725 (615) 397-0742	$1795	BOTH	PC, XT/AT PS-2 or comp.	MENU	B
Ask-Me 2000 ASK-ME Info. Ctr 112 Roberts St., Suite 14 Fargo, ND 58102 (701) 293-1004	$495	EVAL	286/386 comp. VGA, 2MB	ICON	C,D,E
Audio Visual Connection IBM Corp 4111 Northside Parkway Internal Zip H05L1 Atlanta, GA 30327 (800) 627-0920	$544		PS-2 comp. 4MB	MENU	B,C,D,E
Authology CEIT Systems 4800 Great American Pkwy Suite 200 Santa Clara, CA 95054 (408) 986-1101	$2,500	BOTH	XT, AT comp.	MENU	A,B,C,D,E
Authology: MultiMedia CEIT Systems 4800 Great American Pkwy Suite 200 Santa Clara, CA 95054 (408) 986-1101	$4,500	BOTH	386 AT comp. Intel DVI Action Media Board	MENU	A,B,C,D,E
Author Daines Associates Box 75962 St. Paul, MN 55175 (612) 298-1104	$195	DEMO	64K Apple 2E	MENU	A

Key to Special Notes: A - Text editor B - Graphics editor C - Supports videodisc D - Supports CD-ROM E - Supports other peripherals

Directory of Authoring Systems

Company/System	Cost	Demo/Eval Available	Hardware Requirements	System Type	Special Notes
AuthorPlus Color Daines Associates Box 75962 St. Paul, MN 55175 (612) 298-1104	$495	BOTH	IBM PC comp.	MENU	A,B
Authorware Professional Authorware, Inc. 8500 Normandale Lake Blvd, 9th Floor Bloomington, MN 55437 (612) 921-8555	$8,000	BOTH	MacPlus or 286/16 w/2MB	MENU	A,B,C,D,E
Autotrainer Grey Management Consulting Co. 730 Gay St. Westwood, MA 02090 (617) 890-4670	$2,500	BOTH	PC comp.	MENU	A,C,D,E
Cadenza™ Inspiration, Inc. 6 High View Drive High Bridge, NJ 08829 (908) 638-5212	CALL	BOTH	PC 286 w/ VGA	MENU	A,B,E
CAN-8 Homecom Learning Sys. Ltd 920 Yonge Street Toronto, Ont, Canada M4W 3C7 (416) 968-7155	$300		Unix, Xenix MS-DOS, VAX VMS	MENU	A,C,D,E
CD-Author Dataware Technologies 222 Third Street Cambridge, MA 02142 (617) 621-0820	CALL	BOTH	VAX, SUN MS-DOS, Windows	MENU	A,B,D
Cdi Tools Interactive Support Group, Inc. 21032 Devonshire St., Suite 209 Chatsworth, CA 91311 (818) 709-7387	$7,500		Mac II, 4MB 100 MB hard drive	MENU	E
CLAS-CBT Touch Technologies 9990 Mesa Rim Rd. #220 San Diego, CA 92121 (619) 743-0494	$229	BOTH	PC comp Amiga	MENU	A,D,E
Concurrent Vasco Corp 1919 S. Highland, Suite 118-C Lombard, IL 60148 (708) 495-0755	CALL	BOTH	286, 512K	MENU	E
Course Builder Telerobotics Int'l, Inc. 7325 Oak Ridge Hwy. Suite 104 Knoxville, TN 37931 (615) 690-5600	$2,995	BOTH	Mac SE 2 MB	ICON	C,D,E
Coursemaster Interdigital, Inc. 258 Water St. Lebanon, NJ 08833 (201) 832-2463	$495	BOTH	DOS 2.1, 256K	COMM	C,E

