Chemical Process Performance Evaluation

CHEMICAL INDUSTRIES

A Series of Reference Books and Textbooks

Founding Editor

HEINZ HEINEMANN
Berkeley, California

Series Editor

JAMES G. SPEIGHT
Laramie, Wyoming

1. *Fluid Catalytic Cracking with Zeolite Catalysts,* Paul B. Venuto and E. Thomas Habib, Jr.
2. *Ethylene: Keystone to the Petrochemical Industry,* Ludwig Kniel, Olaf Winter, and Karl Stork
3. *The Chemistry and Technology of Petroleum,* James G. Speight
4. *The Desulfurization of Heavy Oils and Residua,* James G. Speight
5. *Catalysis of Organic Reactions,* edited by William R. Moser
6. *Acetylene-Based Chemicals from Coal and Other Natural Resources,* Robert J. Tedeschi
7. *Chemically Resistant Masonry,* Walter Lee Sheppard, Jr.
8. *Compressors and Expanders: Selection and Application for the Process Industry,* Heinz P. Bloch, Joseph A. Cameron, Frank M. Danowski, Jr., Ralph James, Jr., Judson S. Swearingen, and Marilyn E. Weightman
9. *Metering Pumps: Selection and Application,* James P. Poynton
10. *Hydrocarbons from Methanol,* Clarence D. Chang
11. *Form Flotation: Theory and Applications,* Ann N. Clarke and David J. Wilson
12. *The Chemistry and Technology of Coal,* James G. Speight
13. *Pneumatic and Hydraulic Conveying of Solids,* O. A. Williams
14. *Catalyst Manufacture: Laboratory and Commercial Preparations,* Alvin B. Stiles
15. *Characterization of Heterogeneous Catalysts,* edited by Francis Delannay
16. *BASIC Programs for Chemical Engineering Design,* James H. Weber
17. *Catalyst Poisoning,* L. Louis Hegedus and Robert W. McCabe
18. *Catalysis of Organic Reactions,* edited by John R. Kosak
19. *Adsorption Technology: A Step-by-Step Approach to Process Evaluation and Application,* edited by Frank L. Slejko
20. *Deactivation and Poisoning of Catalysts,* edited by Jacques Oudar and Henry Wise
21. *Catalysis and Surface Science: Developments in Chemicals from Methanol, Hydrotreating of Hydrocarbons, Catalyst Preparation, Monomers and Polymers, Photocatalysis and Photovoltaics,* edited by Heinz Heinemann and Gabor A. Somorjai
22. *Catalysis of Organic Reactions,* edited by Robert L. Augustine
23. *Modern Control Techniques for the Processing Industries,* T. H. Tsai, J. W. Lane, and C. S. Lin
24. *Temperature-Programmed Reduction for Solid Materials Characterization,* Alan Jones and Brian McNichol
25. *Catalytic Cracking: Catalysts, Chemistry, and Kinetics,* Bohdan W. Wojciechowski and Avelino Corma
26. *Chemical Reaction and Reactor Engineering,* edited by J. J. Carberry and A. Varma
27. *Filtration: Principles and Practices: Second Edition,* edited by Michael J. Matteson and Clyde Orr
28. *Corrosion Mechanisms,* edited by Florian Mansfeld
29. *Catalysis and Surface Properties of Liquid Metals and Alloys,* Yoshisada Ogino
30. *Catalyst Deactivation,* edited by Eugene E. Petersen and Alexis T. Bell
31. *Hydrogen Effects in Catalysis: Fundamentals and Practical Applications,* edited by Zoltán Paál and P. G. Menon
32. *Flow Management for Engineers and Scientists,* Nicholas P. Cheremisinoff and Paul N. Cheremisinoff
33. *Catalysis of Organic Reactions,* edited by Paul N. Rylander, Harold Greenfield, and Robert L. Augustine
34. *Powder and Bulk Solids Handling Processes: Instrumentation and Control,* Koichi Iinoya, Hiroaki Masuda, and Kinnosuke Watanabe
35. *Reverse Osmosis Technology: Applications for High-Purity-Water Production,* edited by Bipin S. Parekh
36. *Shape Selective Catalysis in Industrial Applications,* N. Y. Chen, William E. Garwood, and Frank G. Dwyer
37. *Alpha Olefins Applications Handbook,* edited by George R. Lappin and Joseph L. Sauer
38. *Process Modeling and Control in Chemical Industries,* edited by Kaddour Najim

