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(54) **WASTEWATER TREATMENT PLANT ONLINE MONITORING AND CONTROL**

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(73) Assignee: **General Electric Company**, Schenectady, NY (US)

(21) Appl. No.: **16/103,886**

(22) Filed: **Aug. 14, 2018**

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(62) Division of application No. 14/234,955, filed on Apr. 22, 2014, now Pat. No. 10,046,995, filed as application No. PCT/US2012/048163 on Jul. 25, 2012.

(60) Provisional application No. 61/574,017, filed on Jul. 26, 2011.

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C02F 3/28	(2006.01)
C02F 3/30	(2006.01)
C02F 3/12	(2006.01)

(52) **U.S. Cl.**

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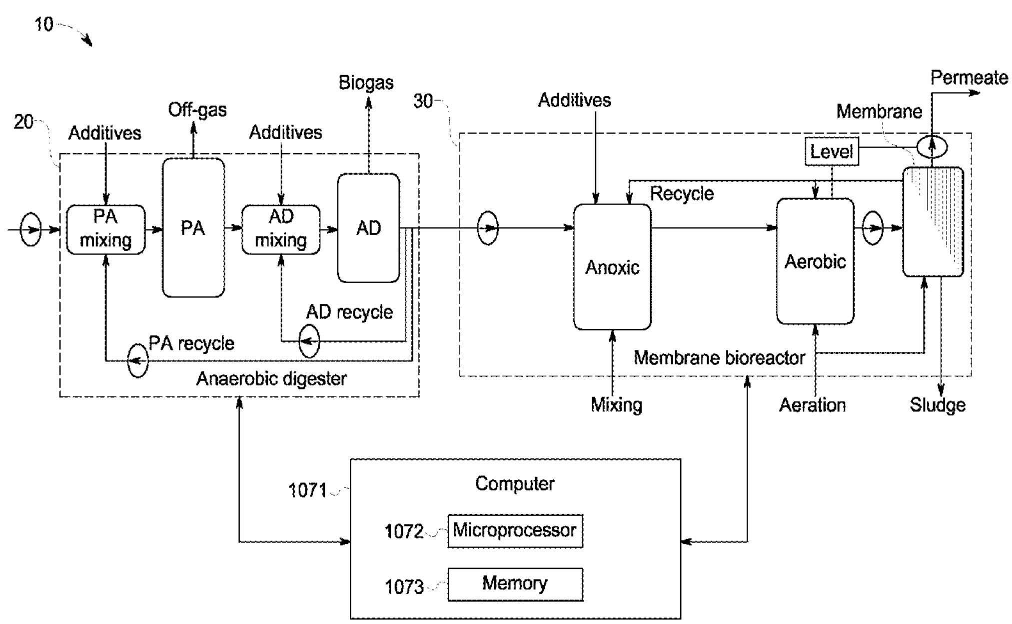
(57) **ABSTRACT**

A method of operating a waste water treatment plant (WWTP) having at least one of an aerobic digester (AD) and a membrane bioreactor (MBR) is described. The method of operating AD is comprised of monitoring and controlling AD in real-time using an online extended Kalman filter (EKF) having a online dynamic model of AD. The EKF uses real-time AD measured data, and online dynamic model of AD to update adapted model parameters and estimate model based inferred variables for AD, which are used for AD control by AD control system having supervisory and low-level control layers. The method of operating MBR is similar to that of AD. The supervisory control ensures the WWTP satisfying the effluent quality requirement while minimize the operation cost. A WWTP having at least one of an AD or MBR is disclosed. The method of operating a WWTP can be implemented using a computer.



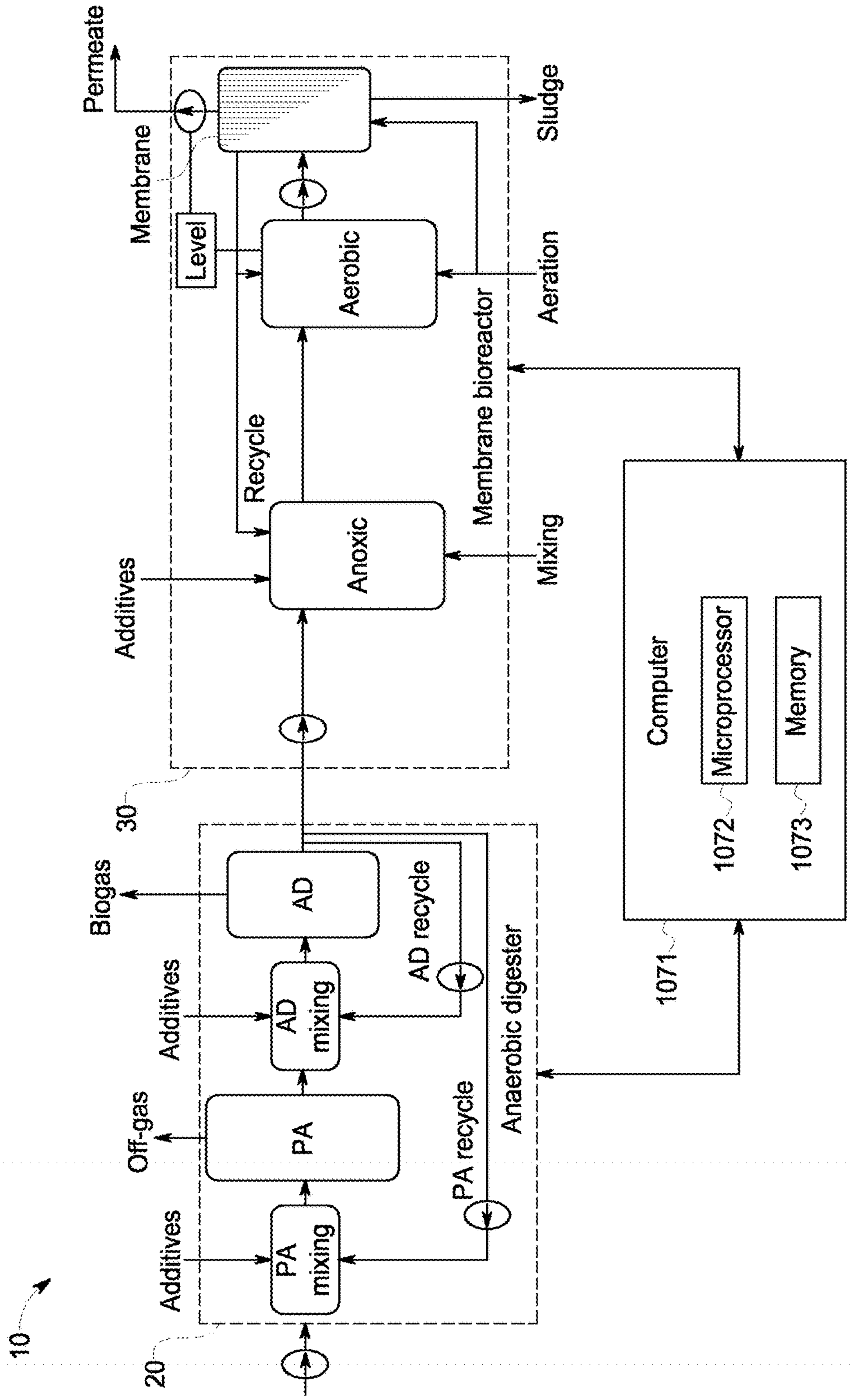

10
20
Additives
PA mixing
PA
Off-gas
PA recycle
Additives
AD mixing
AD recycle
AD
Biogas
Anaerobic digester
30
Additives
Anoxic
Mixing
Recycle
Aerobic
Aeration
Level
Membrane
Permeate
Sludge
Membrane bioreactor
Computer
Microprocessor
Memory
1071
1072
1073

FIG. 1A

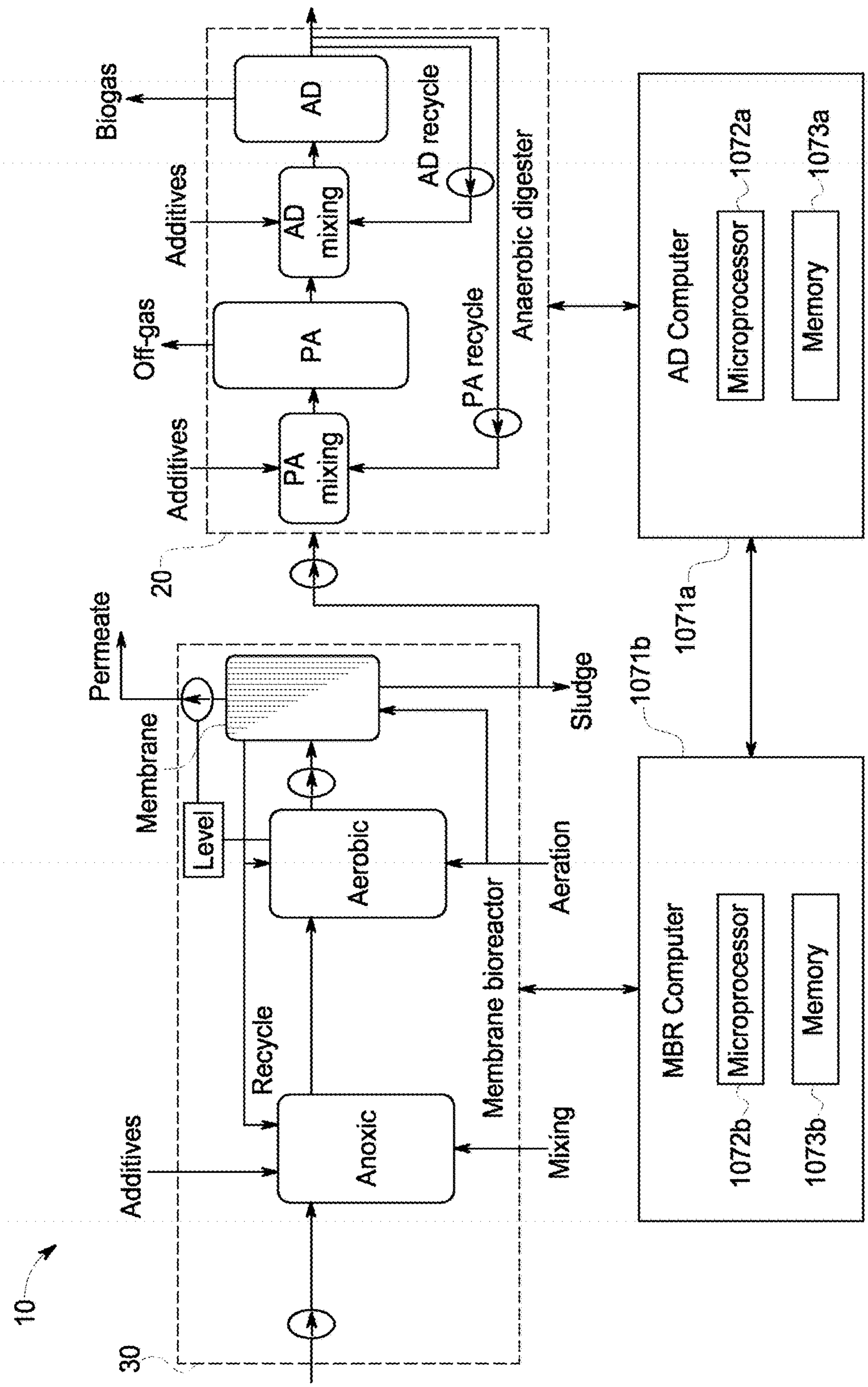

10
30
20
Additives
Anoxic
Mixing
Recycle
Aerobic
Aeration
Level
Membrane
Permeate
Sludge
Membrane bioreactor
Additives
PA mixing
PA
Off-gas
PA recycle
Additives
AD mixing
AD
Biogas
AD recycle
Anaerobic digester
MBR Computer
Microprocessor
Memory
1072b
1073b
1071b
1071a
AD Computer
Microprocessor
Memory
1072a
1073a

FIG. 1B

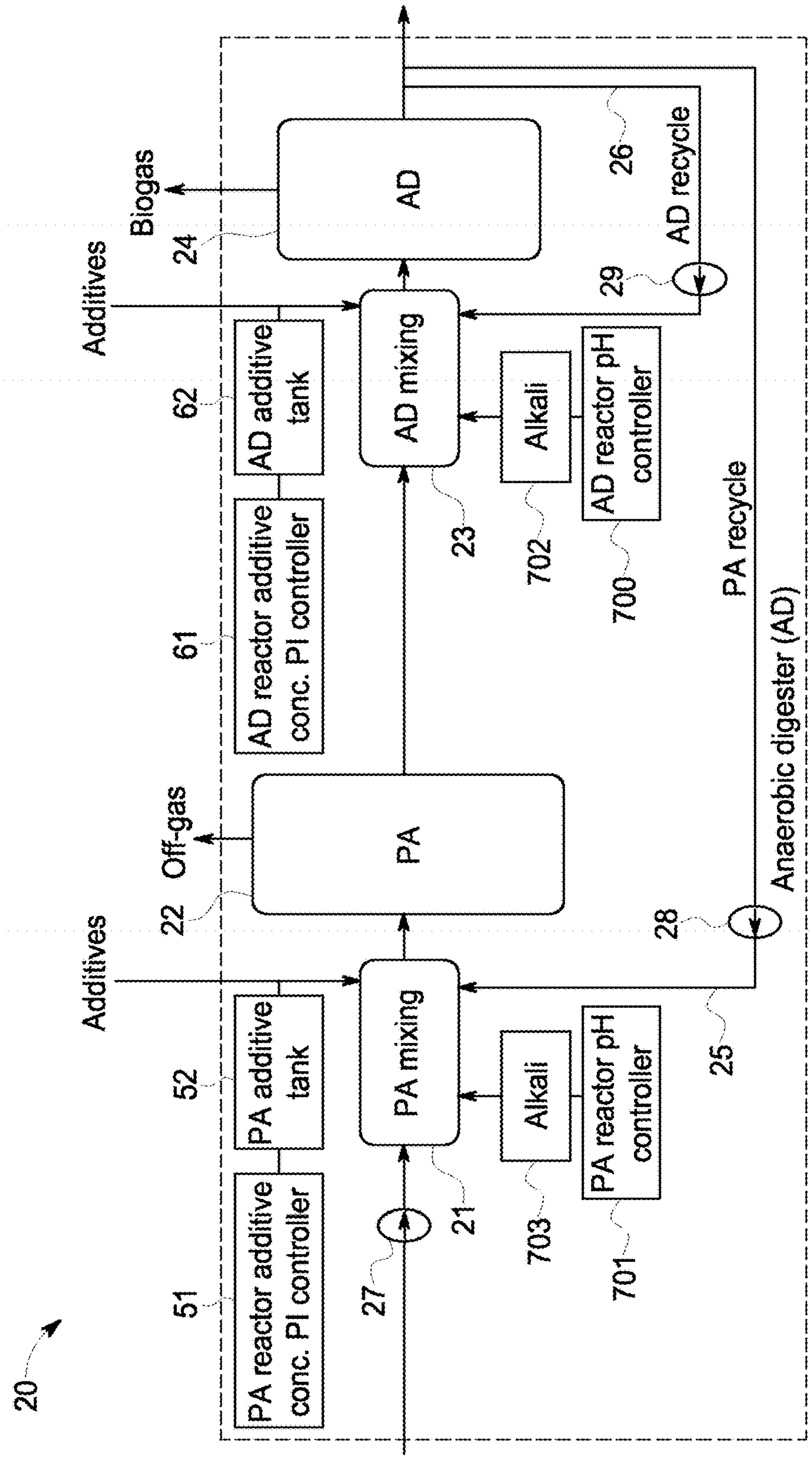

20
PA reactor additive conc. PI controller
51
PA additive tank
52
Additives
27
PA mixing
21
Alkali
703
PA reactor pH controller
701
25
28
PA
22
Off-gas
AD reactor additive conc. PI controller
61
AD additive tank
62
Additives
AD mixing
23
Alkali
702
AD reactor pH controller
700
AD
24
Biogas
29
AD recycle
26
PA recycle
Anaerobic digester (AD)