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CoursePlus Softwords 4252 Commerce Circle Victoria, BC, Canada V8Z 4M2 (604) 727-6522	$349	DEMO	286, 640K	MENU	A,B,E
CoursePlus Two Softwords 4252 Commerce Circle Victoria, BC, Canada V8Z 4M2 (604) 727-6522	$1,995	BOTH	80286, 80386	MENU	A,B,C,E
Desktop Studio Wonder Corp. 51 Winchester St. Newton Highlands, MA 02161 (617) 965-8400	$9,000	DEMO	PC, PS-2 comp.	MENU	C,D,E
DRAKE Authoring Sys Drake Training & Tech 8800 Queen Ave. S. Bloomington, MN 55431 (612) 921-6807	$995		AT or comp. 614K, CGA EGA, or VGA	MENU	B,E
Electronic Publishing Systems™ Intellisance Corp. 1885 Lundy Ave San Jose, CA 95131 (408) 423-0430	$20,000		PC-DOS or DEC VMS	MENU	A,B,C,E
Examiner Technovision, Inc. 5155 Spectrum Way, Unit 31 Mississauga, Ont, Canada L4W 5A1 (416) 625-DISC	CALL		286 w/ network card	MENU	A,C (System specific for driver's testing and evaluation.)
Exemplar BehaviorTech 5215 N. O'Connor Blvd., Suite 2550 Irving, TX 75039 (214) 402-9394	$12,000	BOTH	PC comp. color monitor	RULE 512K	A,B,E
Guide 3.0 Owl International 2800 156th Avenue SE Bellevue, WA 98007 (206) 747-3203	$495	DEMO	286, IMB Windows 2.x	ICON	C,D,E
Hyperdoc 2.1 Hyperdoc, Inc. One Almaden Blvd., #620 San Jose, CA 95113 (408) 292-7970	$1,240	BOTH	386, EGA	MENU	C,D,E
HyperWriter! Ntergaid, Inc. 2490 Black Rock Turnpike Suite 337 Fairfield, CT 06430 (203) 368-0632	$395	BOTH	PC comp.	MENU	A,C,D,E
IconAuthor Aimtech Corp 20 Trafalgar Sq. Nashua, NH 03063 (603) 883-0220	$,1495	BOTH	286 comp Windows 3.0 Unix	ICON	A,B,C,D,E

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I.De.A.S. OmniCom Associates 407 Coddington Rd. Ithaca, NY 14850 (607) 272-7700	$2,500	EVAL	PC comp., 640K MS-DOS 3.3 Colorgraphics Card	MENU	A,C,E
IDI Author Instructional Design Int'l 1775 Church St., NW Washington, DC 20036 (202) 332-5353	$45		MacPlus w/ Hypercard	MENU	C,E
Images Computer Knowledge Int'l 1300 Weathervane La. Suite 200 Akron, OH 44313 (216) 836-1866	$2,000	DEMO	640K Graphics Adapter	MENU	A,B,C,D,E
IMRI Arnowitz Productions 488 Green Glen Way Mill Valley, CA 94941 (415) 383-2878	CALL	DEMO	PC comp., Mac	ICON	A,B,C,D,E
Imsatt 2000 Imsatt Corp 105 W Broad St., Suite 301 George Mason Square Falls Church, VA 22046 (703) 533-7500	CALL	BOTH	PC comp.	MENU	A,B,C,D,E
Infowriter Pro Infowriter 7323 E 59th St. Tulsa, OK 74145 (918) 663-0218	CALL	BOTH	PC-XT comp. 640K, 360 drive	MENU	A,C
Instructional Workbench AT&T 200 Laurel Ave. Middletown, NJ 07748 (908) 957-6187	$800 - $50,000	DEMO	AT&T Unix System V	MENU	A,B,D,E
Instructor BCD Associates Inc 7510 N. Broadway, Suite 205-T Oklahoma City, OK 73116 (405) 843-4574	$395		Apple II	MENU	E
Interact Ashton Interactive Trng PO Box 830 Dandridge, TN 37725 (615) 397-0742	$3,875	BOTH	PC, XT/AT PS-2 or comp.	MENU	B,C,E
Interactive DiskCourse Key Learning Centers 21 S Huckleberry Dr. Norwalk, CT 06850 (203) 847-2368	CALL	DEMO	Mac II	ICON	B,C,D,E
Interactive Virtual Video V_Graph Inc Box 105 1275 Westown Thorton Rd. Westown, PA 19395 (215) 399-1521	$4,500	BOTH	Targa-16, Vision16 CGA, EGA, VGA	MENU	A,B,C,D,E