39. *Clathrate Hydrates of Natural Gases,* E. Dendy Sloan, Jr.
40. *Catalysis of Organic Reactions,* edited by Dale W. Blackburn
41. *Fuel Science and Technology Handbook,* edited by James G. Speight
42. *Octane-Enhancing Zeolitic FCC Catalysts,* Julius Scherzer
43. Oxygen in Catalysis, Adam Bielanski and Jerzy Haber
44. *The Chemistry and Technology of Petroleum: Second Edition, Revised and Expanded,* James G. Speight
45. *Industrial Drying Equipment: Selection and Application,* C. M. van't Land
46. *Novel Production Methods for Ethylene, Light Hydrocarbons, and Aromatics,* edited by Lyle F. Albright, Billy L. Crynes, and Siegfried Nowak
47. *Catalysis of Organic Reactions,* edited by William E. Pascoe
48. *Synthetic Lubricants and High-Performance Functional Fluids,* edited by Ronald L. Shubkin
49. *Acetic Acid and Its Derivatives,* edited by Victor H. Agreda and Joseph R. Zoeller
50. *Properties and Applications of Perovskite-Type Oxides,* edited by L. G. Tejuca and J. L. G. Fierro
51. *Computer-Aided Design of Catalysts,* edited by E. Robert Becker and Carmo J. Pereira
52. *Models for Thermodynamic and Phase Equilibria Calculations,* edited by Stanley I. Sandler
53. *Catalysis of Organic Reactions,* edited by John R. Kosak and Thomas A. Johnson
54. *Composition and Analysis of Heavy Petroleum Fractions,* Klaus H. Altgelt and Mieczyslaw M. Boduszynski
55. *NMR Techniques in Catalysis,* edited by Alexis T. Bell and Alexander Pines
56. *Upgrading Petroleum Residues and Heavy Oils,* Murray R. Gray
57. *Methanol Production and Use,* edited by Wu-Hsun Cheng and Harold H. Kung
58. *Catalytic Hydroprocessing of Petroleum and Distillates,* edited by Michael C. Oballah and Stuart S. Shih
59. *The Chemistry and Technology of Coal: Second Edition, Revised and Expanded,* James G. Speight
60. *Lubricant Base Oil and Wax Processing,* Avilino Sequeira, Jr.
61. *Catalytic Naphtha Reforming: Science and Technology,* edited by George J. Antos, Abdullah M. Aitani, and José M. Parera
62. *Catalysis of Organic Reactions,* edited by Mike G. Scaros and Michael L. Prunier
63. *Catalyst Manufacture,* Alvin B. Stiles and Theodore A. Koch
64. *Handbook of Grignard Reagents,* edited by Gary S. Silverman and Philip E. Rakita
65. *Shape Selective Catalysis in Industrial Applications: Second Edition, Revised and Expanded,* N. Y. Chen, William E. Garwood, and Francis G. Dwyer
66. *Hydrocracking Science and Technology,* Julius Scherzer and A. J. Gruia
67. *Hydrotreating Technology for Pollution Control: Catalysts, Catalysis, and Processes,* edited by Mario L. Occelli and Russell Chianelli
68. *Catalysis of Organic Reactions,* edited by Russell E. Malz, Jr.
69. *Synthesis of Porous Materials: Zeolites, Clays, and Nanostructures,* edited by Mario L. Occelli and Henri Kessler
70. *Methane and Its Derivatives,* Sunggyu Lee
71. *Structured Catalysts and Reactors,* edited by Andrzej Cybulski and Jacob A. Moulijn
72. *Industrial Gases in Petrochemical Processing,* Harold Gunardson
73. *Clathrate Hydrates of Natural Gases: Second Edition, Revised and Expanded,* E. Dendy Sloan, Jr.
74. *Fluid Cracking Catalysts,* edited by Mario L. Occelli and Paul O'Connor
75. *Catalysis of Organic Reactions,* edited by Frank E. Herkes
76. *The Chemistry and Technology of Petroleum: Third Edition, Revised and Expanded,* James G. Speight
77. *Synthetic Lubricants and High-Performance Functional Fluids: Second Edition, Revised and Expanded,* Leslie R. Rudnick and Ronald L. Shubkin
78. *The Desulfurization of Heavy Oils and Residua, Second Edition, Revised and Expanded,* James G. Speight
79. *Reaction Kinetics and Reactor Design: Second Edition, Revised and Expanded,* John B. Butt
80. *Regulatory Chemicals Handbook,* Jennifer M. Spero, Bella Devito, and Louis Theodore
81. *Applied Parameter Estimation for Chemical Engineers,* Peter Englezos and Nicolas Kalogerakis
82. *Catalysis of Organic Reactions,* edited by Michael E. Ford
83. *The Chemical Process Industries Infrastructure: Function and Economics,* James R. Couper, O. Thomas Beasley, and W. Roy Penney
84. *Transport Phenomena Fundamentals,* Joel L. Plawsky
85. *Petroleum Refining Processes,* James G. Speight and Baki Özüm
86. *Health, Safety, and Accident Management in the Chemical Process Industries,* Ann Marie Flynn and Louis Theodore
87. *Plantwide Dynamic Simulators in Chemical Processing and Control,* William L. Luyben
88. *Chemical Reactor Design,* Peter Harriott
89. *Catalysis of Organic Reactions,* edited by Dennis G. Morrell

