

Contents

List of symbols, abbreviations and acronyms	vii
Abstract	xiii
Kurzfassung	xv
1 Introduction	1
2 Nonlinear model-predictive control	5
2.1 Basic idea and scope of model-predictive control	5
2.2 Process models	8
2.3 The optimal control problem	9
2.4 Numerical solution of the optimal control problem	10
2.4.1 Control vector parameterization	11
2.4.2 Discretization of the path constraints	12
2.5 Economic NMPC	12
2.5.1 Economic NMPC as an extension of NMPC	13
2.5.2 Stability	14
3 Wastewater treatment modeling	15
3.1 Wastewater treatment technology	15
3.1.1 Physical and biochemical properties of wastewater	15
3.1.2 Wastewater treatment by the activated sludge process	16
3.1.3 The membrane bioreactor process	18
3.2 Modeling of membrane bioreactor plants	19
3.2.1 Activated sludge models	19
3.2.2 Influent modeling and prediction	24
3.3 Processes and models used in this work	27
3.3.1 The BSM-MBR benchmark model	27
3.3.2 The two-reactor MBR model	33

4	State of the art in activated sludge process control	37
4.1	Current practice	37
4.2	Model-predictive control of activated sludge processes	41
4.2.1	Setpoint-based MPC	41
4.2.2	Economic NMPC	42
4.3	Conclusions	43
4.3.1	Limitations of the current practice in MBR control	43
4.3.2	Perspectives of setpoint-based and economic NMPC for MBR	44
5	Estimating the potential of economic NMPC of MBR under ideal conditions	47
5.1	Design of the economic NMPC law for the BSM-MBR process	48
5.1.1	General form of the dynamic optimization problem	49
5.1.2	Objective function	49
5.1.3	Control horizon	50
5.1.4	Constraints	51
5.1.5	Control inputs	52
5.1.6	Discretization of inputs and path constraints	53
5.2	Simulation procedure and implementation	55
5.2.1	Effluent limits	56
5.2.2	Configuration of the state-of-the-art reference controllers	57
5.2.3	Modification of the benchmarking simulation procedure for economic NMPC	58
5.2.4	Implementation of the simulation	60
5.3	Results of the benchmarking simulation	60
5.3.1	Operating case 1: default BSM-MBR effluent limits	60
5.3.2	Operating case 2: strict effluent limits	65
5.4	Discussion	68
6	Economic and ecological NMPC of MBR with output feedback	71
6.1	Hybrid nonlinear model-predictive control for MBR	72
6.1.1	Basic idea of hybrid NMPC and previous work	74
6.1.2	The hybrid NMPC law	77
6.1.3	Extension and generalization of the hybrid NMPC law for closed-loop MBR control	81
6.2	State estimation for the MBR process	87
6.2.1	State of the art in state estimation for wastewater treatment	88
6.2.2	The Extended Kalman Filter and its variants	89

6.2.3	Sensor model and EKF implementation for the MBR process . . .	95
6.3	Control architecture design	99
6.3.1	Hierarchically structured approaches to model-based control . . .	99
6.3.2	A hierarchical control architecture for economic and ecological NMPC	103
6.3.3	Tracking controller	104
6.4	Application to the MBR process model	106
6.4.1	Prediction and realization of the feed flow and pollutant con- centrations	107
6.4.2	Controller and state estimator tuning	109
6.4.3	Results	113
6.5	Discussion	123
7	Conclusions and outlook	125
A	ASM model equations	129
A.1	ASM 1	129
A.2	ASM 3	129
B	MBR process model equations	135
B.1	BSM-MBR process model	135
B.2	Two-tank MBR model	138
C	Appendix to Chapter 5	142
C.1	Reference controller parameters for BSM-MBR	142
C.2	Detailed eNMPC simulation results	145
D	Appendix to Chapter 6	148
D.1	Output prediction used in the tracking controller algorithm	148
D.2	Transformations of logical expressions	151
D.3	Objective function bounds for the controller sequences	152
	Bibliography	154
	Curriculum Vitae	171