Directory of Authoring Systems

Company/System	Cost	Demo/Eval Available	Hardware Requirements	System Type	Special Notes
InterFlex Catharon Productions, Inc. Konig Rd. Ghent, NY 12075 (518) 392-9003	$2,000	BOTH	286 comp. EGA	TEMP	C,D,E
IV-D Computer Sciences Corp. 813 Diligence Dr. #110 Newport News, VA 23606 (804) 873-1024	$995	DEMO	PC, XT, AT comp.	MENU	A,C,E
IWPS IBM Corp 4111 Northside Pkwy. Internal Zip H05L1 Atlanta, GA 30327 (800) 627-0920	$6,000		PS-2	MENU	C,D,E
KAware Disk Publisher Knowledge Access Int'l 2685 Marini Way, Suite 1305 Mountain View, CA 94043 (415) 969-0606	$995	BOTH	PC	MENU	D
KSS: Author Comware Inc 4225 Malsbary Rd. Cincinnati, OH 45242 (513) 791-4224	$995	EVAL	PC, XT, AT comp. 512K	MENU	A,C,D,E
LessonCard™ C.H. Love & Co. Inc. 220 Cypress Abilene, TX 79601 (800) 527-4248	$200	BOTH	MacPlus, 1MB	MENU	A,B,C,D,E
Leverage Language Authoring Sys. Creative Learning Systems 7901 4th Street North, Suite 207 St. Petersburg, FL 33702 (813) 579-4597	CALL	BOTH	XT 512K	COMM	A,B,E
Linkway IBM Corp 4111 Northside Pkwy. Internal Zip H05L1 Atlanta, GA 30327 (800) 627-0920	$140		PC, XT, AT PS-2 comp. 512K Graphic Display	MENU	A,B,C,D,E
Linx™ Warren-Forthought, Inc. 1212 N. Velasco Angleton, TX 77515 (409) 849-1239	$695 - $9,000	BOTH	Mac color Quickdraw	MENU	A,B,C,D,E
LS/1 IBM Corp 4111 Northside Pkwy. Internal Zip H05L1 Atlanta, GA 30327 (800) 627-0920	$6,500		XT	MENU	B,C,D,E
MacVideo Interactive Edudisc, Inc 1400 Tyne Blvd. Nashville, TN 37215 (615) 373-2506	$1,995	BOTH	Mac II, Apple or Radius Monitor MacVideo Board	ICON	A,C,D,E

Directory of Authoring Systems

Company/System	Cost	Demo/Eval Available	Hardware Requirements	System Type	Special Notes
Mesa Interactive Tech Inc PO Box 948 Springdale, AR 72765 (501) 442-0301	$495	DEMO	PC comp.	MENU	A,C,E
MicroInstructor Mosby Co. 11830 Westline Industrial Dr. St. Louis, MO 63146 (800) 325-4177	CALL	BOTH	IBM PC comp. Apple comp.	MENU	A
NATAL Softwords 4252 Commerce Circle Victoria, BC, Canada V8Z 4M2 (604) 727-6522	$1,495	DEMO	PC,XT, AT comp.	MENU	C,E
PC Interact Ridgewood Industries, Inc. PO Box 409 Glenview, IL 60025 (708) 724-9273	$495		PC, XT, AT, PS-2 comp.	MENU	A,B
Plato W.R. Roach Organization 4660 W 77th St. Edina, MN 55435 (800) 869-2000	CALL		MS-DOS 386 LAN, 640K	MENU	A,B,D
Phoenix Micro Goal Sys Intl. 7965 N. High St. Columbus, OH 43235 (614) 888-1775	CALL	BOTH	PC comp., 530K	MENU	A,B,C,D,E
Propi Asys Computer Sys 104 Viewcrest Rd. Bellingham, WA 98225 (206) 734-2553	CALL	EVAL		MENU	A,B,C,D,E
PCS Sage Software 1700 NW 167th Pl. Beaverton, OR 97006 (800) 547-4000	$495	BOTH	DOS comp.	MENU	A,B,C,D,E
Quest Allen Communications 5225 Wiley Post Way Salt Lake City, UT 84116 (801) 537-7800	$1795	BOTH	640K, EGA, VGA 2MB Hard Drive	MENU	A,B,C,D,E
Quest Synesis Corporation 200 Hembree Circle Dr. Roswell, GA 30076 (404) 457-6788	$1795	BOTH	DOS comp.	MENU	A,B,C,D,E
Reference Set™ Reference Technology 5775 Flatiron Pkwy. Boulder, CO 80301 (303) 449-4157	$12,000	BOTH	IBM AT Hard Drive	MENU	D