FIG. 2

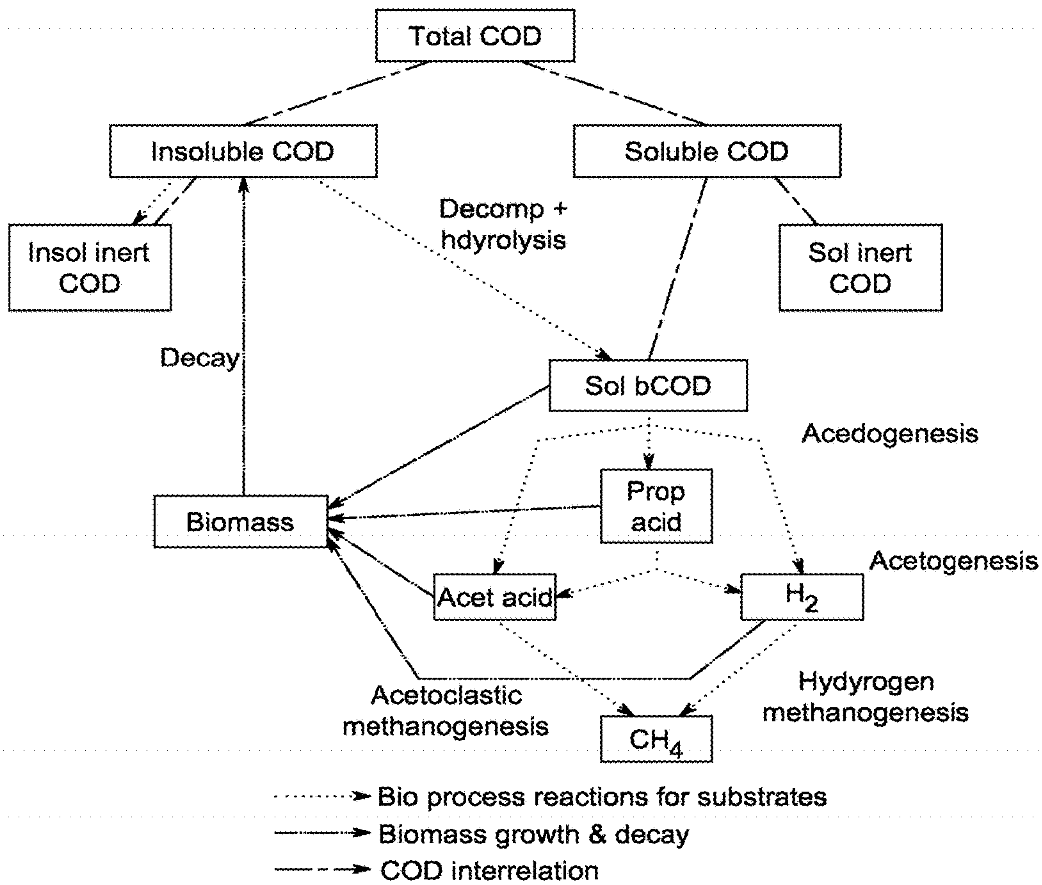

Total COD
Insoluble COD
Soluble COD
Insol inert COD
Sol inert COD
Decomp + hdyrolysis
Decay
Sol bCOD
Acedogenesis
Biomass
Prop acid
Acetogenesis
Acet acid
H_2
Acetoclastic methanogenesis
Hydyrogen methanogenesis
CH_4
Bio process reactions for substrates
Biomass growth & decay
COD interrelation

FIG. 3

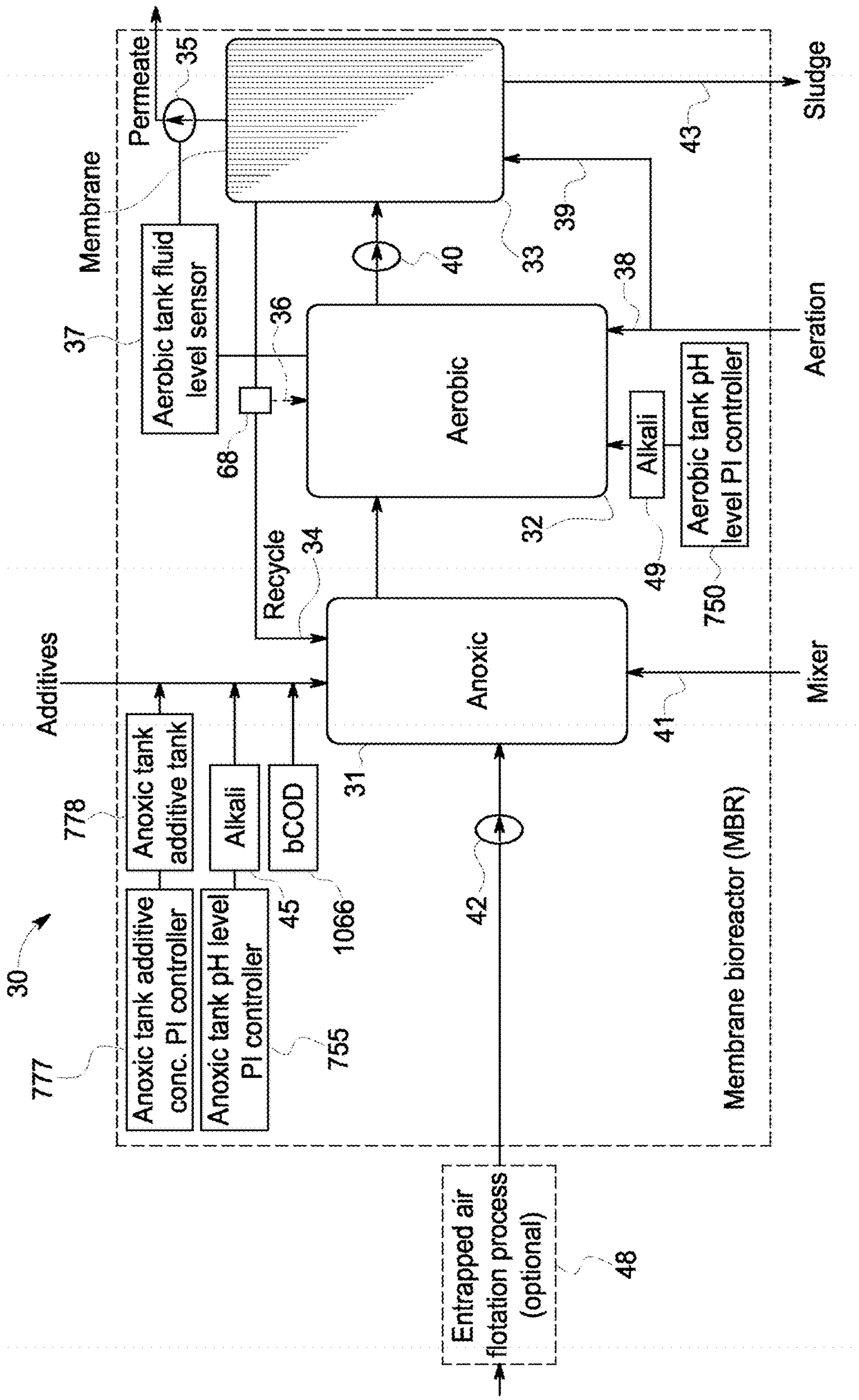

30
777
Anoxic tank additive conc. PI controller
778
Anoxic tank additive tank
Additives
Anoxic tank pH level PI controller
755
Alkali
45
bCOD
1066
42
31
Anoxic
41
Mixer
Recycle
34
Aerobic
32
Alkali
49
Aerobic tank pH level PI controller
750
37
Aerobic tank fluid level sensor
68
36
40
38
Aeration
Membrane
Permeate
35
33
39
43
Sludge
Membrane bioreactor (MBR)
Entrapped air flotation process (optional)
48

FIG. 4A

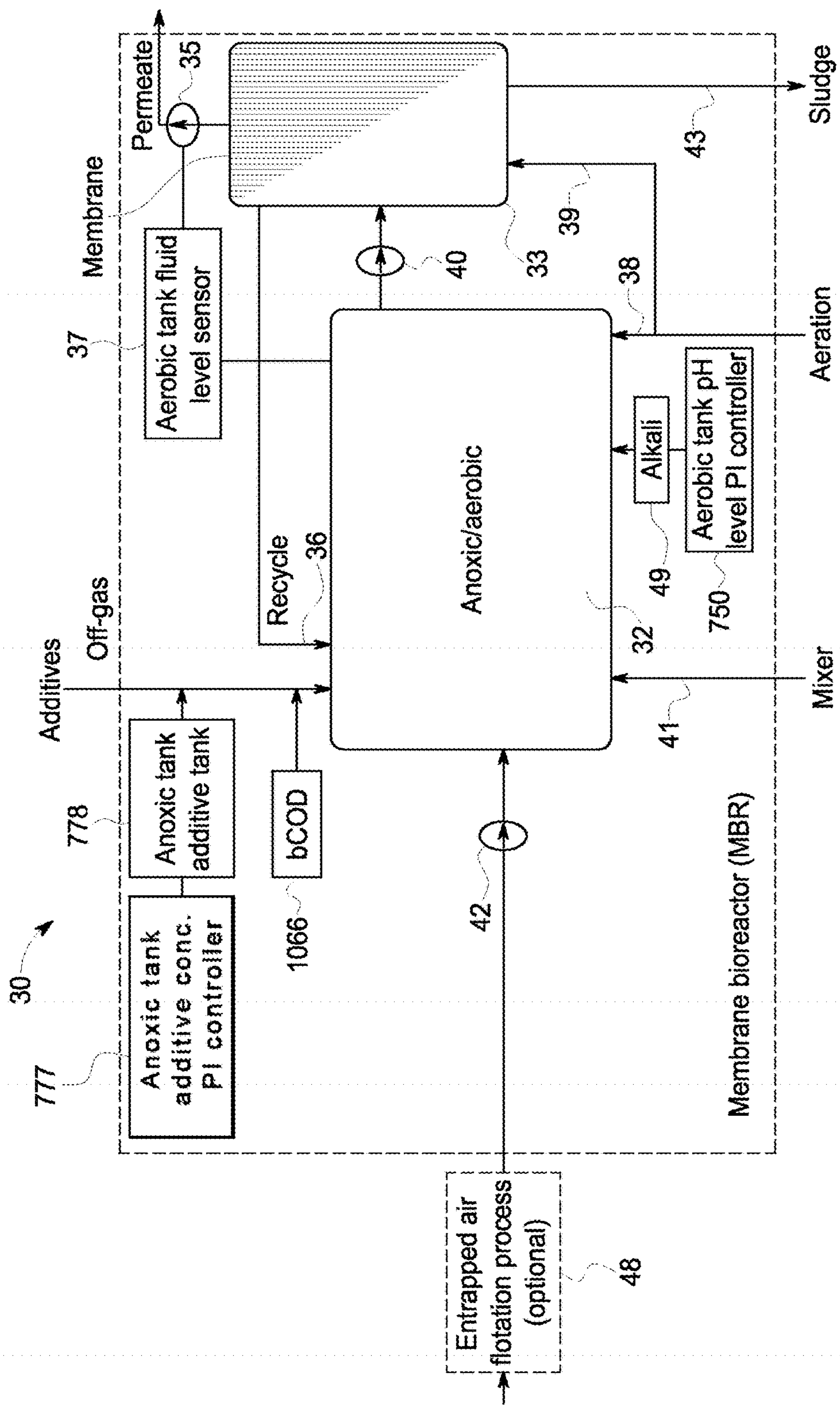

30
777
Anoxic tank additive conc. PI controller
778
Anoxic tank additive tank
1066
bCOD
Additives
Off-gas
Recycle
36
37
Aerobic tank fluid level sensor
Membrane
Permeate
35
Anoxic/aerobic
32
40
33
39
38
43
Sludge
Aeration
Alkali
49
Aerobic tank pH level PI controller
750
Mixer
41
42
Membrane bioreactor (MBR)
Entrapped air flotation process (optional)
48

FIG. 4B

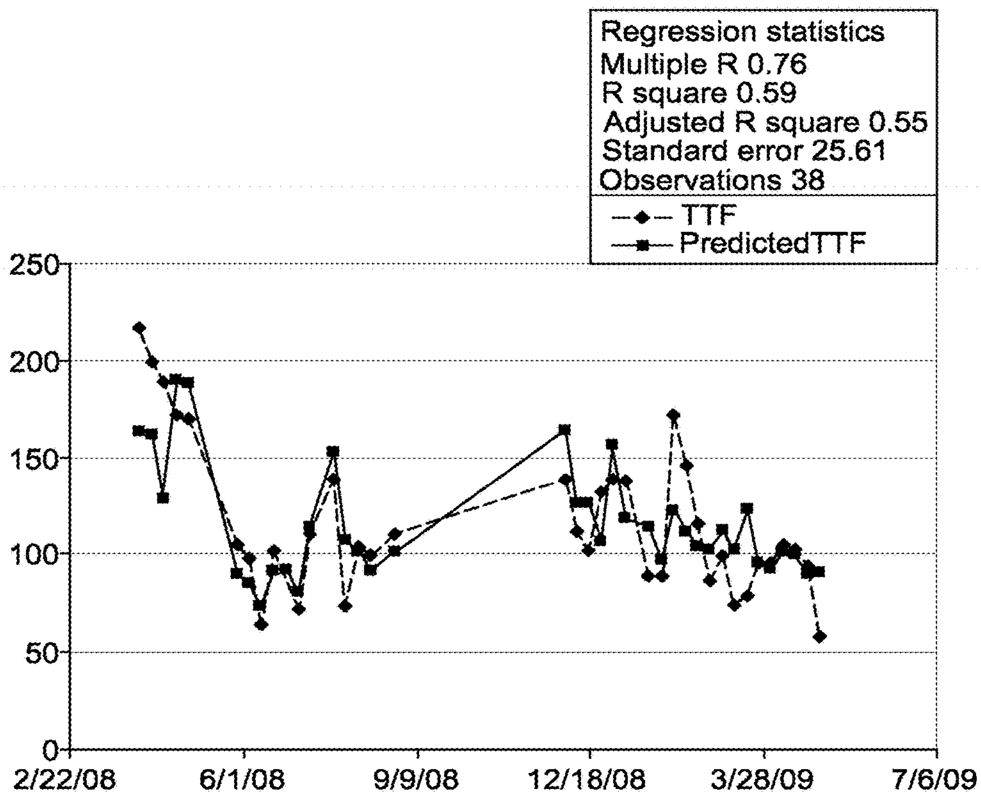

Regression statistics
Multiple R 0.76
R square 0.59
Adjusted R square 0.55
Standard error 25.61
Observations 38
TTF
PredictedTTF
250
200
150
100
50
0
2/22/08
6/1/08
9/9/08
12/18/08
3/28/09
7/6/09

FIG. 5

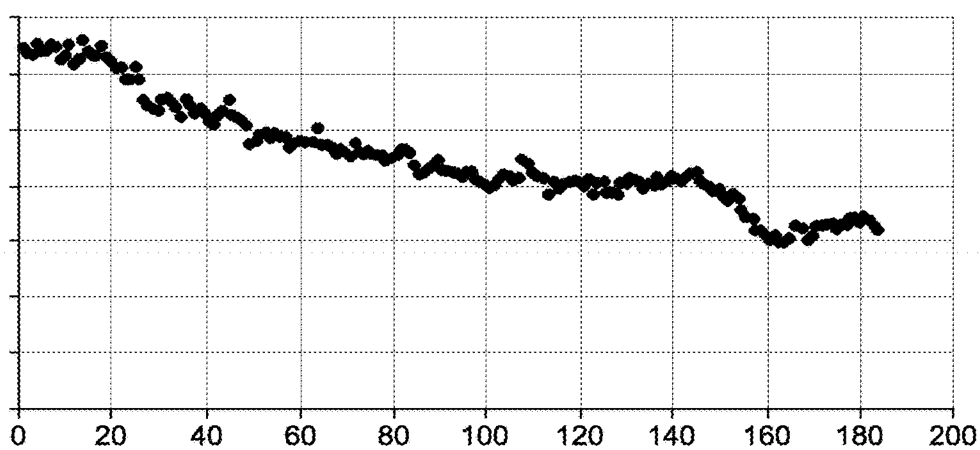


FIG. 6

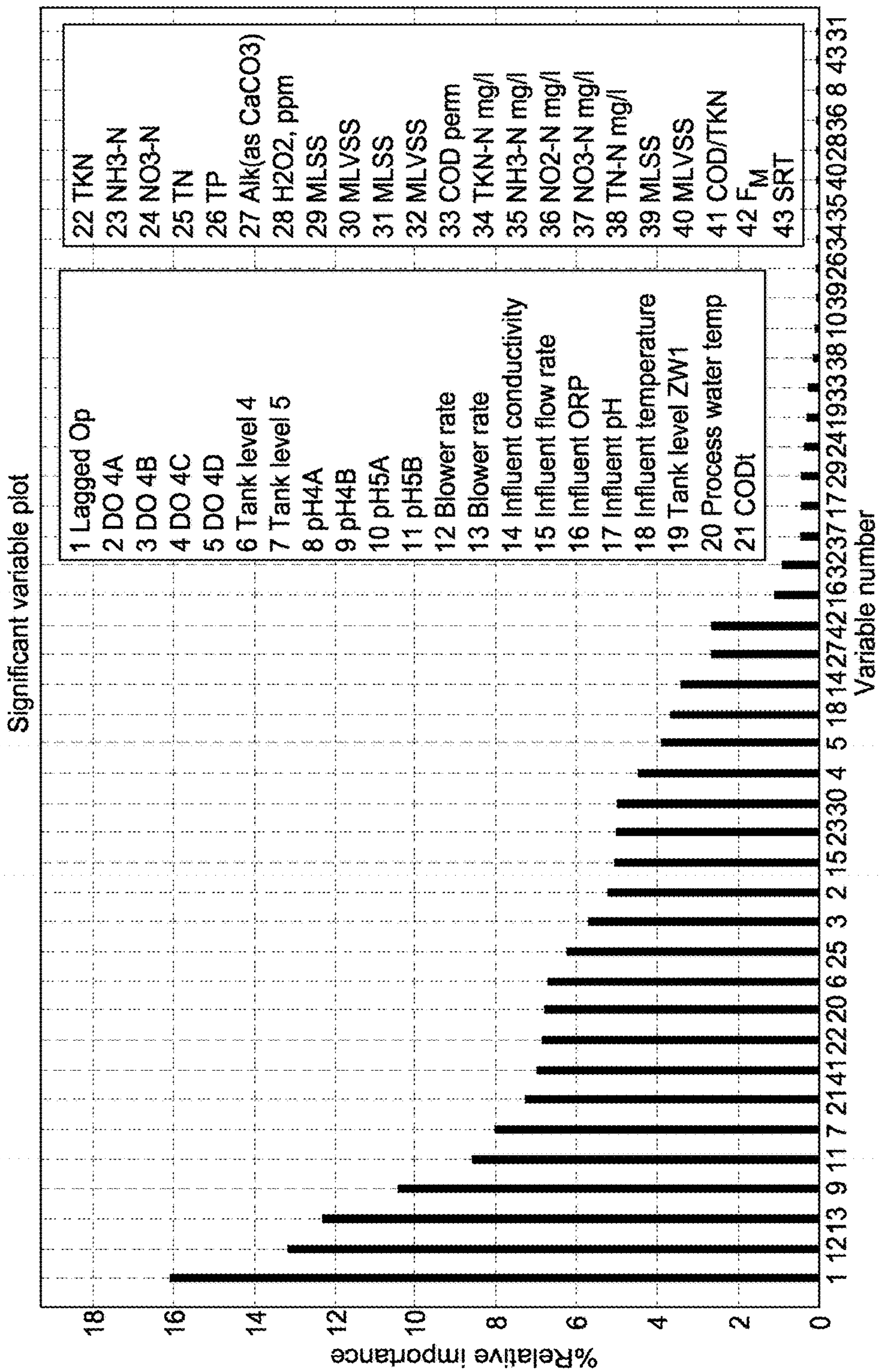

Significant variable plot
%Relative importance
Variable number
1 Lagged Op
2 DO 4A
3 DO 4B
4 DO 4C
5 DO 4D
6 Tank level 4
7 Tank level 5
8 pH4A
9 pH4B
10 pH5A
11 pH5B
12 Blower rate
13 Blower rate
14 Influent conductivity
15 Influent flow rate
16 Influent ORP
17 Influent pH
18 Influent temperature
19 Tank level ZW1
20 Process water temp
21 CODt
22 TKN
23 NH3-N
24 NO3-N
25 TN
26 TP
27 Alk(as CaCO3)
28 H2O2, ppm
29 MLSS
30 MLVSS
31 MLSS
32 MLVSS
33 COD perm
34 TKN-N mg/l
35 NH3-N mg/l
36 NO2-N mg/l
37 NO3-N mg/l
38 TN-N mg/l
39 MLSS
40 MLVSS
41 COD/TKN
42 F M
43 SRT