90. *Lubricant Additives: Chemistry and Applications*, edited by Leslie R. Rudnick
91. *Handbook of Fluidization and Fluid-Particle Systems*, edited by Wen-Ching Yang
92. *Conservation Equations and Modeling of Chemical and Biochemical Processes*, Said S. E. H. Elnashaie and Parag Garhyan
93. *Batch Fermentation: Modeling, Monitoring, and Control*, Ali Çinar, Gülnur Birol, Satish J. Parulekar, and Cenk Ündey
94. *Industrial Solvents Handbook, Second Edition*, Nicholas P. Cheremisinoff
95. *Petroleum and Gas Field Processing*, H. K. Abdel-Aal, Mohamed Aggour, and M. Fahim
96. *Chemical Process Engineering: Design and Economics*, Harry Silla
97. *Process Engineering Economics*, James R. Couper
98. *Re-Engineering the Chemical Processing Plant: Process Intensification*, edited by Andrzej Stankiewicz and Jacob A. Moulijn
99. *Thermodynamic Cycles: Computer-Aided Design and Optimization*, Chih Wu
100. *Catalytic Naphtha Reforming: Second Edition, Revised and Expanded*, edited by George T. Antos and Abdullah M. Aitani
101. *Handbook of MTBE and Other Gasoline Oxygenates*, edited by S. Halim Hamid and Mohammad Ashraf Ali
102. *Industrial Chemical Cresols and Downstream Derivatives*, Asim Kumar Mukhopadhyay
103. *Polymer Processing Instabilities: Control and Understanding*, edited by Savvas Hatzikiriakos and Kalman B . Migler
104. *Catalysis of Organic Reactions*, John Sowa
105. *Gasification Technologies: A Primer for Engineers and Scientists*, edited by John Rezaiyan and Nicholas P. Cheremisinoff
106. *Batch Processes*, edited by Ekaterini Korovessi and Andreas A. Linninger
107. *Introduction to Process Control*, Jose A. Romagnoli and Ahmet Palazoglu
108. *Metal Oxides: Chemistry and Applications*, edited by J. L. G. Fierro
109. *Molecular Modeling in Heavy Hydrocarbon Conversions*, Michael T. Klein, Ralph J. Bertolacini, Linda J. Broadbelt, Ankush Kumar and Gang Hou
110. *Structured Catalysts and Reactors, Second Edition*, edited by Andrzej Cybulski and Jacob A. Moulijn
111. *Synthetics, Mineral Oils, and Bio-Based Lubricants: Chemistry and Technology*, edited by Leslie R. Rudnick
112. *Alcoholic Fuels*, edited by Shelley Minteer
113. *Bubbles, Drops, and Particles in Non-Newtonian Fluids, Second Edition*, R. P. Chhabra
114. *The Chemistry and Technology of Petroleum, Fourth Edition*, James G. Speight
115. *Catalysis of Organic Reactions*, edited by Stephen R. Schmidt
116. *Process Chemistry of Lubricant Base Stocks*, Thomas R. Lynch
117. *Hydroprocessing of Heavy Oils and Residua*, edited by James G. Speight and Jorge Ancheyta
118. *Chemical Process Performance Evaluation*, Ali Cinar, Ahmet Palazoglu, and Ferhan Kayihan

Chemical Process Performance Evaluation

Ali Cinar
Illinois Institute of Technology
Chicago, Illinois, U.S.A.