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Saber Pinnacle Courseware Inc 4340 Stevens Creek Blvd. Suite 202 Cupertino, CA 95129 (408) 249-8383	CALL	BOTH	PC comp.	MENU	A,C,D,E
Sage WICAT Systems Inc 1875 S. State St. Orem, UT 84057 (801) 224-6400	CALL	BOTH	PC comp.	MENU	A,B,C,D,E
SAM Technology Applications Group 1700 West Big Beaver Rd. Suite 265 Troy, MI 48084 (313) 649-5200	$2,500	BOTH 640K	XT w/CGA	MENU	A,B,C,D,E
SAM for Windows Technology Applications Group 1700 West Big Beaver Rd. Suite 265 Troy, MI 48084 (313) 649-5200	$3,000	BOTH	Windows 3.0	MENU	A,B,C,D,E
Showcase California Synfuels Research PO Box 7000-47 Palos Verdes Pen., CA 90274 (213) 375-7772	$595		PC, XT, AT, PS-2	COMM	C,D,E
Socratic Authoring System Solutions Unlimited PO Box 140 Edgecomb, ME (207) 882-6222	$695	DEMO	PC,PS-2 comp. 640K	MENU	A,B,C
Summit Conceptual Systems Inc 1010 Wayne Ave., Suite 1420 Silver Spring, MD 20910 (301) 589-1800	$2,500	BOTH	XT,AT,PS-2 512K Color Monitor	MENU	A,B,C,D,E
Syllabus Teaching by Computer, Inc. 25 Regent Circle Brookline, MA 02146 (617) 734-2128	$5,000	BOTH	PC comp.	MENU	A.B,C,E
Teachers Aide Selection Sys Inc 2731 77th St. SE Mercer Island, WA 98040 (206) 236-2700	$7,200	BOTH	MS-DOS 350K Color Monitor	MENU	A,B,C,E
tbt AUTHOR HyperGraphics Corp 308 N Carroll Denton, TX 76201 (817) 565-0004	$2,500	BOTH	PC comp.	MENU	A,B,C,E
TenCORE Computer Teach. Corp 1713 S. Neil St. Champaign, IL 61820 (217) 352-6363	$2,400	BOTH	PC, XT, AT, PS-2 comp., 512K	MENU	A,B,C,D,E

Directory of Authoring Systems

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TenCORE Producer Computer Teach. Corp 1713 S. Neil St. Champaign, IL 61820 (217) 352-6363	$1,800	BOTH	PC, XT, AT, PS-2 comp., 512K	MENU	A,B,C,D,E
TIE Global Info. Sys. Tech. 1800 Woodfield Dr. Savoy, IL 61874 (217) 352-1165	$2,500	EVAL	386, VGA, 2MB Wjndows 3.0	MENU	A,B,C,E
Trainer Wonder Corp. 51 Winchester St. Newton Highlands, MA 02161 (617) 965-8400	$1,900	DEMO	PC, PS-2 comp.	MENU	C,D,E
Trainer 4000 Computer Sys Research Inc 40 Darling Dr. Avon, CT 06001 (800) 922-1190	$1,820	BOTH	PC comp Color monitor	MENU	A,B,C,E
Tutor-Tech Techware Corp. PO Box 151085 Altamonte Springs, FL 32715 (407) 695-9000	$195	BOTH	Apple II series Laser 128	MENU	A,B,C,D,E
Unison Courseware Applications 481 Devonshire Dr. Champaign, IL 61820 (217) 359-1878	$345	BOTH	PC comp.	COMM	A,B,C,D,E
Unix Author Mentor Resources 1 Tara Blvd. Nashua, NH 03062 (603) 888-2580	$5,000	DEMO	Unix System V 386	Menu	A
Virtual Video Producer V_Graph Inc Box 105 1275 Westown Thorton Rd. Westown, PA 19395 (215) 399-1521	$199	BOTH	PC, CGA, EGA VGA	MENU	A,B,C,D,E
VideodiscWriter Whitney Educational Services PO Box 25147 San Mateo, CA 94402 (415) 341-5818	$389		MacPlus	MENU	A,B,C,D,E
VidKit 2.0 Videodiscovery 1515 Dexter Ave. N. Seattle, WA 98109 (800) 548-3472	$275		PC,XT,AT PS-2 Model 25	MENU	A,C
VS Author Mentor Resources Inc 1 Tara Blvd. Nashua, NH 03062 (603) 888-2580	$5,000	BOTH	WANG VS	MENU	A
Wise WICAT Systems Inc 1875 S. State St. Orem, UT 84057 (801) 224-6400	CALL	BOTH	PC comp.	MENU	A,B,C,D,E

MATLAB Functions for the Analysis and Design of Model Predictive Control Systems

By Professor Manfred Morari, California Institute of Technology, and Professor N. Lawrence Ricker, University of Washington [1]