FIG. 7

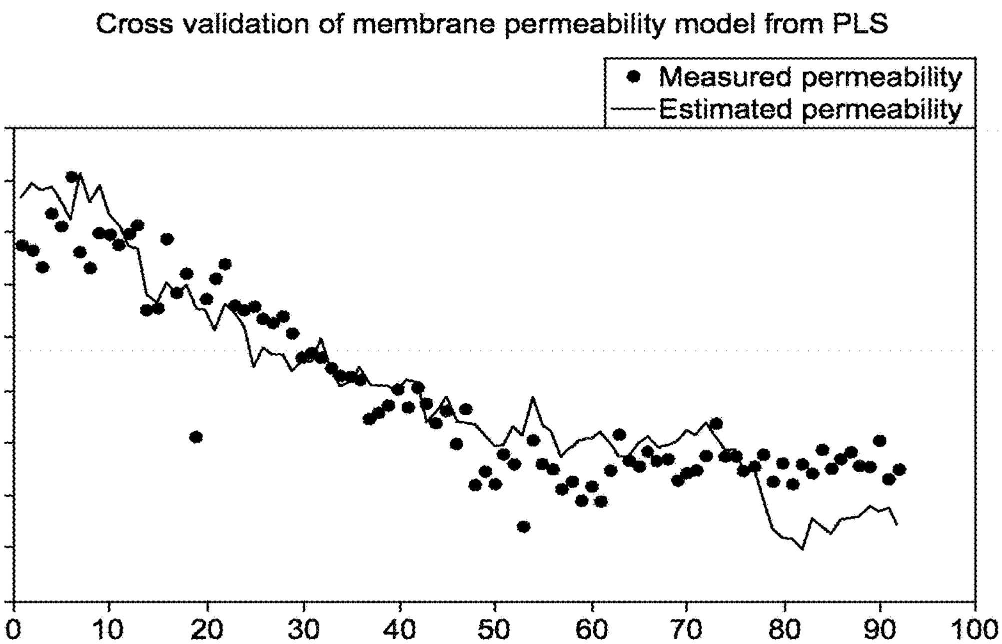

Cross validation of membrane permeability model from PLS
Measured permeability
Estimated permeability
0
10
20
30
40
50
60
70
80
90
100

FIG. 8

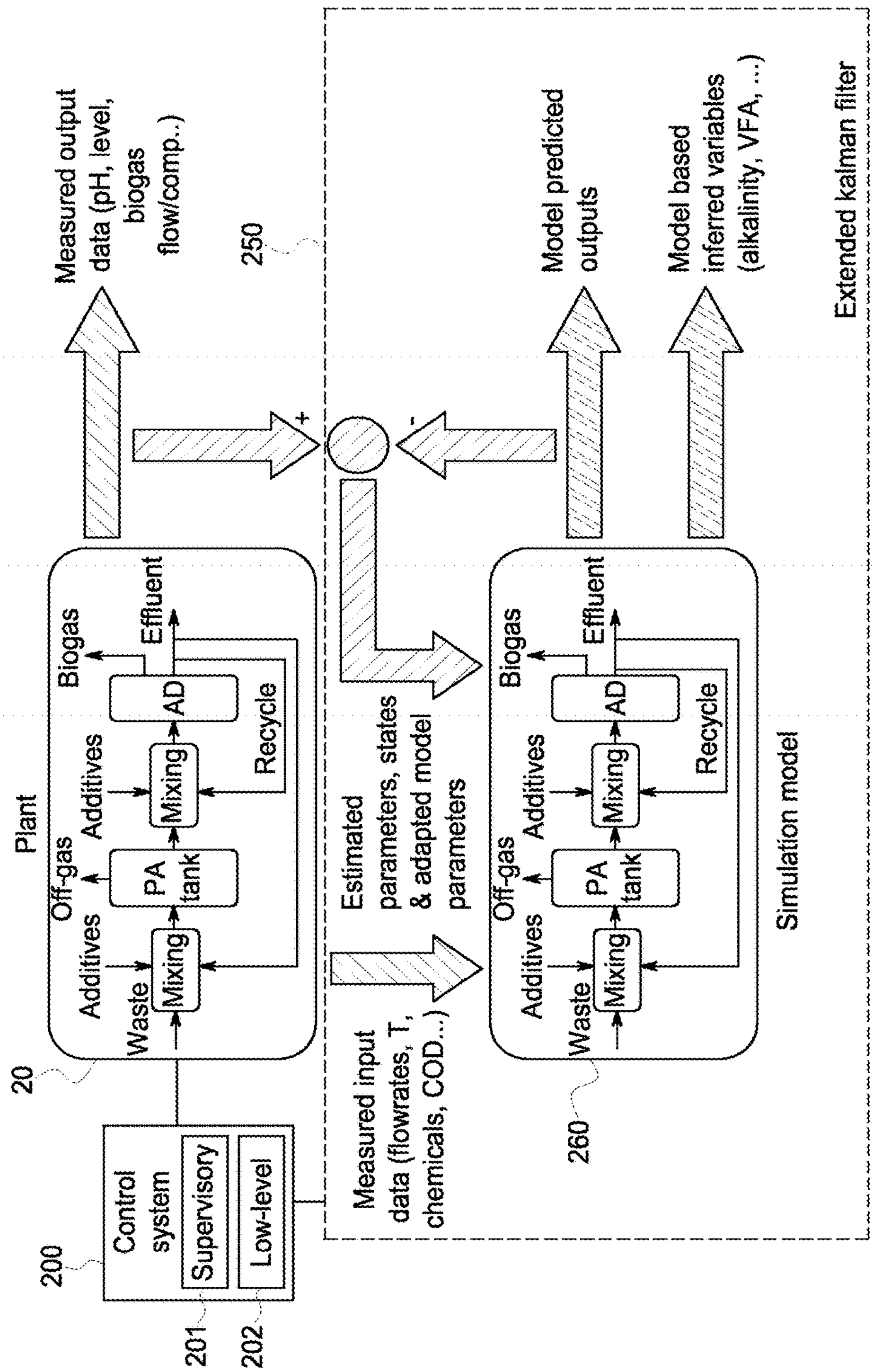

200
Control system
Supervisory
Low-level
201
202
20
Plant
Waste
Additives
Mixing
Off-gas
PA tank
Additives
Mixing
AD
Biogas
Effluent
Recycle
Measured output data (pH, level, biogas flow/comp..)
250
+
-
Measured input data (flowrates, T, chemicals, COD...)
Estimated parameters, states & adapted model parameters
260
Waste
Additives
Mixing
Off-gas
PA tank
Additives
Mixing
AD
Biogas
Effluent
Recycle
Simulation model
Model predicted outputs
Model based inferred variables (alkalinity, VFA, ...)
Extended kalman filter

FIG. 9

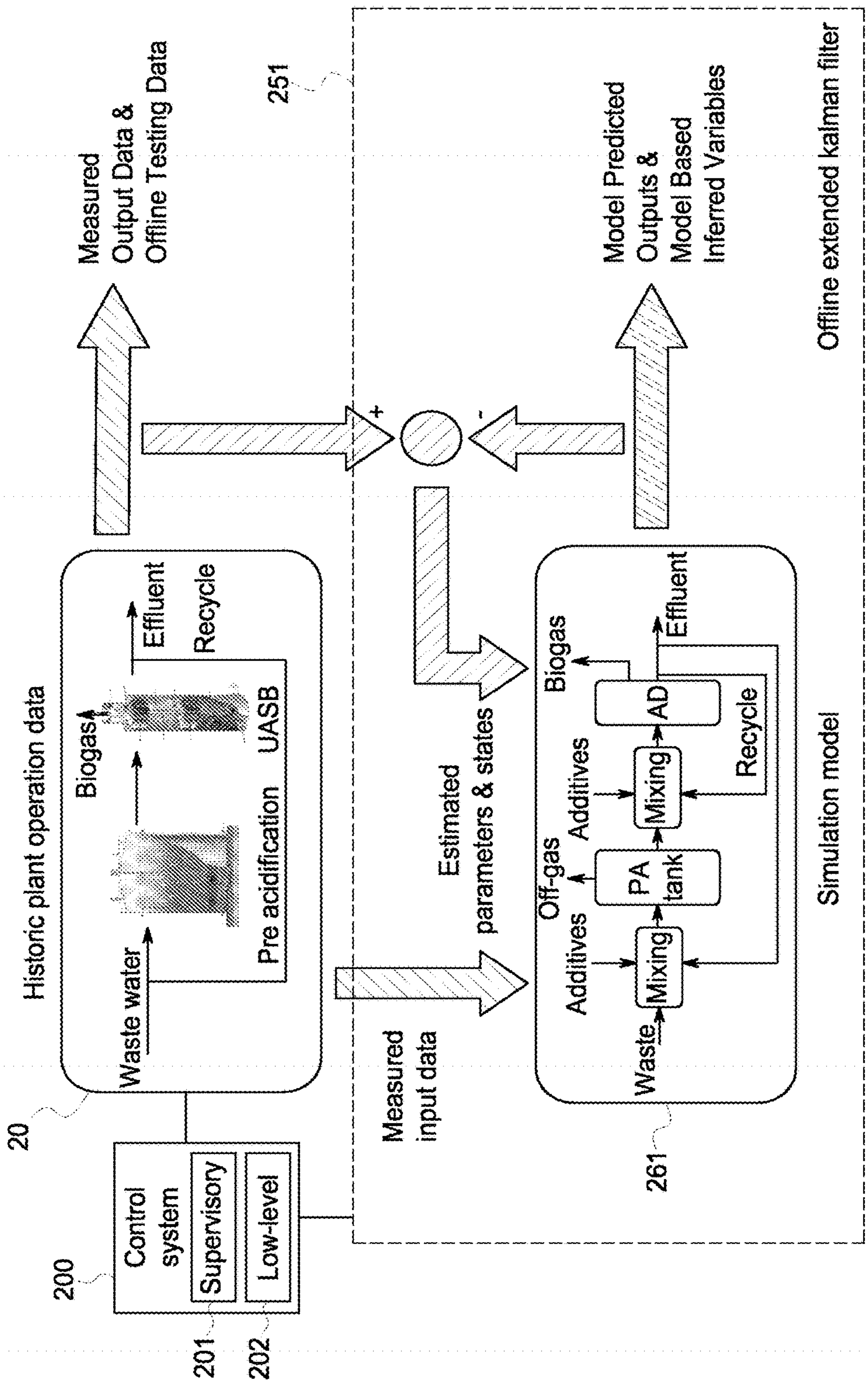

Measured
Output Data &
Offline Testing Data
251
Model Predicted
Outputs &
Model Based
Inferred Variables
Offline extended kalman filter
+
-
Historic plant operation data
Waste water
Pre acidification
Biogas
UASB
Effluent
Recycle
Estimated
parameters & states
Measured
input data
Waste
Additives
Mixing
Off-gas
PA
tank
Additives
Mixing
Recycle
AD
Biogas
Effluent
Simulation model
20
200
Control
system
Supervisory
Low-level
201
202
261

FIG. 10

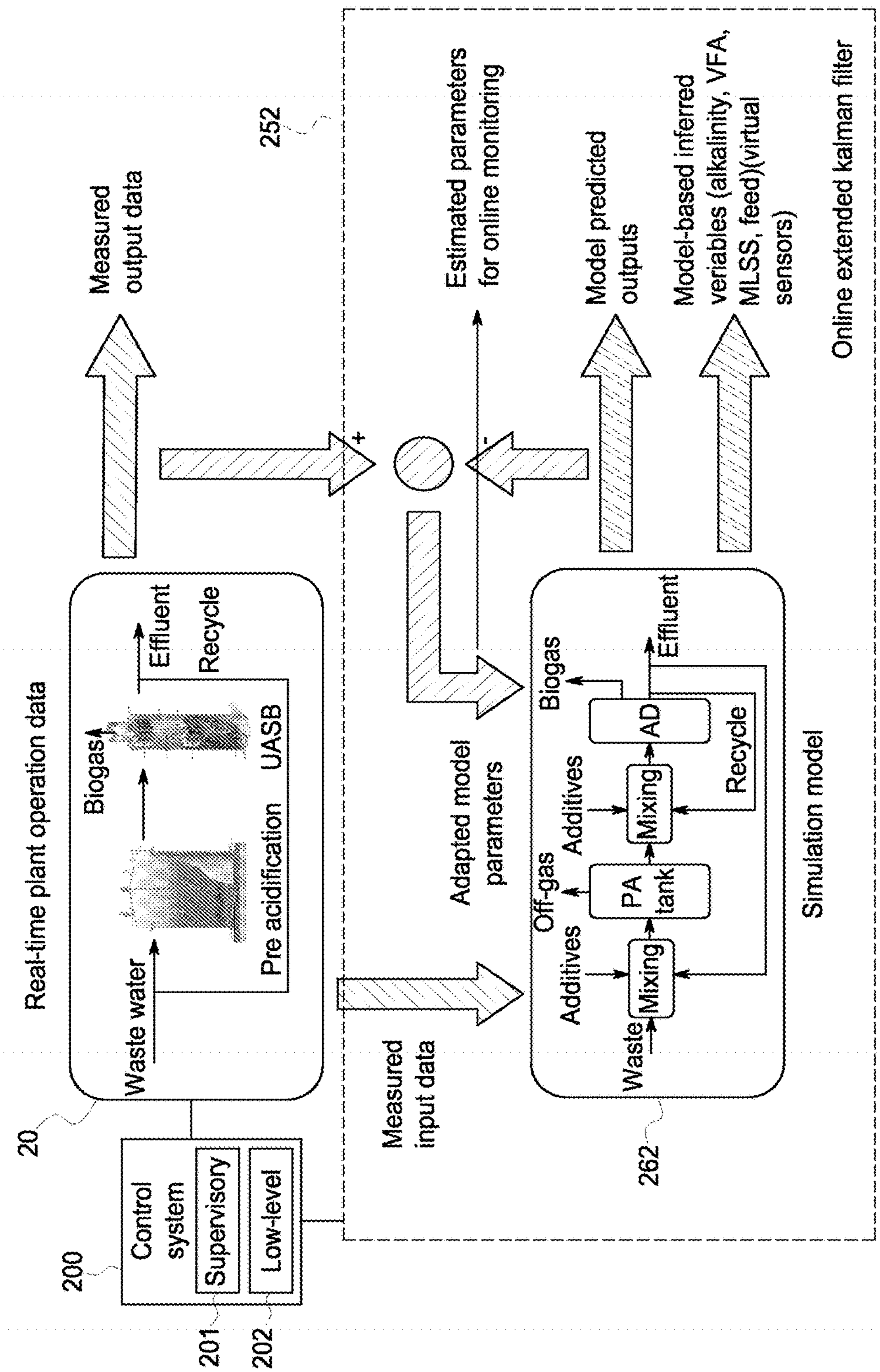

Real-time plant operation data
Waste water
Pre acidification
Biogas
UASB
Effluent
Recycle
Measured output data
252
Estimated parameters for online monitoring
+
-
Model predicted outputs
Model-based inferred veriables (alkalinity, VFA, MLSS, feed)(virtual sensors)
Online extended kalman filter
Adapted model parameters
Measured input data
Waste
Additives
Mixing
Off-gas
PA tank
Additives
Mixing
AD
Biogas
Effluent
Recycle
Simulation model
Control system
Supervisory
Low-level
200
201
202
20
262