Ahmet Palazoglu
University of California
Davis, California, U.S.A.

Ferhan Kayihan
Integrated Engineering Technologies
Tacoma, Washington, U.S.A.

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an informa business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works
Printed in the United States of America on acid-free paper
10 9 8 7 6 5 4 3 2 1

International Standard Book Number-10: 0-8493-3806-9 (Hardcover)
International Standard Book Number-13: 978-0-8493-3806-9 (Hardcover)

Library of Congress Cataloging-in-Publication Data

Cinar, Ali.
Chemical process performance evaluation / Ali Cinar, Ahmet Palazoglu, Ferhan Kayihan.
p. cm. -- (Chemical industries ; 117)
Includes bibliographical references and index.
ISBN 0-8493-3806-9 (alk. paper)
1. Chemical process control--Statistical methods. 2. Chemical industry--Quality control--Statistical methods. I. Palazoglu, Ahmet. II. Kayihan, Ferhan, 1948- III. Title. IV. Series.

TP155.75.C55 2007
660'.281--dc22 2006051787

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

To Mine, Bedirhan and to the memory of my parents
(A. Cinar)

To Mine, Aycan, Omer and my parents
(A. Palazoglu)

To Gulsevin, Arkan, Tarhan and to the memory of my parents
(F. Kayihan)

for Their Love, Support and Inspiration.

Preface

As the demand for profitability and competitiveness increases in the global marketplace, industrial manufacturing operations face a growing pressure to maintain safety, flexibility and environmental compliance. This is a result of pushing the operational boundaries to maximize productivity that may sometimes compromise the safe and rational operational practices. To minimize costly plant shut-downs and to diminish the probability of accidents and catastrophic events, an industrial plant is kept under close surveillance by computerized process supervision and control systems that collect data from process units and analyze the data to assess process status. Over the years, analysis and diagnosis methods have evolved from simple control charts to more sophisticated statistical techniques and signal processing capabilities. The goal of this book is to introduce the reader to the fundamentals and applications of a variety of process performance evaluation approaches, including process monitoring, controller performance monitoring and fault diagnosis. The material covered represents a culmination of decades of theoretical and practical research carried out by the authors and is based on the early notes that supported several short courses that the authors gave over the years. It is intended as advanced study material for graduate students and can be used as a textbook for undergraduate or graduate courses on process monitoring. By emphasizing the balance between the practice and the theory of statistical monitoring and fault diagnosis, it would also be an excellent reference for industrial practitioners, as well as a resource for training courses.

The reader is expected to have a rudimentary knowledge of statistics and have an awareness of general monitoring and control concepts such as fault detection, diagnosis and feedback control. The book will be constructed upon these basic building blocks, introducing new concepts and techniques when necessary. The early chapters of the book present the reader with the use of multivariate statistics and various tools that one can use for process monitoring and diagnosis. This includes a chapter on empirical process modeling and another chapter on the modeling of process signals. In later chapters, several fault diagnosis methods and the means to discriminate between sensor faults and process upsets are discussed in detail. Then, the statistical modeling techniques are extended to the assessment of control performance. The book concludes with an extensive discussion on the use of data analysis techniques for the special case of web and sheet processes. Several case studies are included to demonstrate the implementation of the discussed methods and hopefully to motivate the readers to explore these ideas further in solving their own specific problems. The focus of this

book is on continuous processes. However, there are a number of process applications, especially in pharmaceuticals and specialty chemicals, where the batch mode of operation is used. The monitoring of such processes has been discussed in detail in another book by Cinar *et al.* [41].

For further information on the authors, the readers are referred to the individual Web pages: Ali Cinar, *www.chee.iit.edu/~ cinar/*, Ahmet Palazoglu, *www.chms.ucdavis.edu/research/web/pse/ahmet/*, and Ferhan Kayihan, *ietek.net/*. Furthermore, for supplementary materials and corrections, the readers can access the publisher's Web site *www.crcpress.com* [1].

We are indebted to all our students and colleagues who, over the years, set the challenges and provided the enthusiasm that helped us tackle such an exciting and rewarding set of problems. Specifically, we would like to thank our students S. Beaver, J. DeCicco, F. Doymaz, S. Kendra, F. Kosebalaban-Tokatli, A. Negiz, A. Norvilas, A. Raich, W. Sun, E. Tatara, C. Undey and J. Wong, who have conducted the research related to the techniques discussed in the book. We thank our colleagues, Y. Arkun, F. J. Doyle III, K. A. McDonald, T. Ogunnaike, J. A. Romagnoli and D. Smith for many years of fruitful discussions, colored with lots of fun and good humor. We also would like to acknowledge CRC Press / Taylor & Francis for supporting this book project. This has been a wonderful experience for us and we hope that our readers share our excitement about the future of the field of process monitoring and evaluation.