CACHE-Tools is a collection of functions (commands) developed for the analysis and design of model predictive control systems. Model predictive control was conceived in the 1970s primarily by industry. Its popularity has steadily increased throughout the 1980s. At present, there is little doubt that it is the most widely used multivariable control algorithm in the chemical process industries and in other areas. While MPC is suitable for almost any kind of problem, it displays its main strength when applied to problems with

- a large number of manipulated and controlled variables
- constraints imposed on both the manipulated and controlled variables
- changing control objectives and / or equipment (sensor / actuator) failure
- time delays

Some of the popular names associated with model predictive control are Dynamic Matrix Control (DMC), IDCOM, model algorithmic control, etc. While these algorithms differ in certain details, the main ideas behind them are very similar. Indeed, in its basic unconstrained form MPC is closely related to linear quadratic optimal control. In the constrained case, however, MPC leads to an optimization problem which is solved on-line in real time at each sampling interval. MPC takes full advantage of the power available in today's control computer hardware.

The software and the accompanying manual are not intended to teach the user the basic ideas behind MPC. Background material is available in standard textbooks like those authored by Seborg, Edgar and Mellichamp (1989)[2], Deshpande and Ash (1988)[3], and the monograph devoted solely to this topic authored by Morari and coworkers (Morari et al., 1992)[4]. The following article assumes some familiarity with the basic features of MATLAB (see the article by J. Kantor, CACHE Newsletter, Spring 1989, **28**: 27-36).

The package is intended for the classroom and for the practicing engineer. It can assist in communicating the concepts of MPC to a student in an introductory control course. At the same time it is sophisticated enough to allow an engineer in industry to become trained in MPC. For more complex applications MPC-Tools is recommended which can be obtained from MathWorks and includes tolls for model identification, noise filtering, and stability and performance analysis.

The MPC Toolbox runs on all computers for which MATLAB is available.[5]

The MPC analysis and simulation algorithms are numerical intensive and require approximately 1MB of memory on an Apple Macintosh or IBM-PC compatible computer, depending on the number of inputs and outputs. The available memory on either a Macintosh or an IBM-PC compatible computer may limit the size of the systems handled by the CACHE-Tools package. A numerical co-processor chip is essential.

Step Response Models

Step response models are based on the following idea. Assume that the system is at rest. For a linear time-invariant single-input single-output (SISO) system let the output change for a unit input change Δv be given by

$$\{0, s_1, s_2, \ldots, s_n, s_n, \ldots\}$$

Here we assume that the system settles exactly after n steps.

1 This article was written in cooperation with Douglas B. Raven, Yaman Arkun, Nikolaos Bekiaris, Marc S. Gelormino, Evelio Hernandez, Jay H. Lee, Yusha Liu, Simone L. Oliveira, Shwu-Yien Yang, and Zhi Q. Zheng.

2 D.E. Seborg, T.F. Edgar, D.A. Mellichamp; Process Dynamics and Control; John Wiley & Sons, 1989

3 P.B. Deshpande, R.H. Ash; *Computer Process Control with Advanced Control Applications*, 2nd ed., ISA, 1988

4 M. Morari, C.E. Garcia, J.H. Lee, D.M. Prett; *Model Predictive Control;* Prentice Hall, 1992

5 To enquire about MATLAB licenses contact The Math Works, Inc.; phone (508) 653-1415, fax (508) 653-2997, e-mail: info@mathworks.com.

The step response $\{s_1, s_2, \ldots, s_n\}$ constitutes a complete model of the system, which allows us to compute the system output for any input sequence:

$$y(k) = \sum_{i=1}^{n} s_i \Delta v(k-i) + s_n v(k-n-1)$$

Step response models can be used for both stable and integrating processes. For an integrating process it is assumed that the slope of the response remains constant after *n* steps, i.e.

$$s_n - s_{n-1} = s_{n+1} - s_n = s_{n+2} - s_{n+1} = \ldots$$

For a multi-input multi-output (MIMO) process with n_v inputs and n_y outputs, one obtains a series of step response coefficient matrices

$$S_i = \begin{bmatrix} s_{1,1,i} & s_{1,2,i} & \cdots & s_{1,n_v,i} \\ s_{2,1,i} & & & \\ \vdots & & & \\ s_{n_y,1,i} & s_{n_y,2,i} & \cdots & s_{n_y,n_v,i} \end{bmatrix}$$

where $s_{\ell,m,i}$ is the m^{th} step response coefficient relating the input to the i^{th} output.