FIG. 11

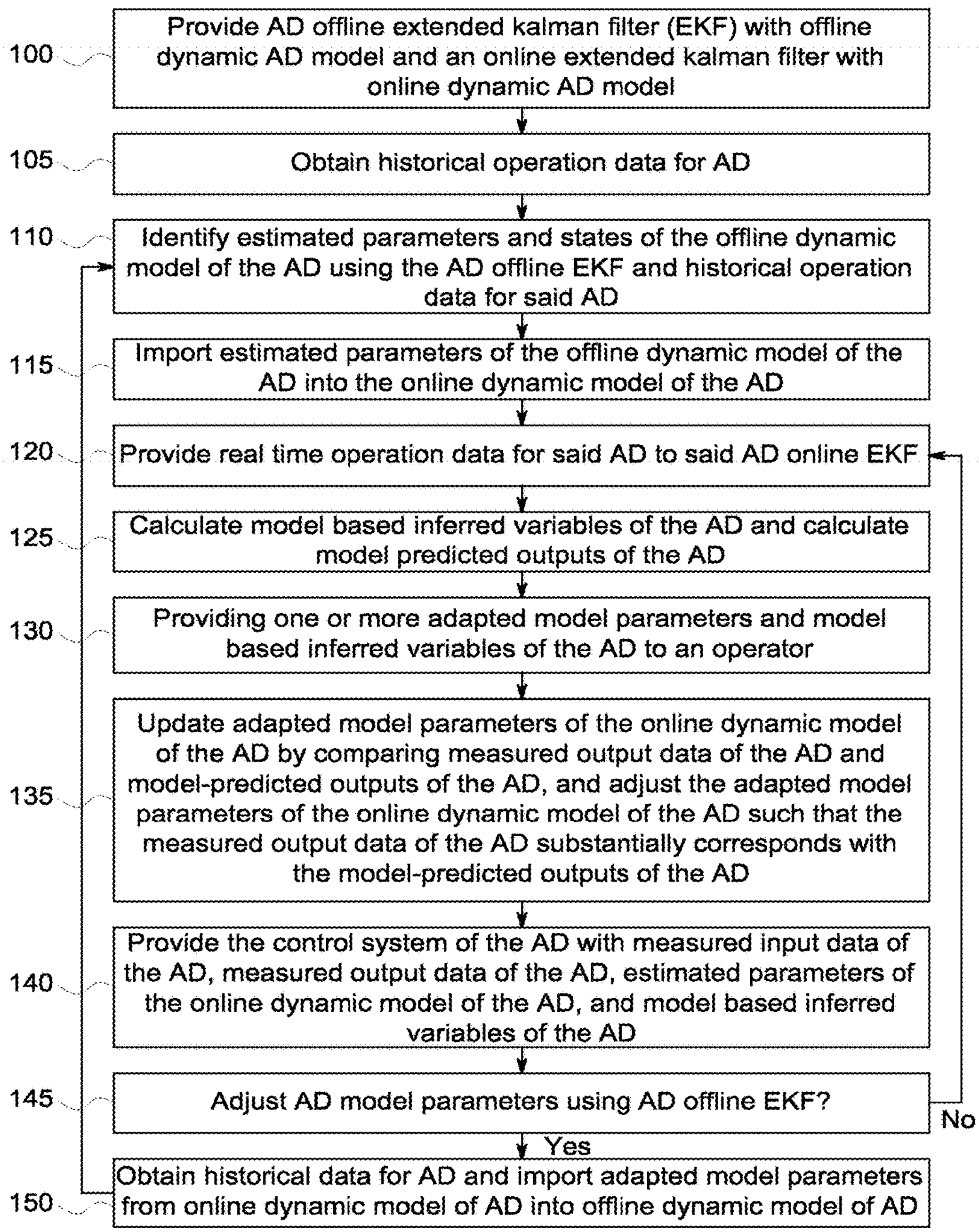

100
Provide AD offline extended kalman filter (EKF) with offline dynamic AD model and an online extended kalman filter with online dynamic AD model
105
Obtain historical operation data for AD
110
Identify estimated parameters and states of the offline dynamic model of the AD using the AD offline EKF and historical operation data for said AD
115
Import estimated parameters of the offline dynamic model of the AD into the online dynamic model of the AD
120
Provide real time operation data for said AD to said AD online EKF
125
Calculate model based inferred variables of the AD and calculate model predicted outputs of the AD
130
Providing one or more adapted model parameters and model based inferred variables of the AD to an operator
135
Update adapted model parameters of the online dynamic model of the AD by comparing measured output data of the AD and model-predicted outputs of the AD, and adjust the adapted model parameters of the online dynamic model of the AD such that the measured output data of the AD substantially corresponds with the model-predicted outputs of the AD
140
Provide the control system of the AD with measured input data of the AD, measured output data of the AD, estimated parameters of the online dynamic model of the AD, and model based inferred variables of the AD
145
Adjust AD model parameters using AD offline EKF?
No
Yes
150
Obtain historical data for AD and import adapted model parameters from online dynamic model of AD into offline dynamic model of AD

FIG. 12A

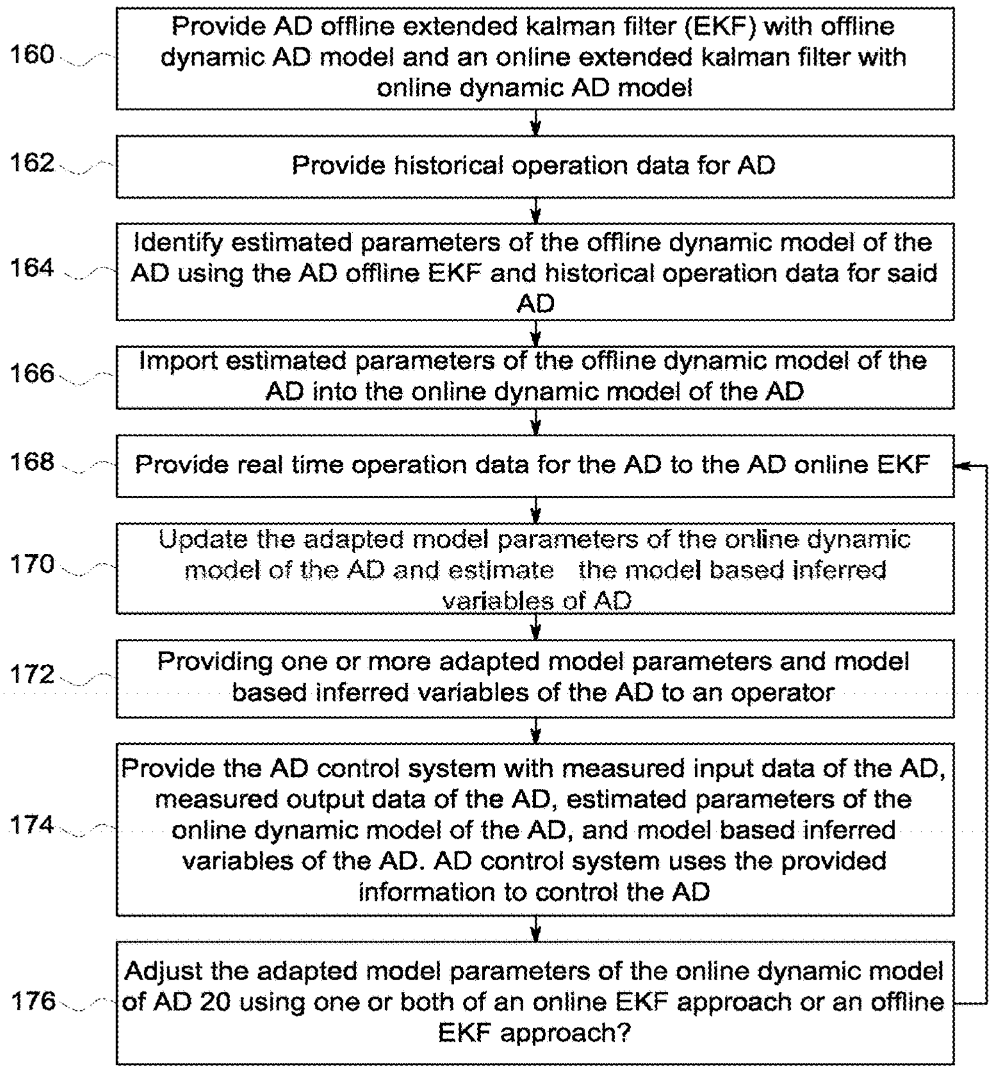

160
Provide AD offline extended kalman filter (EKF) with offline dynamic AD model and an online extended kalman filter with online dynamic AD model
162
Provide historical operation data for AD
164
Identify estimated parameters of the offline dynamic model of the AD using the AD offline EKF and historical operation data for said AD
166
Import estimated parameters of the offline dynamic model of the AD into the online dynamic model of the AD
168
Provide real time operation data for the AD to the AD online EKF
170
Update the adapted model parameters of the online dynamic model of the AD and estimate the model based inferred variables of AD
172
Providing one or more adapted model parameters and model based inferred variables of the AD to an operator
174
Provide the AD control system with measured input data of the AD, measured output data of the AD, estimated parameters of the online dynamic model of the AD, and model based inferred variables of the AD. AD control system uses the provided information to control the AD
176
Adjust the adapted model parameters of the online dynamic model of AD 20 using one or both of an online EKF approach or an offline EKF approach?

FIG. 12B

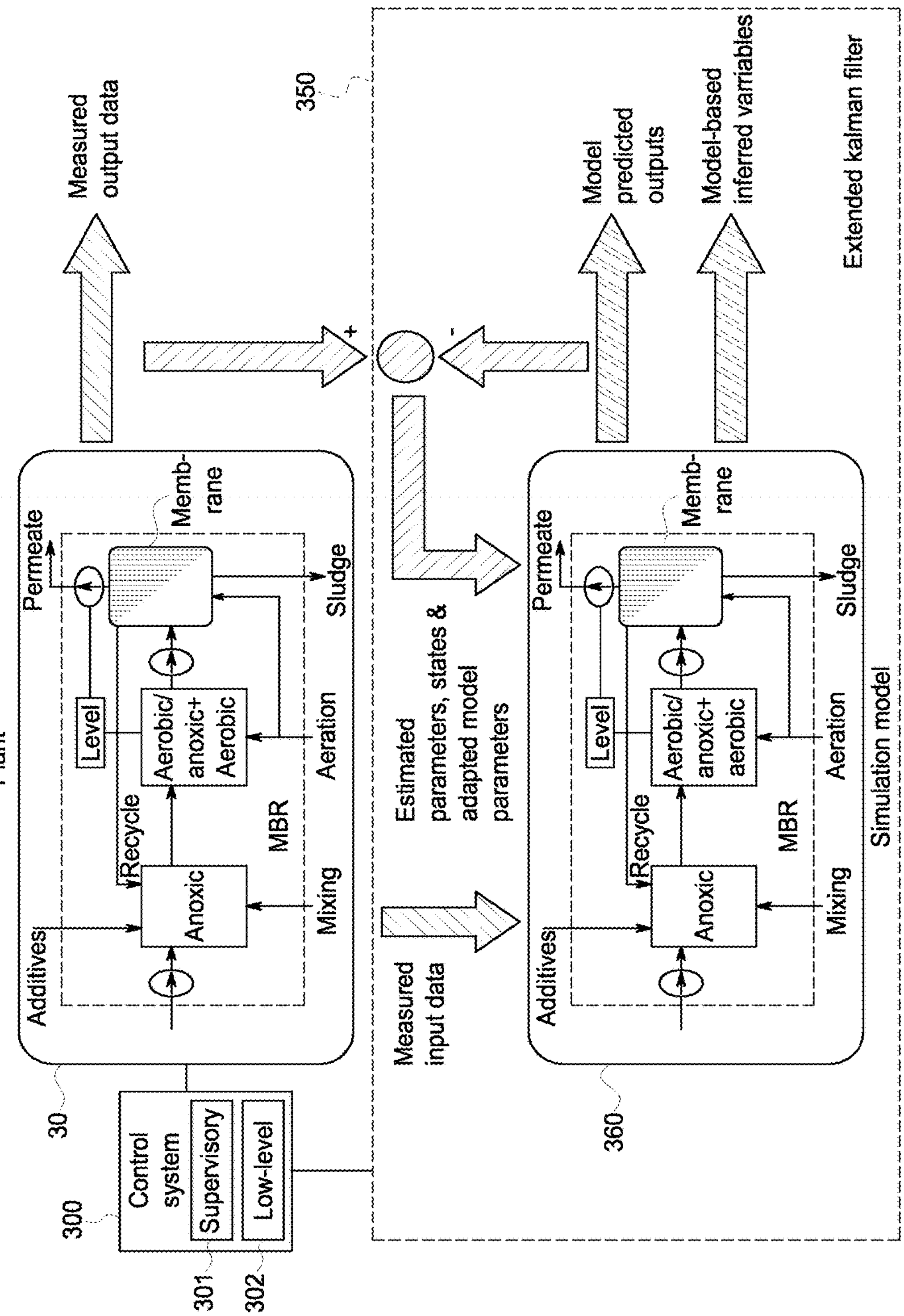

Plant
30
300
Control system
Supervisory
Low-level
301
302
Additives
Anoxic
Mixing
Recycle
Aerobic/ anoxic+ Aerobic
Aeration
Level
MBR
Permeate
Memb- rane
Sludge
Measured output data
+
-
350
Model predicted outputs
Model-based inferred varriables
Extended kalman filter
Estimated parameters, states & adapted model parameters
Measured input data
360
Additives
Anoxic
Mixing
Recycle
Aerobic/ anoxic+ aerobic
Aeration
Level
MBR
Permeate
Memb- rane
Sludge
Simulation model

FIG. 13

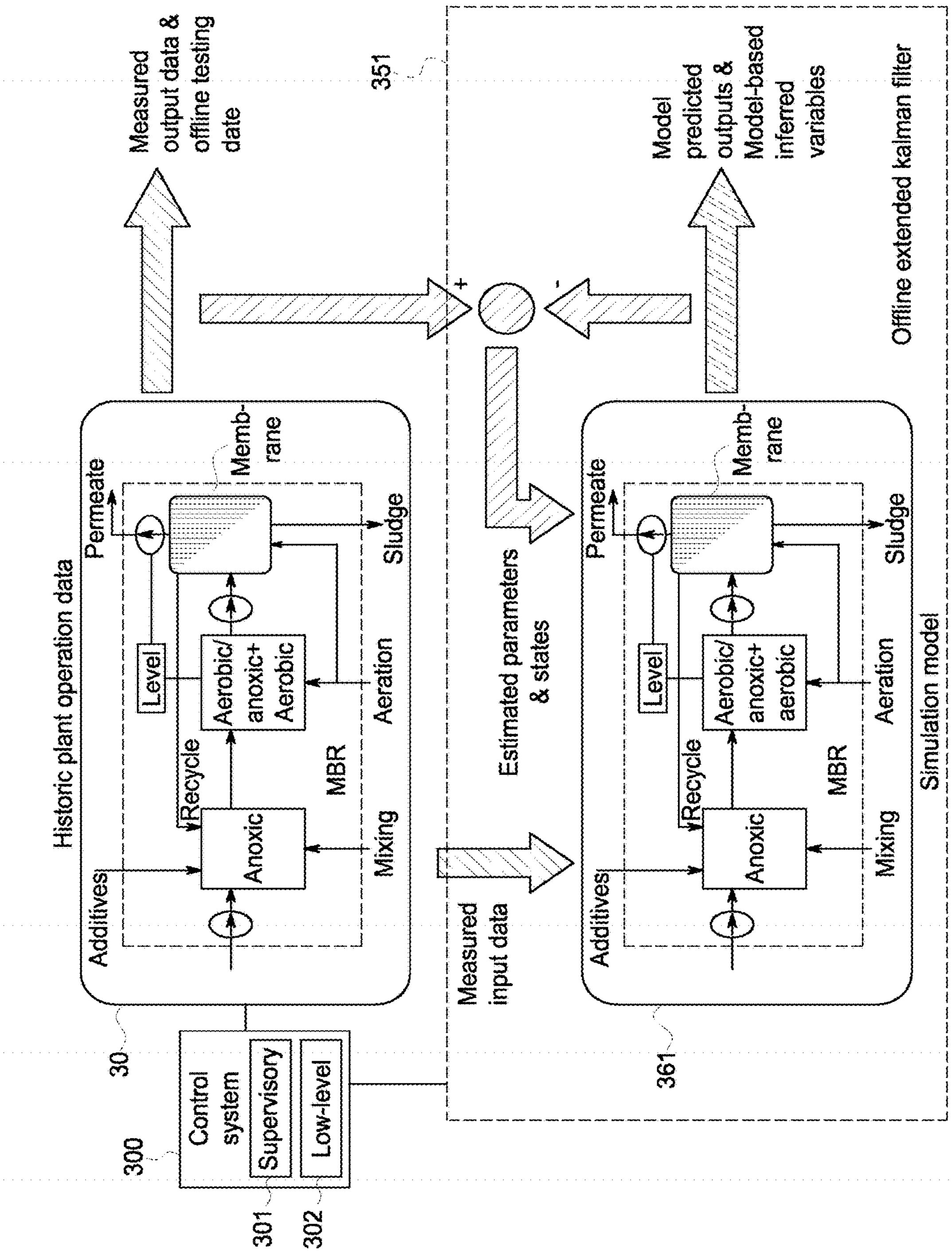

Historic plant operation data
Additives
Anoxic
Recycle
Level
Aerobic/ anoxic+ Aerobic
Permeate
Memb- rane
Sludge
Aeration
Mixing
MBR
Measured output data & offline testing date
351
Measured input data
Estimated parameters & states
+
-
Model predicted outputs & Model-based inferred variables
Offline extended kalman filter
Additives
Anoxic
Recycle
Level
Aerobic/ anoxic+ aerobic
Permeate
Memb- rane
Sludge
Aeration
Mixing
MBR
Simulation model
30
300
Control system
Supervisory
Low-level
301
302
361