Ali Cinar
Ahmet Palazoglu
Ferhan Kayihan

[1] Under the menu Electronic Products located on the left side of the screen, click on Downloads & Updates. A list of books in alphabetical order with Web downloads will appear. Locate this book by a search, or scroll down to it. After clicking on the book title, a brief summary of the book will appear. Go to the bottom of this screen and click on the hyperlinked 'Download' that is in a zip file.

Contents

Nomenclature

Symbols

a	Number of principal components retained for a PC model
$a_{i \leftarrow j}$	Transition probability between states i and j
$\mathbf{A} \leftarrow \mathbf{B}$	State and input coefficient matrices in continuous state–space systems
b_i	Inner relation regression coefficient in PLS
b_j	Probability distribution for observation j
$d_i^{\,Q}(\mathbf{x})$	Quadratic discrimination score for the ith population
c_A	Concentration of species A
$CONT_{i \leftarrow j}^{T^2}$	Total contribution of variable x_j to T^2
$cont_{i \leftarrow j}^{T^2}$	Contribution of variable x_j to the normalized score $t_i \triangleleft S_i^2$
$\mathbf{C} \leftarrow \mathbf{D}$	State and input coefficient matrices in output equation of state–space systems
$d(\mathbf{x} \leftarrow \mathbf{y})$	Distance between $\mathbf{x}$ and $\mathbf{y}$
$d_i(\mathbf{x})$	Linear discriminant score for the ith population
$\mathbf{E}$	Residuals matrix $(n \times m)$
$e(k)$	Prediction error (residual) at time k
$E_{[a \leftarrow b]}$	Episode of a signal between points a and b
$\mathbf{F}$	Residuals matrix of quality variables in PLS
F	Feature space

$F_L(d)$, $F_H(d)$	Soft–thresholding and hard–thresholding wavelet filters
$F_W(d)$	Wiener wavelet filter
$\mathbf{F}$, $\mathbf{G}$	State and input coefficient matrices in discrete–time state–space systems
J	Cost function, CPM performance measure
$K(\mathbf{u}, \mathbf{v})$	Kernel function
$\mathbf{M}$	Sphering matrix in ICA
M	Control horizon in MPC
m	Number of process variables in a data set
n	Number of samples in a data set
O	An observable output sequence in a HMM
$\mathbf{P}$	Loadings matrix $(m \times a)$
$\mathbf{p}$	Loadings vector $(m \times 1)$
$\mathbf{p}_i$	PC loading i, ordered eigenvector i of $\mathbf{X}^\mathbf{T}\mathbf{X}$
P	Prediction horizon in MPC
$\mathbf{Q}$	Weight matrix of quality variables in PLS
q	Flow rate
q	Number of quality variables in a data set
q	Shift operator in time series models
q^{-1}	Backward shift operator in time series models
$\mathbf{Q}$, $\mathbf{R}$	Positive definite weight matrices in MPC
$\mathbf{R}$	Residuals block matrix in multipass sensor FDD
R_i	Range of variable i
r_i	Residual based on the PC model for fault i
r_l	Autocorrelation at lag l
$r_{s,index}$	Sensor index of residuals
$r_{x,y}$	Crosscorrelation between x and y
$RCI_{j,\alpha}$	Residual contribution index for jth variable with confidence level α
$\mathbf{S}$	Covariance matrix
S	A Markov state
s_i	Score distance based on the PC model for fault i
s_i^2	Variance of variable i
$SCI_{j,\alpha}$	Scores contribution index for jth variable with confidence level α
$\mathbf{S}_B$	Between–class scatter matrix
$\mathbf{S}_W$	Within–class scatter matrix
$\mathbf{S}_Y$	Total scatter matrix
$\mathbf{T}$	Scores matrix $(n \times a)$
$\mathbf{t}$	Scores vector $(n \times 1)$
T	Length of observation sequence in a HMM
T	Temperature
T^2	Hotelling's T^2 statistic
$TRAN$	Matrix defined in Eq. 7.2
$\mathbf{U}$	Scores matrix of quality variables in PLS
v	An observation symbol in a HMM
$\mathbf{v}_P$	Plant noise
$\mathbf{v}_y$	Output sensor noise
$\mathbf{w}$	FDA vectors to maximize scatter between classes
$w(t-\tau)$	A STFT window function centered at τ
$\mathbf{W}_1$, $\mathbf{W}_2$	Disturbance coefficients matrix to state variables and outputs, respectively
$\mathbf{W}$	Weight matrix of process variables in PLS