The step response can be obtained directly from identification experiments, or generated from a continuous or discrete transfer function or state-space model. For example, if the discrete system description (sampling time $T = 0.1$) is

$$y(k) = -0.5y(k-1) + v(k-3)$$

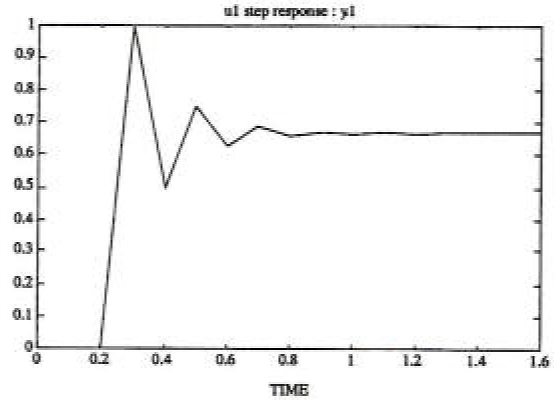
then the transfer function is

$$g(z) = \frac{z^{-3}}{1 + 0.5z^{-1}}$$

The following commands generate the step response model for this system and plot it:

```
num = 1; % numerator polynomial coefficients
den = [1 0.5]; % denominator polynomial
   coefficients
delt1 = 0.1; % sampling time
delay = 2;
g = poly2tf (num,den,delt1,delay); % Set up
   the model in tf format
tfinal = 1.6;
delt2 = delt1;
nout = 1; % indicates that system is
   nonintegrating/stable
```

```
plant = tf2step (tfinal,delt2,nout,g); %
   Calculate the step response
plotstep (plant) % Plot the step response
```

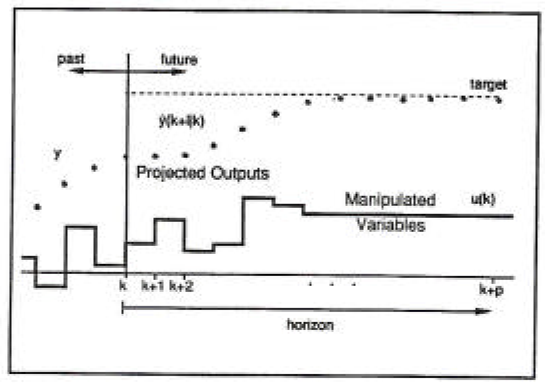


We can get some information on the contents of a matrix in CACHE-Tools via the command inform. For our example, `inform(plant)` returns:

```
This is a matrix in MPC Step format.
   sampling time = 0.1
   number of inputs = 1
   number of outputs = 1
number of step response coefficients = 16
All outputs are stable.
```

Unconstrained Model Predictive Control

The MPC control law can be most easily derived by referring to the following figure.



For any assumed set of present and future control moves $\Delta v(k), \Delta v(k+1), \ldots, \Delta v(k+m-1)$ the future behavior of the process outputs $y(k+1|k), y(k+2|k), \ldots, y(k+p|k)$ can be predicted over a horizon p. The m present and future control proves $(m \leq p)$ are computed to minimize a quadratic objective of the type

$$\min_{u(k)\ldots u(k+m-1)} \sum_{\ell=1}^{p} \|\Gamma_\ell^y [y(k+\ell|k) - r(k+\ell)]\|^2 + \sum_{\ell=1}^{m} \|\Gamma_\ell^u [\Delta u(k+\ell-1)]\|^2.$$

Here Γ_ℓ^y and Γ_ℓ^u are weighting matrices to penalize particular components of y or u at particular future time intervals. $r(k+\ell)$ is the (possibly time-varying) vector of future reference values (setpoints). Though m control moves are calculated, only the first one $(\Delta u(k))$ is implemented. At the next sampling interval, new values of the measured output are obtained, the control horizon is shifted forward by one step and the same computations are repeated. The resulting control law is referred to as "moving horizon" or "receding horizon".

The predicted process outputs $y(k+1|k), \ldots, y(k+p|k)$ depend on the current measurement $\hat{y}(k)$ and the assumptions we make about the unmeasured disturbances and the measurement noise affecting the outputs. CACHE-Tools assumes that the unmeasured disturbances for each output are steps and that there is no measurement noise. The same assumption is used in conventional Dynamic Matrix Control (DMC).

Under the stated assumptions, it can be shown that a linear time-invariant feedback control law results

$$\Delta u(k) = K_{MPC} E_p(k+1|k)$$

where $E_p(k+1|k)$ is the vector of predicted future errors over the horizon p which would result if all present and future manipulated variable moves were equal to zero $\Delta u(k) = \Delta u(k+1) = 0$.