FIG. 14

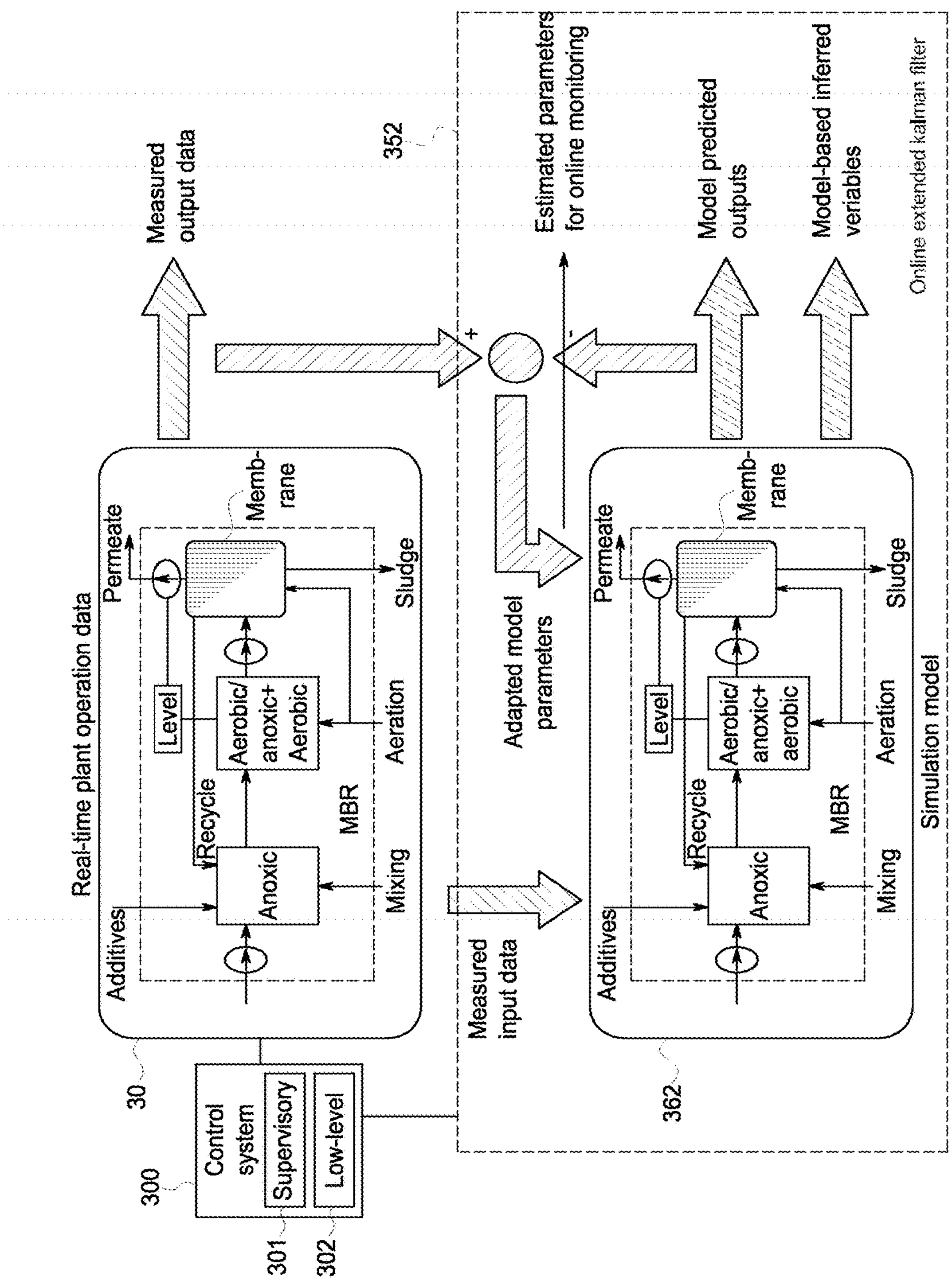

Real-time plant operation data
Additives
Anoxic
Recycle
Level
Aerobic/ anoxic+ Aerobic
Permeate
Memb- rane
MBR
Mixing
Aeration
Sludge
Measured output data
Control system
Supervisory
Low-level
300
301
302
30
Measured input data
Adapted model parameters
Estimated parameters for online monitoring
352
+
-
Model predicted outputs
Model-based inferred veriables
Online extended kalman filter
Additives
Anoxic
Recycle
Level
Aerobic/ anoxic+ aerobic
Permeate
Memb- rane
MBR
Mixing
Aeration
Sludge
Simulation model
362

FIG. 15

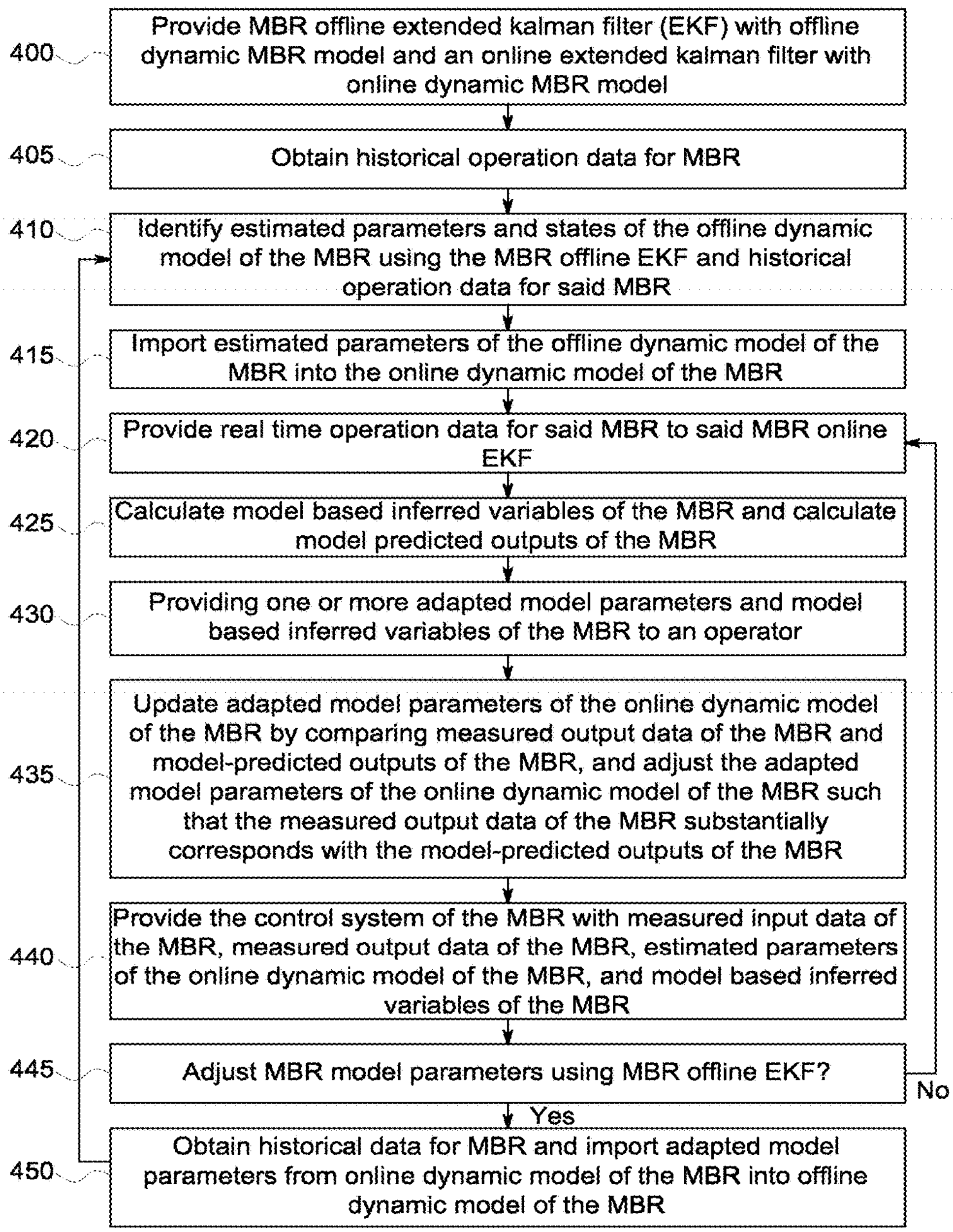

400
Provide MBR offline extended kalman filter (EKF) with offline dynamic MBR model and an online extended kalman filter with online dynamic MBR model
405
Obtain historical operation data for MBR
410
Identify estimated parameters and states of the offline dynamic model of the MBR using the MBR offline EKF and historical operation data for said MBR
415
Import estimated parameters of the offline dynamic model of the MBR into the online dynamic model of the MBR
420
Provide real time operation data for said MBR to said MBR online EKF
425
Calculate model based inferred variables of the MBR and calculate model predicted outputs of the MBR
430
Providing one or more adapted model parameters and model based inferred variables of the MBR to an operator
435
Update adapted model parameters of the online dynamic model of the MBR by comparing measured output data of the MBR and model-predicted outputs of the MBR, and adjust the adapted model parameters of the online dynamic model of the MBR such that the measured output data of the MBR substantially corresponds with the model-predicted outputs of the MBR
440
Provide the control system of the MBR with measured input data of the MBR, measured output data of the MBR, estimated parameters of the online dynamic model of the MBR, and model based inferred variables of the MBR
445
Adjust MBR model parameters using MBR offline EKF?
No
Yes
450
Obtain historical data for MBR and import adapted model parameters from online dynamic model of the MBR into offline dynamic model of the MBR

FIG. 16A

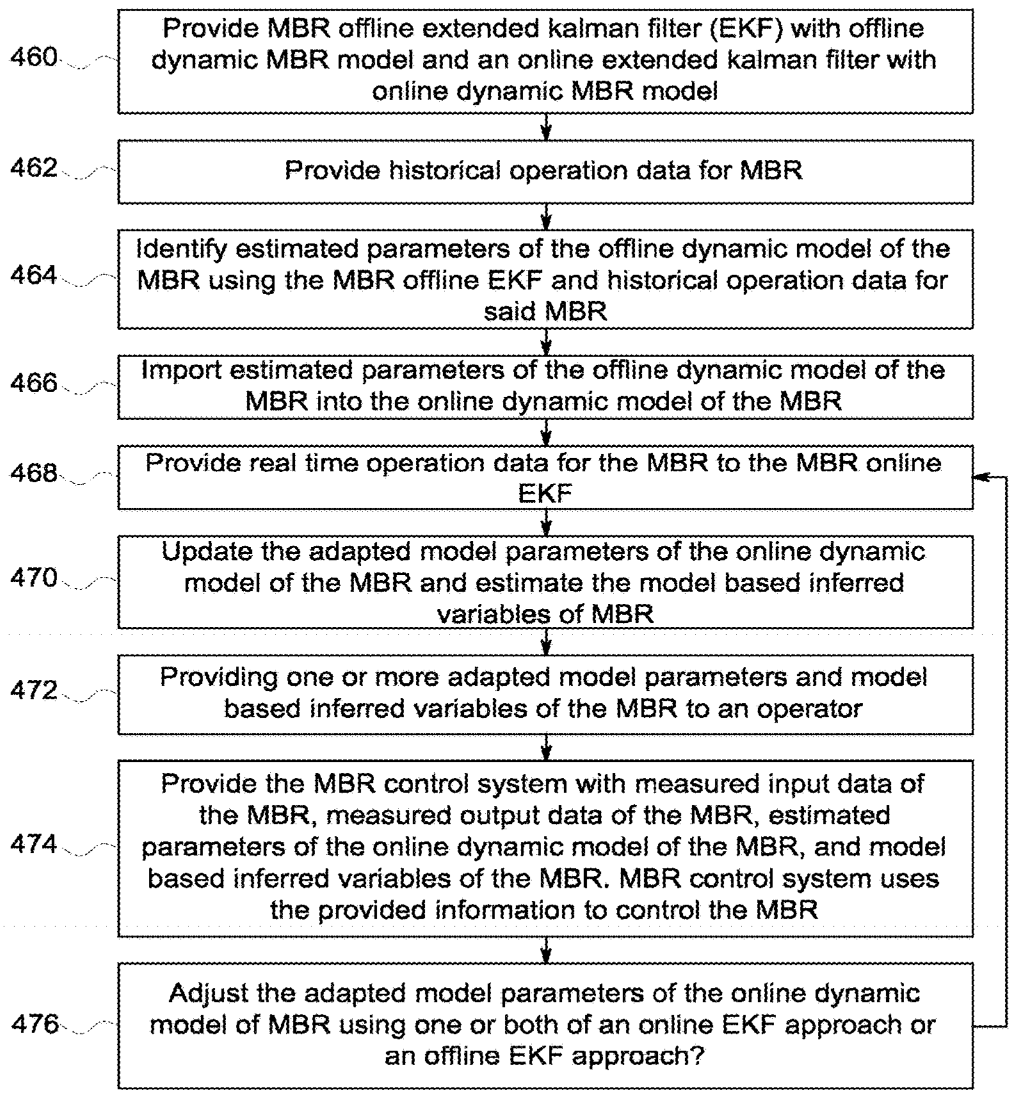

460
Provide MBR offline extended kalman filter (EKF) with offline dynamic MBR model and an online extended kalman filter with online dynamic MBR model
462
Provide historical operation data for MBR
464
Identify estimated parameters of the offline dynamic model of the MBR using the MBR offline EKF and historical operation data for said MBR
466
Import estimated parameters of the offline dynamic model of the MBR into the online dynamic model of the MBR
468
Provide real time operation data for the MBR to the MBR online EKF
470
Update the adapted model parameters of the online dynamic model of the MBR and estimate the model based inferred variables of MBR
472
Providing one or more adapted model parameters and model based inferred variables of the MBR to an operator
474
Provide the MBR control system with measured input data of the MBR, measured output data of the MBR, estimated parameters of the online dynamic model of the MBR, and model based inferred variables of the MBR. MBR control system uses the provided information to control the MBR
476
Adjust the adapted model parameters of the online dynamic model of MBR using one or both of an online EKF approach or an offline EKF approach?