$\mathbf{W}$	Projection matrix
$\bar{x}$	Sample mean of variable x
$\mathbf{X}$	Process variables data matrix $(x \times m)$
$\mathbf{Y}$	Quality variables data matrix $(x \times q)$
$z(k)$	A discrete signal evaluated at time instant k
$z(t)$	A continuous signal evaluated at time t

Greek Characters

β	Low–pass filter constant
$\boldsymbol{\beta}$	Vector of regression coefficients
Δ	Magnitude of step change
ϵ	Random variation (uncorrelated zero-mean Gaussian), measurement error
$\gamma_{\#}$	CPM performance measures (#: *hist*, *des*)
κ	Ridge parameter
λ	A HMM
λ	Forgetting factor
λ_i	ith eigenvalue
ω	Frequency
π	Initial HMM state distribution
π_i	Classes of events such as distinct operation modes $i = 1, \ldots, g$
$\boldsymbol{\Sigma}$	Covariance matrix
σ	Standard deviation
$\boldsymbol{\theta}$	Model parameters vector
θ_E	Euclidian angle between points a and b with vertex at the origin
θ_M	Mahalanobis angle between a and b with vertex at origin
τ	Target for the mean, first–order system time constant
$\boldsymbol{\Phi}$	MPC cost function
ϕ	Autoregressive parameter, residual Mahalanobis angle
$\phi(k)$	MPC cost function at time k
$\phi : X \rightarrow F$	Nonlinear map from input space X to feature space F
$\psi(t)$	A wavelet function
$\psi_{s,u}$	A wavelet function with dilation parameter s and translation parameter u

Subscripts

$0, \mathbf{0}$	Initial conditions
c	Coolant
f	Feed
min	Minimum value of a variable
m, max	Maximum values of a variable
r	Reference state/value
s	Steady–state

Superscripts

T	Transpose of a matrix

Abbreviations

AIC	Akaike information criteria
ANN	Artificial neural network
AR	Autoregressive

ARIMA	Autoregressive integrated moving average
ARL	Average run length
ARMA	Autoregressive moving average
ARMAX	Autoregressive moving average with exogenous inputs
ARX	Autoregressive model with exogenous inputs
ASM	Abnormal situation management
ASR	Automatic speech recognition
BESI	Backward elimination sensor identification
BJ	Box-Jenkins
BSSIR	Backward substitution for sensor identification and reconstruction
CC	Correlation coefficient
CWT	Continuous wavelet transform
CLP	Closed-loop potential
CPCA	Consensus principal components analysis
CPM	Controller performance monitoring
CQI	Continuous quality improvement
CSTR	Continuous stirred tank reactor
CUMPRESS	Cumulative prediction sum of squares
CUSUM	Cumulative sum
CV	Canonical variate
CVA	Canonical variates analysis
CVSS	Canonical variate state space (models)
CL	Centerline of SPM chart
DWT	Discrete wavelet transform
DCS	Distributed control system
DMC	Dynamic matrix control
ECM	Expected cost of misclassification
EM	Expectation maximization
EWMA	Exponentially weighted moving average
FDA	Fisher's discriminant analysis
FDD	Fault detection and diagnosis
FFT	Fast Fourier transform
FPE	Final prediction error
FT	Fourier transform
GUI	Graphical user interface
HMM	Hidden Markov model
HMT	Hidden Markov tree
HPCA	Hierarchical principal components analysis
HPLS	Hierarchical partial least squares
HTST	High–temperature short–time pasteurization
ICA	Independent component analysis
KBS	Knowledge–based system
KDE	Kernel density estimation
LCL	Lower control limit
LWL	Lower warning limit
LFCM	Liquid–fed ceramic melter
LQG	Linear quadratic Gaussian (control problem)
LV	Latent variable
MSE	Mean square error
MA	Moving average
MBPCA	Multiblock principal components analysis
MBPLS	Multiblock partial least squares