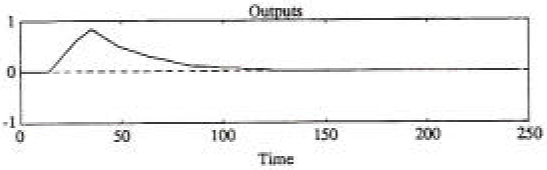
The stability of the closed-loop system depends only on K_{MPC} which in turn is affected by the horizon p, the number of moves m and the weighting matrices Γ_ℓ^y and Γ_ℓ^u. No precise conditions on m, p, Γ_ℓ^u and Γ_ℓ^y exist which guarantee closed-loop stability. In general, decreasing m relative to p makes the control action less aggressive and tends to stabilize a system. More commonly, Γ_ℓ^u is used as a tuning parameter. Under certain mild assumptions, it can be shown that a closed-loop system can always be stabilized by choosing Γ_ℓ^u sufficiently large. Increasing Γ_ℓ^u always has the effect of making the control action less aggressive.

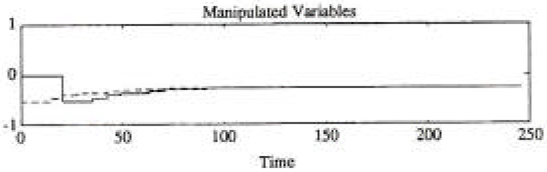
All controllers designed with CACHE-Tools track steps asymptotically error-free (Type 1). If the model is integrating, ramps are also tracked error-free (Type 2).

Example

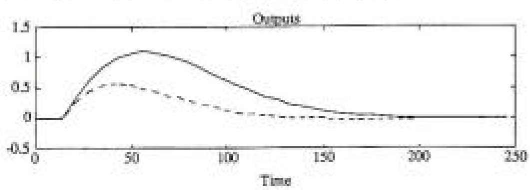
```
% Plant transfer function: g = 5.72exp(-
   14s)/60s+1)
% Disturbance transfer function:  gd =
   1.52exp (-15s)/(25s+1)
%
% Build the step response models for a
   sampling period of 7.
delt1=0; % continuous model
delay1=14; num1=5.72;
den1=[60 1]
g = poly2tf(num1,den1,delt1,delay1);
tfinal = 245;
delt2 = 7;
nout1 = 1;
plant = tf2step(tfinal,delt2, nout1, g); %
   step response of plant
delay2 = 15;
num2 = 1.52;
den2 = [25,1];
gd = poly2tf(num2,den2,delt2,nout2, gd); %
   step response of disturbance model
%
% Calculate the MPC controller gain matrix
   for
% No plant/model mismatch,
% Output Weight = 1, Input Weight = 0
% Input Horizon = 5, Output Horizon = 20
model = plant;
ywt = 1; uwt = 0;
M = 5; P = 20;
Kmpc1 = mpccon (model,ywt,uwt,M,P);
%
% Simulate and plot response for unmeasured
   and measured
% step disturbance through dplant.
tend = 245;
r = []; usat = []; tfilter = [];
dmodel = []; % unmeasured disturbances,
   i.e. no feed forward
dstep = 1;
[y1,u1] = mpcsim (plant,model,Kmpc1,
   tend,r,usat,tfilter,dplant,
   dmodel,dstep);
dmodel = dplant; % measured disturbance,
   i.e. feed forward
[y2,u2] = mpcsim (plant,model,Kmpc1,
   tend,r,usat,tfilter,dplant,
   dmodel,dstep);
plotall ([y1,y2],[u1,u2],delt2);
pause; % Perfect rejection for measured
   disturbance case.
```

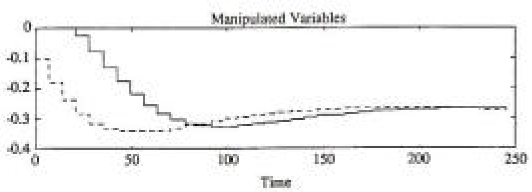
![]






```
%
%  Calculate a new MPC controller gain
   matrix for
%  No plant/model mismatch,
%  Output Weight = 1, Input Weight = 10
%  Input Horizon = 5, Output Horizon = 20
model = plant;
ywt = 1; uwt = 10;
M = 5; P = 20;
Kmpc2 = mpccon (model,ywt,uwt,M,P);
%
%  Simulate and plot response for unmeasured
   and measured
%  step disturbance through dplant.
tend = 245;
r = []; usat = []; tfilter = [];
dmodel = [];
dstep = 1;
[y^3,u^3] = mpcsim (plant,model,Kmpc2,
   tend,r,usat,tfilter,dplant,
   dmodel,dstep);
dmodel = dplant; % measured disturbance
[y^4,u^4] = mpcsim (plant,model,Kmpc2,
   tend,r,usat,tfilter,dplant,
   dmodel,dstep);
plotall ([y^3,y^4],[u^3,u^4],delt2);
```





Constrained Model Predictive Control

The control action can be computed subject to hard constraints on the manipulated variables and the outputs.