FIG. 16B

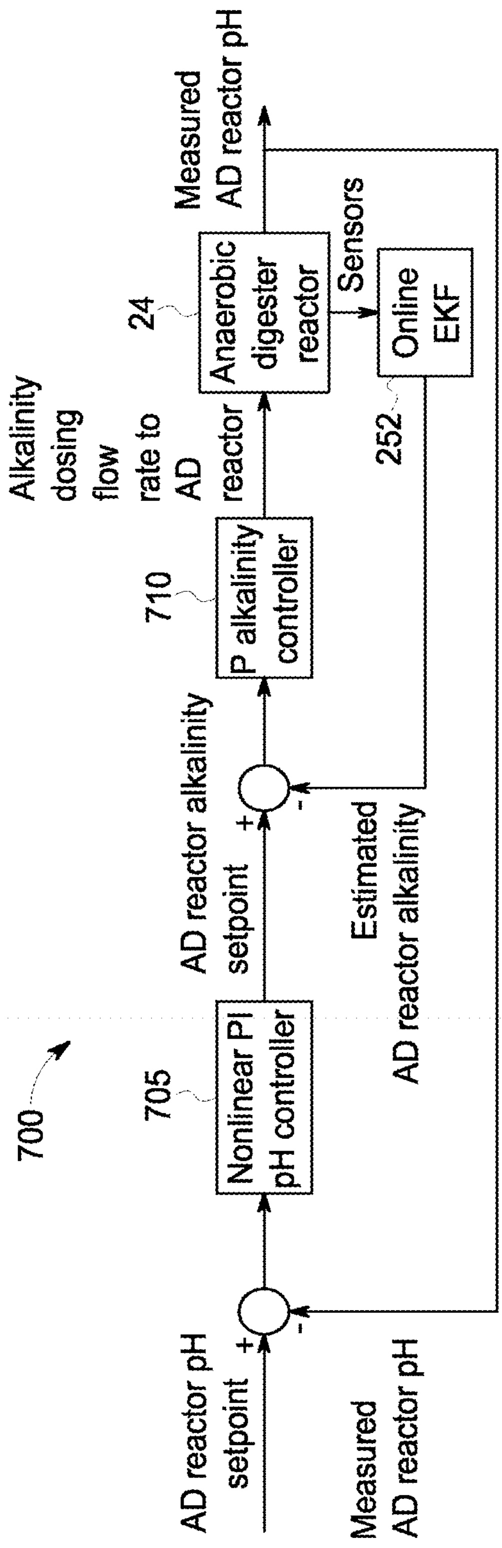

700
AD reactor pH setpoint
+
-
Measured AD reactor pH
705
Nonlinear PI pH controller
AD reactor alkalinity setpoint
+
-
Estimated AD reactor alkalinity
710
P alkalinity controller
Alkalinity dosing flow rate to AD reactor
24
Anaerobic digester reactor
Sensors
252
Online EKF
Measured AD reactor pH

FIG. 17A

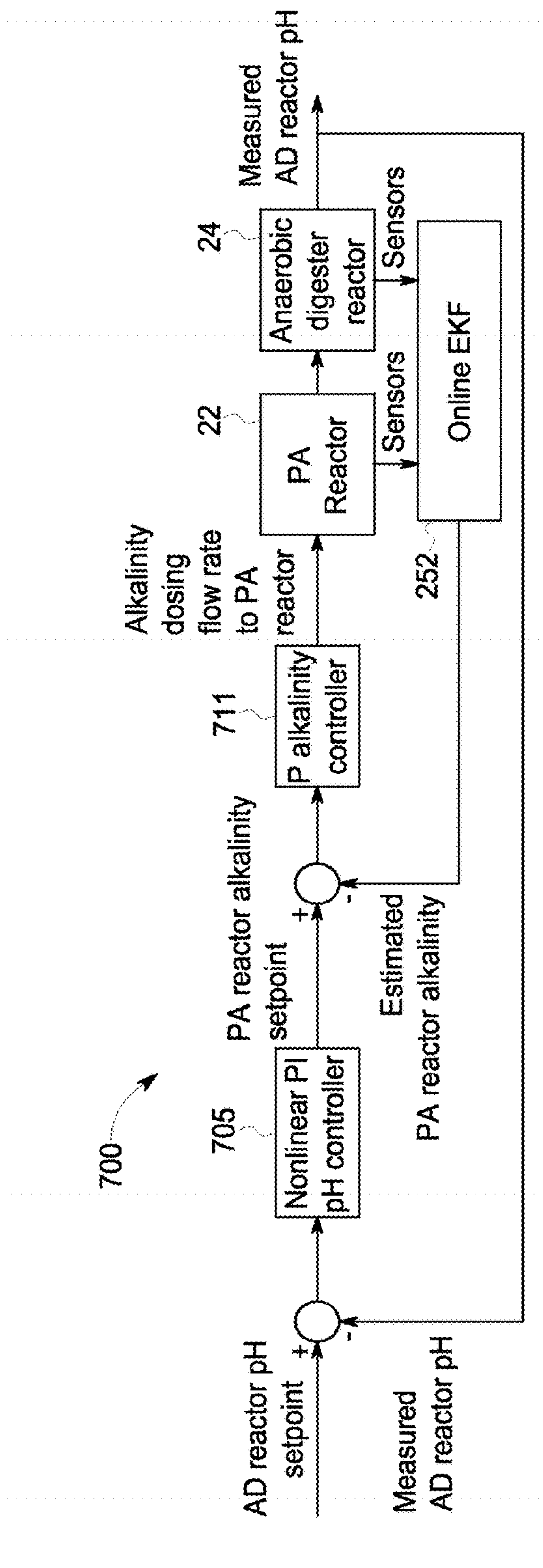

700
AD reactor pH setpoint
Measured AD reactor pH
+
-
705
Nonlinear PI pH controller
PA reactor alkalinity setpoint
Estimated PA reactor alkalinity
711
P alkalinity controller
Alkalinity dosing flow rate to PA reactor
22
PA Reactor
24
Anaerobic digester reactor
Sensors
Sensors
252
Online EKF
Measured AD reactor pH

FIG. 17B

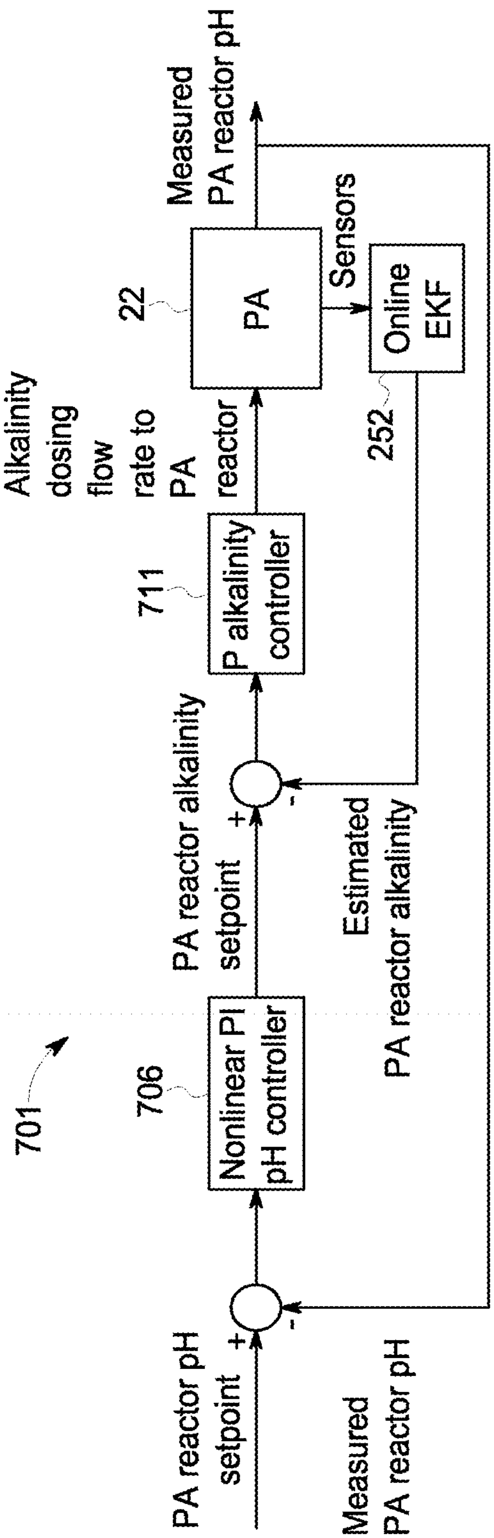

701
PA reactor pH setpoint
+
-
Measured PA reactor pH
706
Nonlinear PI pH controller
PA reactor alkalinity setpoint
+
PA reactor alkalinity
-
Estimated PA reactor alkalinity
711
P alkalinity controller
Alkalinity dosing flow rate to PA reactor
22
PA
Sensors
252
Online EKF
Measured PA reactor pH

FIG. 18

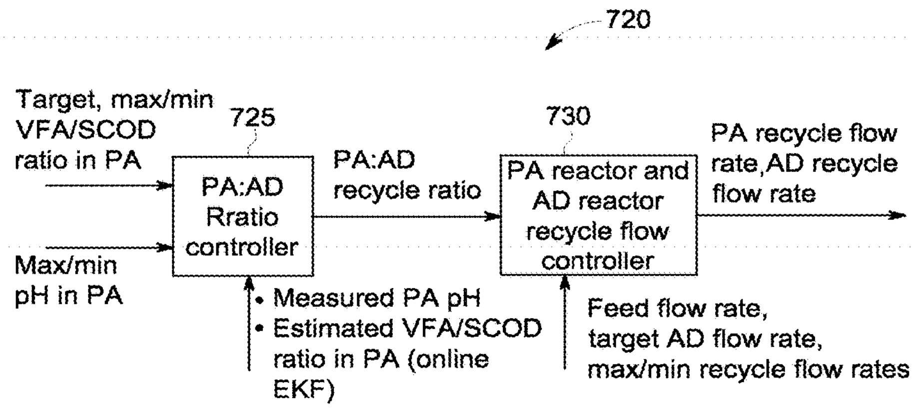


FIG. 19A

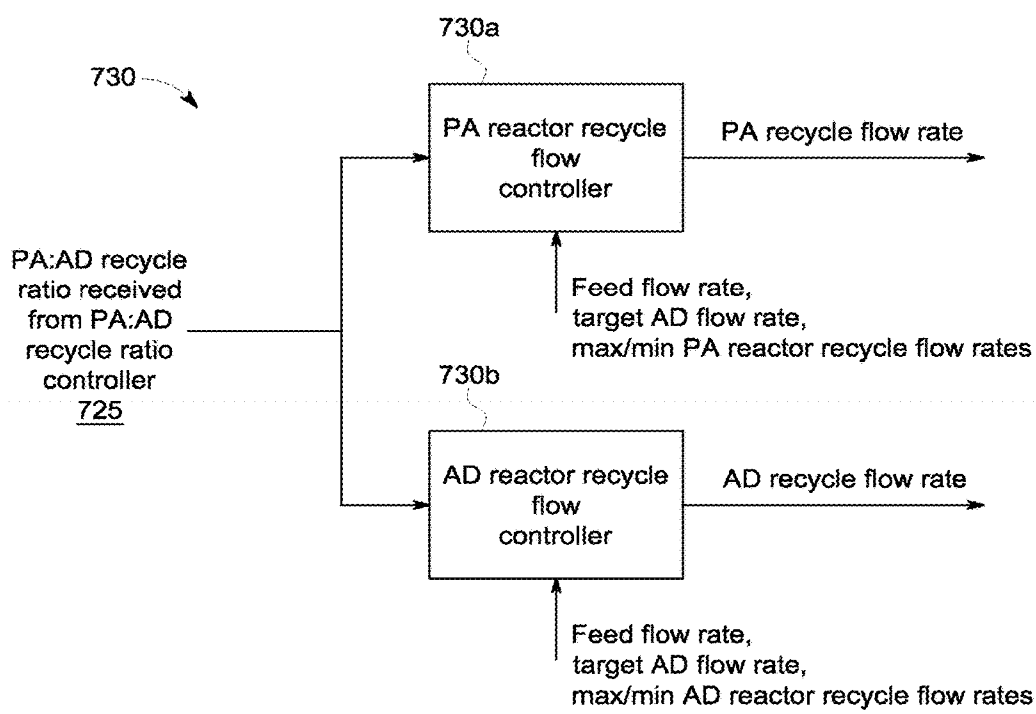


FIG. 19B

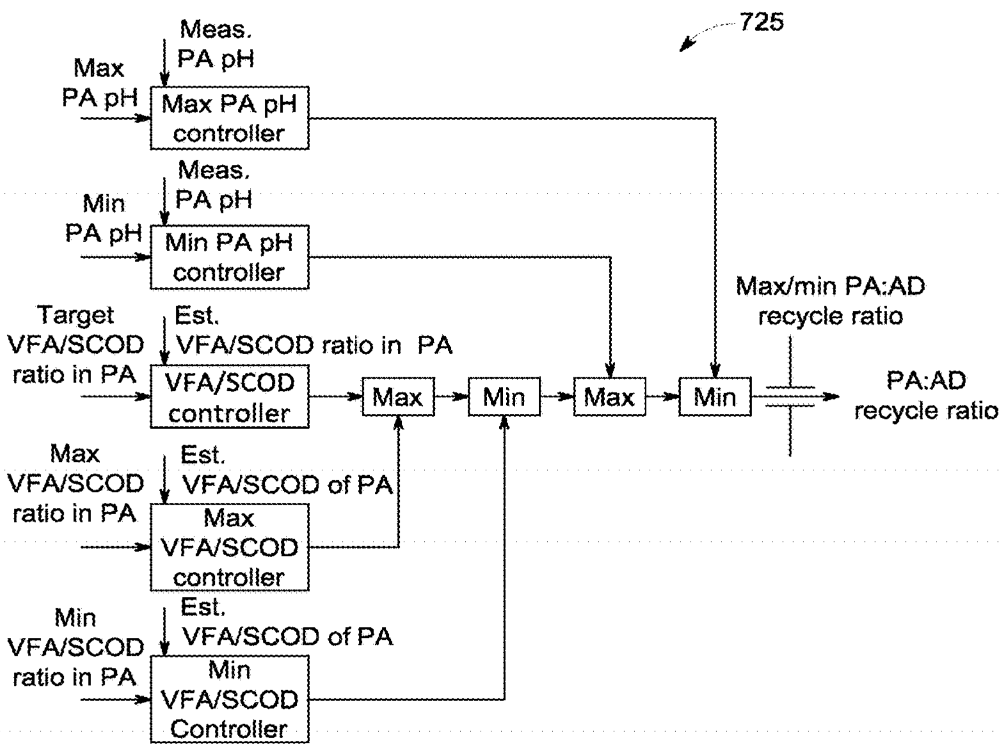

725
Meas.
PA pH
Max
PA pH
Max PA pH
controller
Meas.
PA pH
Min
PA pH
Min PA pH
controller
Target
VFA/SCOD
ratio in PA
Est.
VFA/SCOD ratio in PA
VFA/SCOD
controller
Max
Min
Max
Min
Max/min PA:AD
recycle ratio
PA:AD
recycle ratio
Max
VFA/SCOD
ratio in PA
Est.
VFA/SCOD of PA
Max
VFA/SCOD
controller
Min
VFA/SCOD
ratio in PA
Est.
VFA/SCOD of PA
Min
VFA/SCOD
Controller

FIG. 20

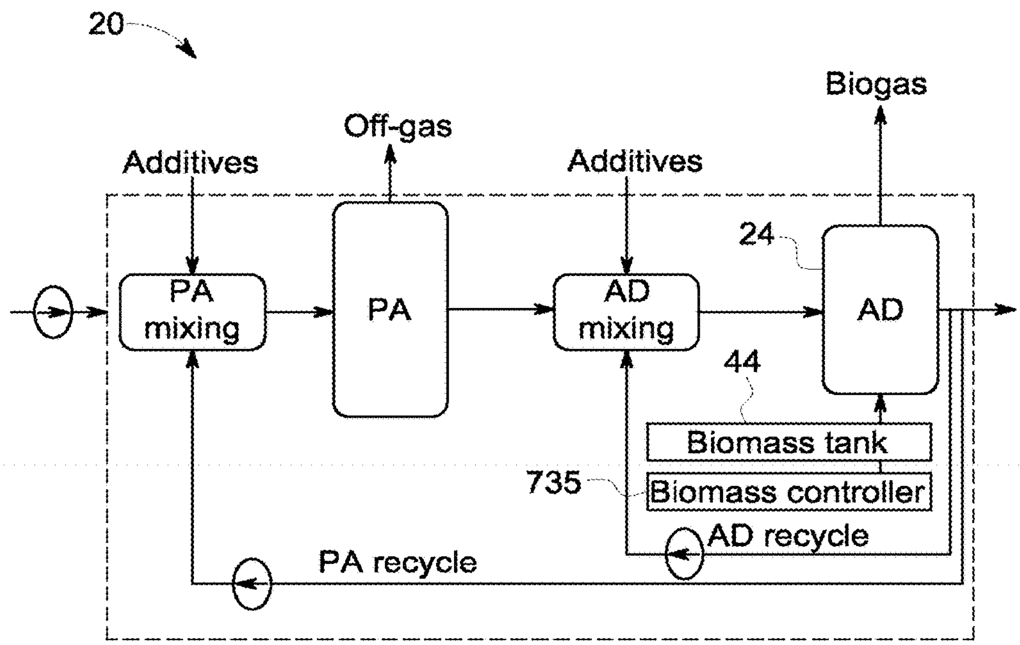
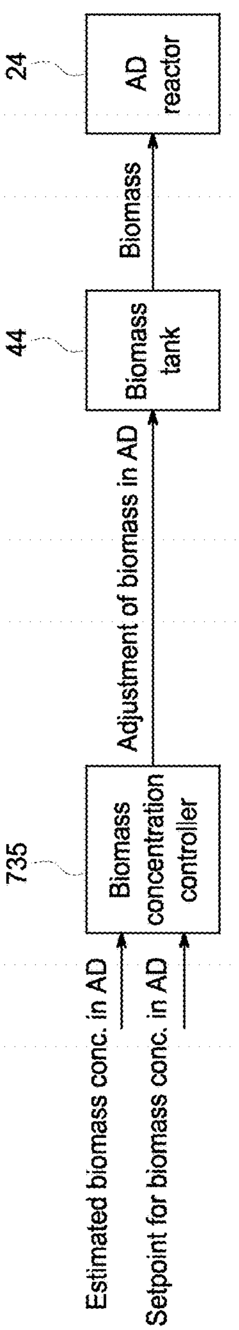
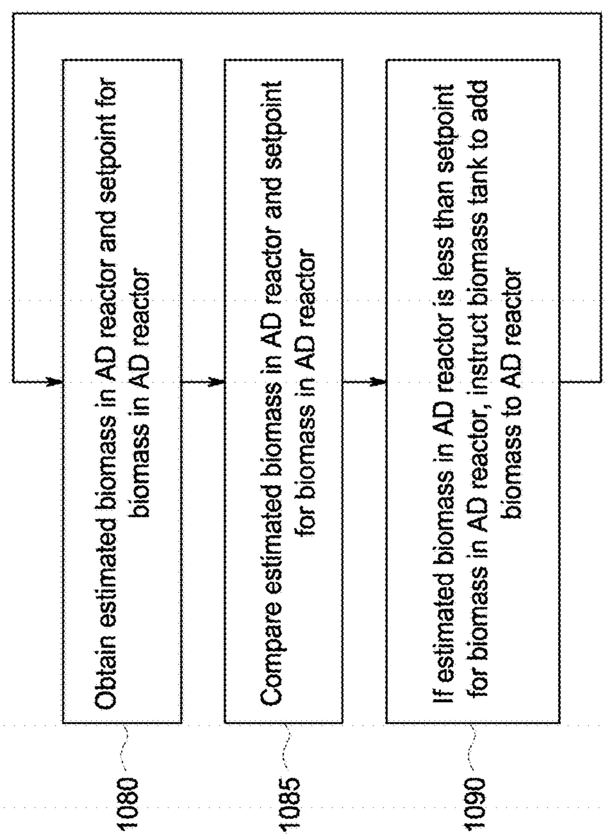

20
Biogas
Off-gas
Additives
Additives
24
PA mixing
PA
AD mixing
AD
44
Biomass tank
735
Biomass controller
AD recycle
PA recycle

FIG. 21



Estimated biomass conc. in AD
Setpoint for biomass conc. in AD
735
Biomass concentration controller
Adjustment of biomass in AD
44
Biomass tank
Biomass
24
AD reactor

FIG. 22



1080
Obtain estimated biomass in AD reactor and setpoint for biomass in AD reactor
1085
Compare estimated biomass in AD reactor and setpoint for biomass in AD reactor
1090
If estimated biomass in AD reactor is less than setpoint for biomass in AD reactor, instruct biomass tank to add biomass to AD reactor

FIG. 23

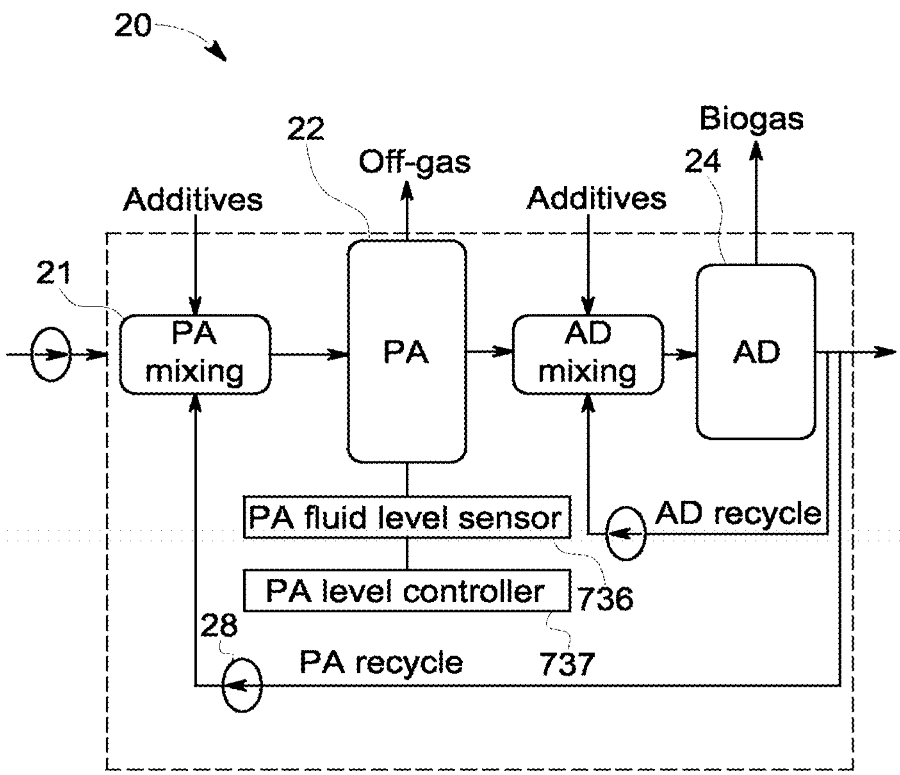
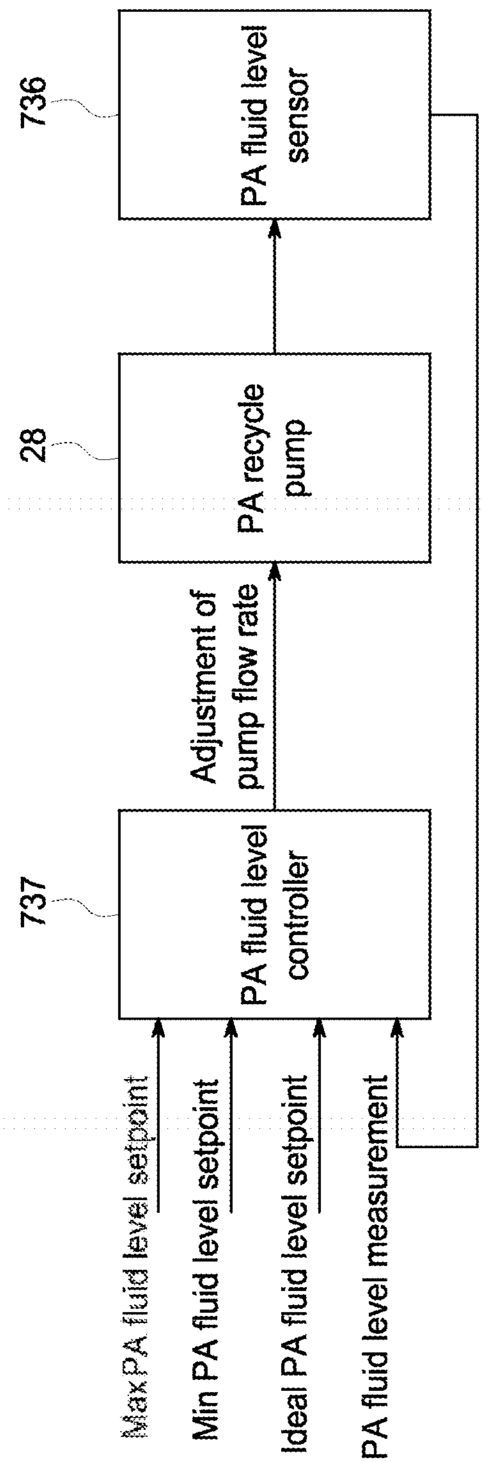

20
22
Off-gas
Biogas
24
Additives
Additives
21
PA
mixing
PA
AD
mixing
AD
PA fluid level sensor
AD recycle
PA level controller
736
28
PA recycle
737

FIG. 24



736
PA fluid level sensor
28
PA recycle pump
Adjustment of pump flow rate
737
PA fluid level controller
Max PA fluid level setpoint
Min PA fluid level setpoint
Ideal PA fluid level setpoint
PA fluid level measurement

FIG. 25

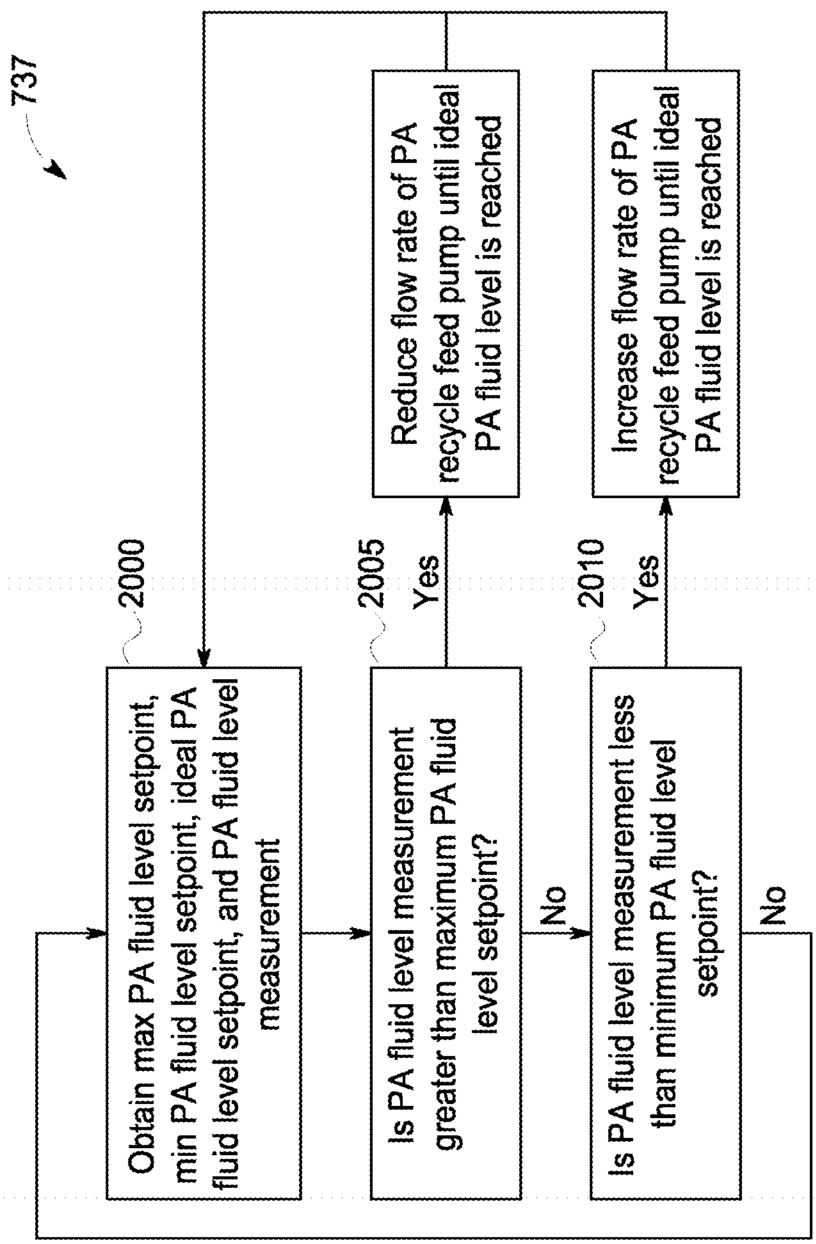

737
2000
Obtain max PA fluid level setpoint, min PA fluid level setpoint, ideal PA fluid level setpoint, and PA fluid level measurement
2005
Is PA fluid level measurement greater than maximum PA fluid level setpoint?
Yes
Reduce flow rate of PA recycle feed pump until ideal PA fluid level is reached
No
2010
Is PA fluid level measurement less than minimum PA fluid level setpoint?
Yes
Increase flow rate of PA recycle feed pump until ideal PA fluid level is reached
No

FIG. 26

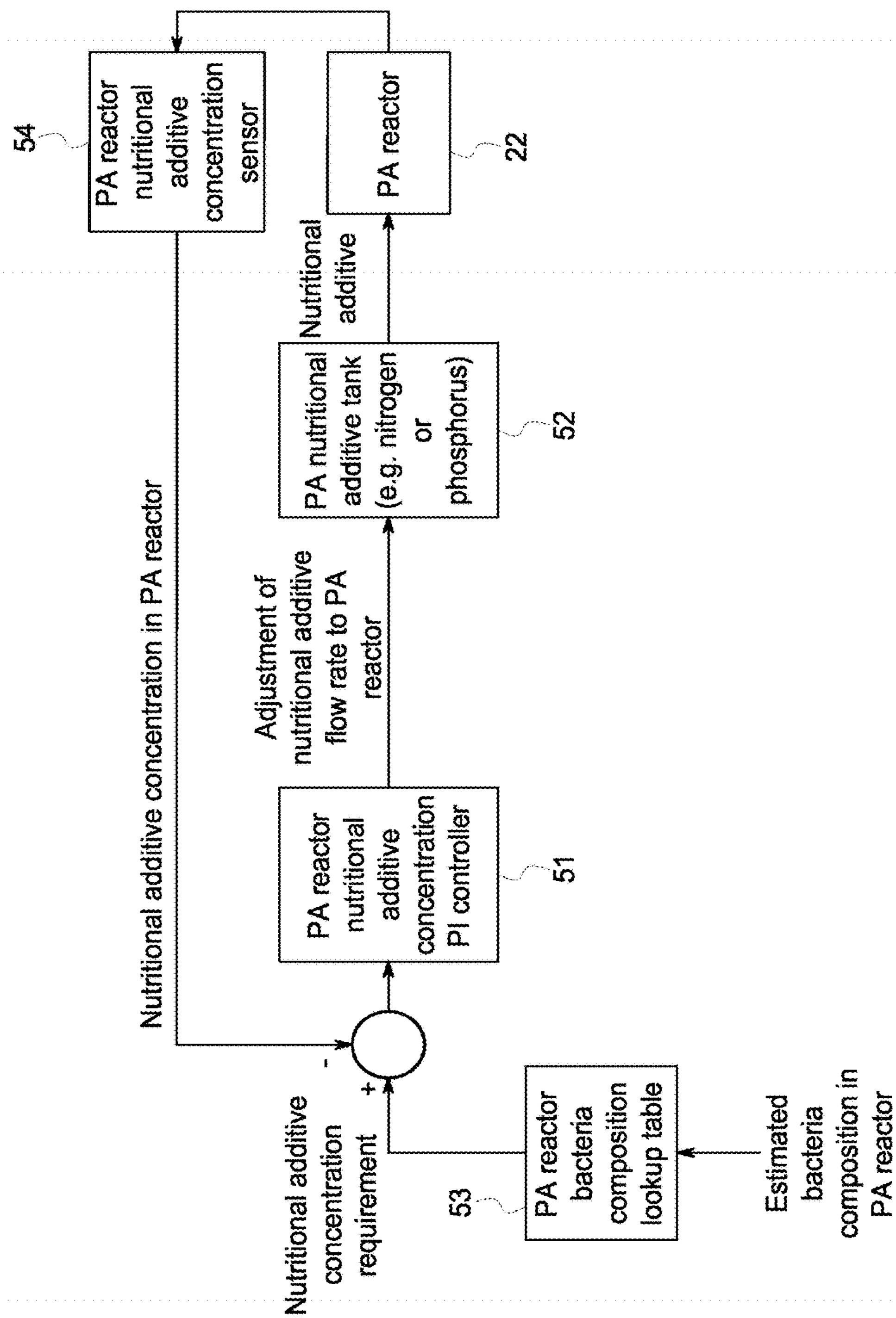

PA reactor nutritional additive concentration sensor
54
PA reactor
22
Nutritional additive
PA nutritional additive tank (e.g. nitrogen or phosphorus)
52
Nutritional additive concentration in PA reactor
Adjustment of nutritional additive flow rate to PA reactor
PA reactor nutritional additive concentration PI controller
51
-
+
Nutritional additive concentration requirement
PA reactor bacteria composition lookup table
53
Estimated bacteria composition in PA reactor

FIG. 27

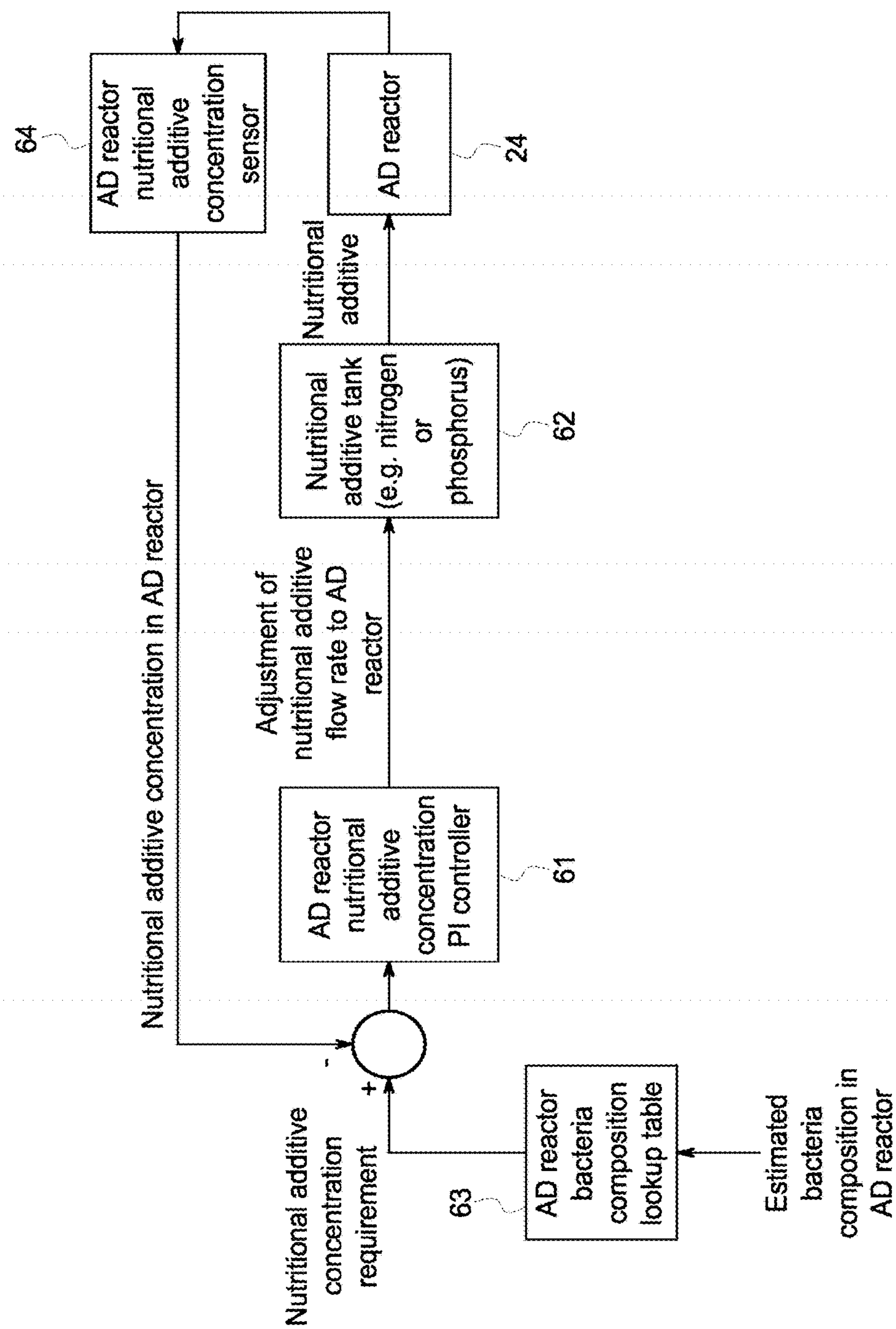

Estimated bacteria composition in AD reactor
AD reactor bacteria composition lookup table
63
Nutritional additive concentration requirement
+
-
Nutritional additive concentration in AD reactor
AD reactor nutritional additive concentration PI controller
61
Adjustment of nutritional additive flow rate to AD reactor
Nutritional additive tank (e.g. nitrogen or phosphorus)
62
Nutritional additive
AD reactor
24
AD reactor nutritional additive concentration sensor
64