Manipulated variable constraints:

$$u_{min}(\ell) \leq u(k+\ell) \leq u_{max}(\ell)$$

Manipulated variable rate constraints:

$$|\Delta u(k+\ell)| \leq \Delta u_{max}(\ell)$$

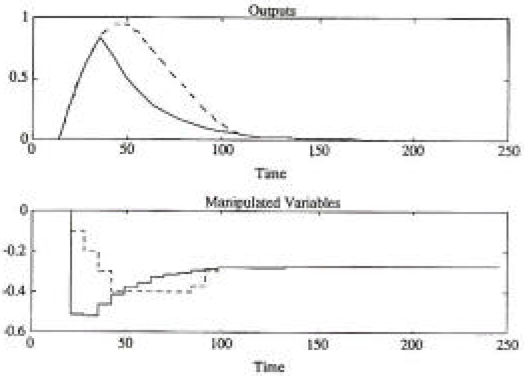
Output variable constraints:

$$y_{min}(\ell) \leq y(k+\ell|k) \leq y_{max}(\ell)$$

When hard constraints of this form are imposed, a quadratic program has to be solved at each time step to determine the control action and the resulting control law is generally nonlinear. The performance of such a control system has to be evaluated via simulation.

Example

```
%  Simulate and plot response for unmeasured
   step
%  disturbance through dplant with and
   without
%  input constraints.
%  No plant/model mismatch,
%  Output Weight = 1, Input Weight = 0
%  Input Horizon = 5, Output Horizon = 20
model = plant;
ywt = 1; uwt = 0;
M =5; P = 20;
tend = 245;
r = 0;
ulim = []; % no constraints
ylim = []; tfilter = []; dmodel = [];
dstep = 1;
[y^9,u^9] = cmpc (plant,model,ywt,uwt,
   M,P,tend,r,ulim,ylim,tfilter, dplant,
   dmodel,dstep);
%  Minimum Constraint on Input = -0.4
%  Maximum Constraint on Input = inf
%  Delta Constraint on Input = 0.1
ulim = [-0.4, inf, 0.1]; % impose con-
   straints
[y^10,u^10] = cmpc (plant,model,ywt,
   uwt,M,P,tend,r,ulim,ylim,tfilter,dplant,
   dmodel,dstep);
plotall ([y^9,y^10],[u^9,u^10],delt2);
```



CACHE - Tools Commands Grouped by Function

Model Conversions

imp2step	Combines MISO impulse response models to form MIMO models in MPC *step* format.
poly2tf	Converts a transfer function in poly format to MPC *tf* format.
ss2step	Converts a state-space model to MPC *step* format.
tf2step	Converts a model in MPC *tf* format to MPC *step* format.

Controller Design and Simulation MPC *step* format

cmpc	Solves the quadratic programming problem to simulate performance of a closed-loop system with input and output constraints.
mpccon	Calculates the unconstrained controller gain matrix for MPC.
mpcsim	Simulates a closed-loop system with optional saturation constraints on the manipulated variables.

Plotting and Matrix Information

inform	Outputs matrix type and attributes of system representation.
plotall	Plots outputs and inputs from a simulation run on one graph.
ploteach	Makes separate plots of outputs and / or inputs from a simulation run.
plotstep	Plots the coefficients of a model in MPC *step* form.

Utility Functions

dantzgmp	Solves quadratic programs.
stair	Creates the "stairstep" format used to plot manipulated variables.
cp2dp	Converts a continuous-time SISO system to the discrete time version.

CACHE
Model Predictive Control Toolbox
(CACHE-Tools)

MATLAB Functions for the Analysis and Design of Model Predictive Control Systems

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Microcomputer Chemical Engineering Programs (developed by Professors)

Modern Authoring Systems for Computer Based Educational Materials

MATLAB Functions for the Analysis and Design of Model Predictive Control Systems

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