FIG. 28

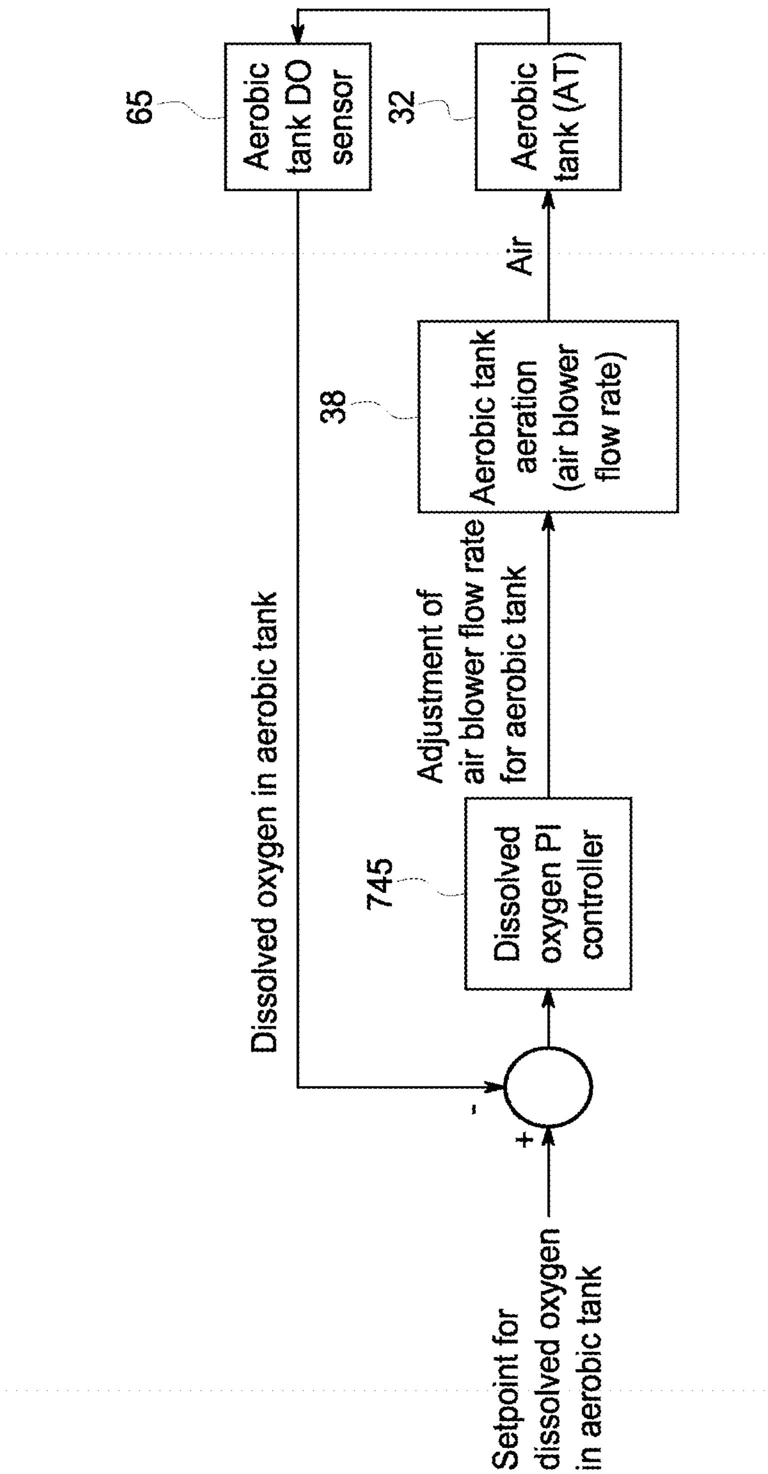

65
Aerobic tank DO sensor
32
Aerobic tank (AT)
Air
38
Aerobic tank aeration (air blower flow rate)
Dissolved oxygen in aerobic tank
Adjustment of air blower flow rate for aerobic tank
745
Dissolved oxygen PI controller
-
+
Setpoint for dissolved oxygen in aerobic tank

FIG. 29

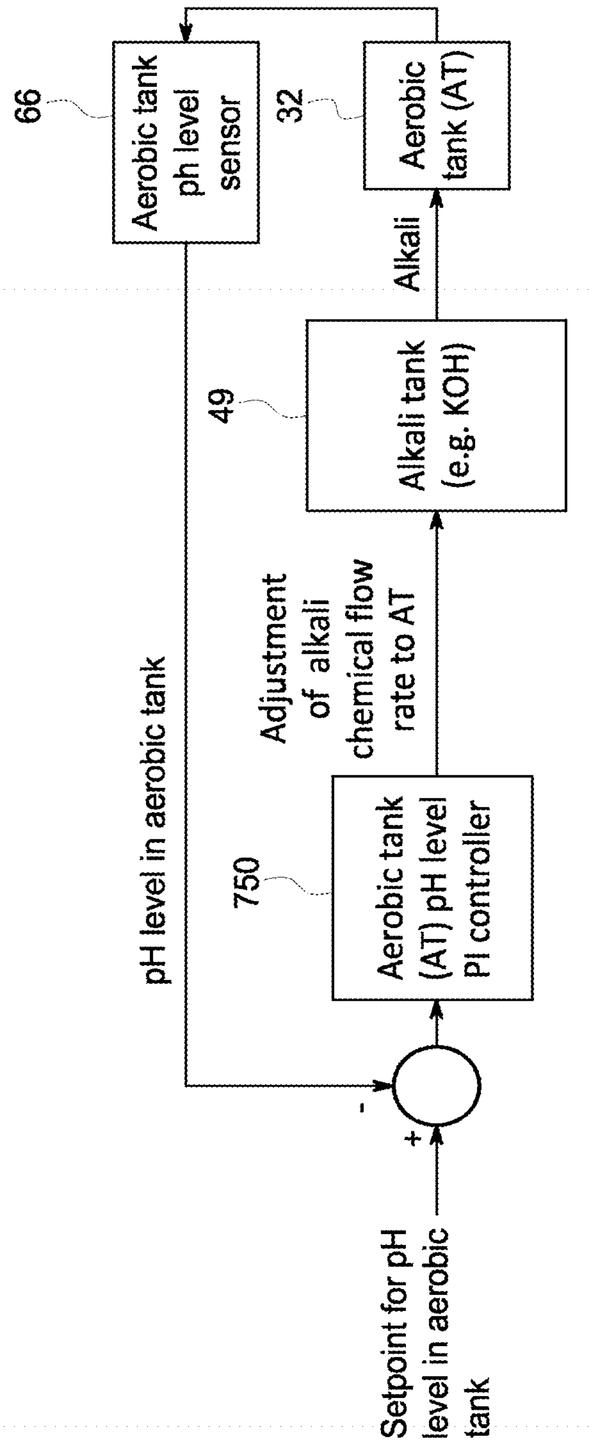

Setpoint for pH level in aerobic tank
+
-
pH level in aerobic tank
750
Aerobic tank (AT) pH level PI controller
Adjustment of alkali chemical flow rate to AT
49
Alkali tank (e.g. KOH)
Alkali
32
Aerobic tank (AT)
66
Aerobic tank ph level sensor

FIG. 30

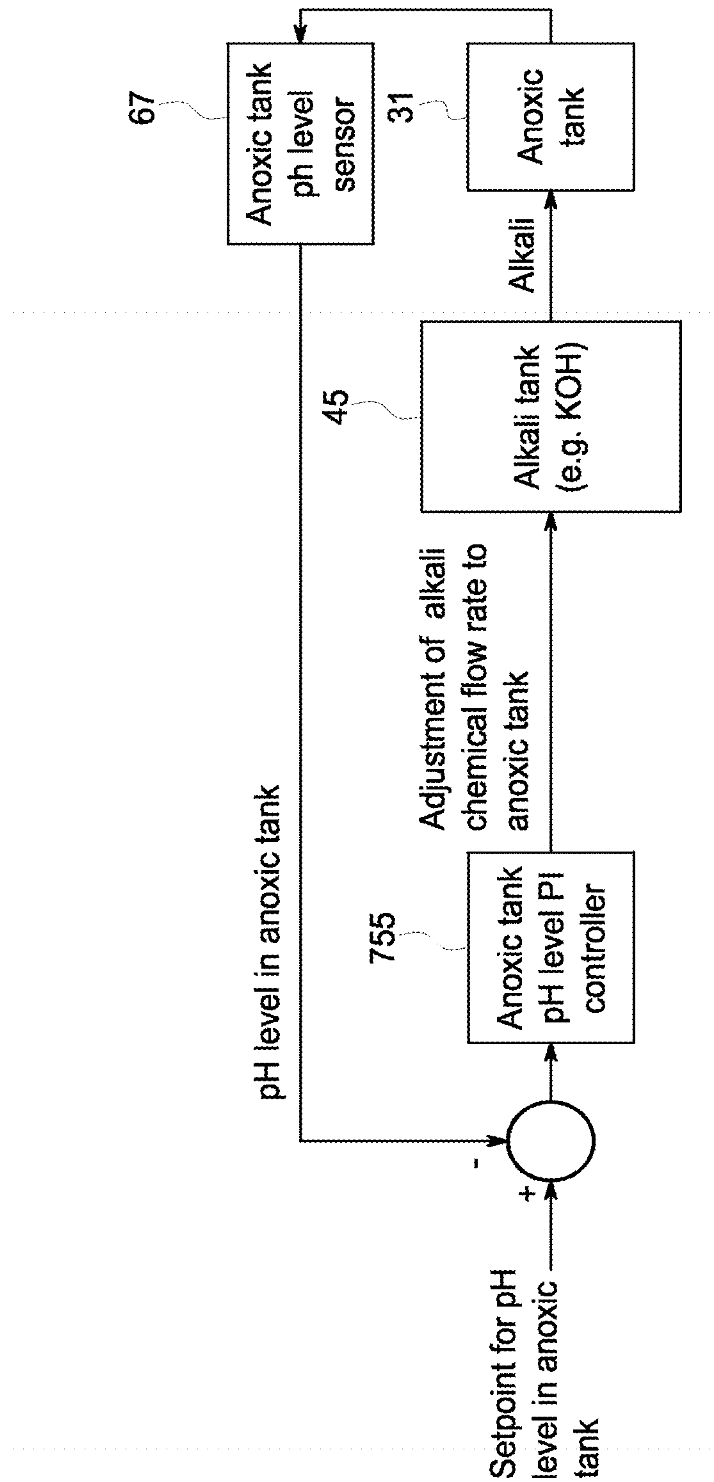

67
Anoxic tank ph level sensor
31
Anoxic tank
Alkali
45
Alkali tank (e.g. KOH)
pH level in anoxic tank
Adjustment of alkali chemical flow rate to anoxic tank
755
Anoxic tank pH level PI controller
-
+
Setpoint for pH level in anoxic tank

FIG. 31

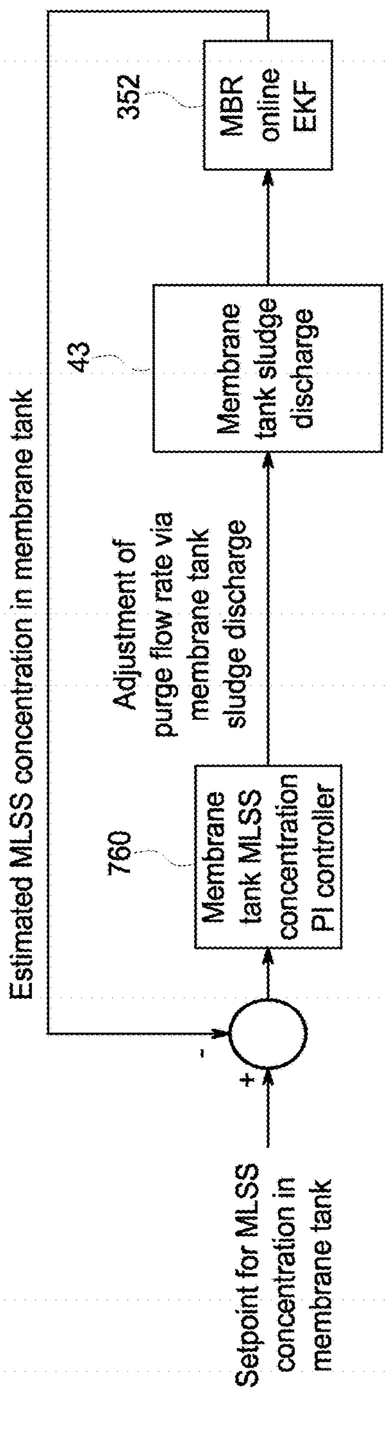


FIG. 32A

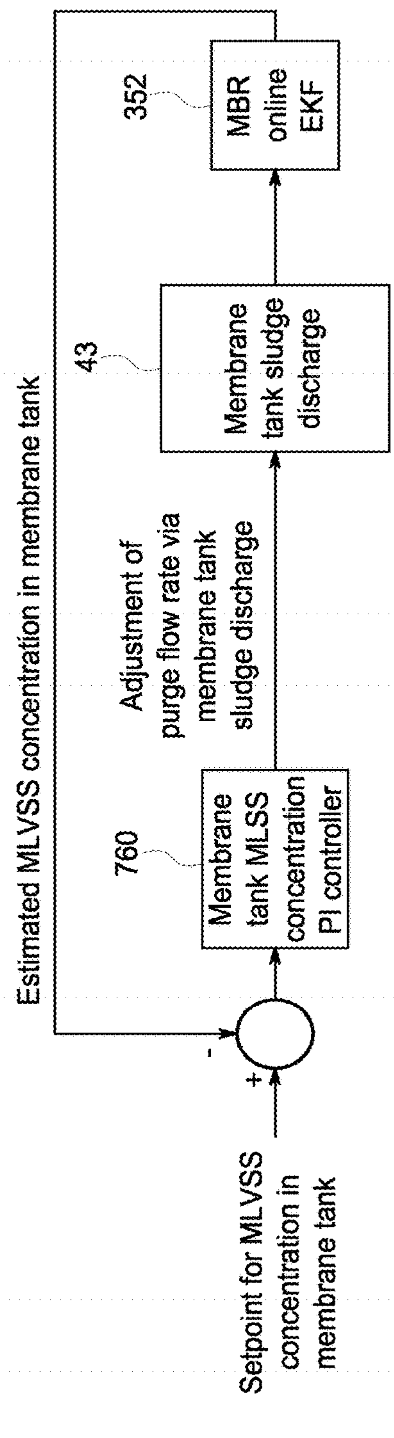


FIG. 32B

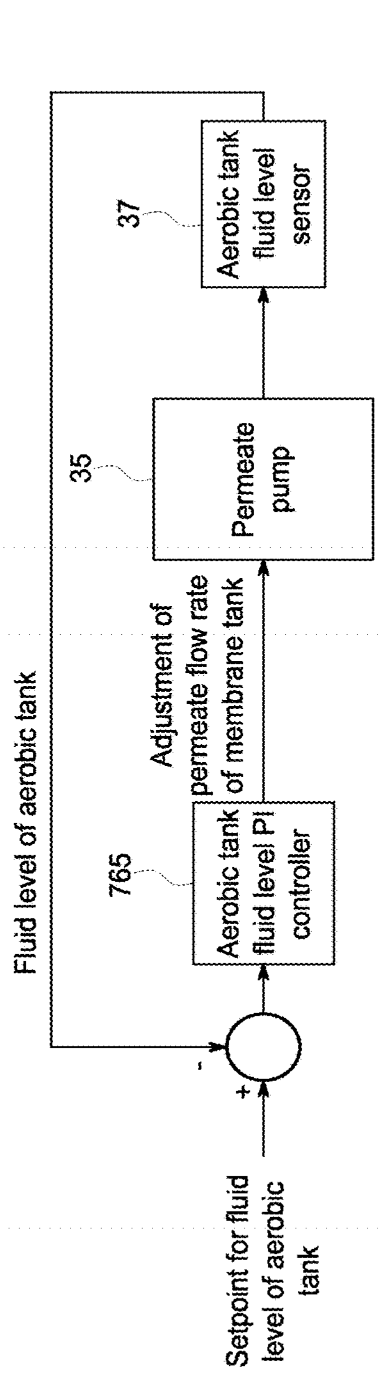

Setpoint for fluid level of aerobic tank
+
-
Fluid level of aerobic tank
765
Aerobic tank fluid level PI controller
Adjustment of permeate flow rate of membrane tank
35
Permeate pump
37
Aerobic tank fluid level sensor

FIG. 33

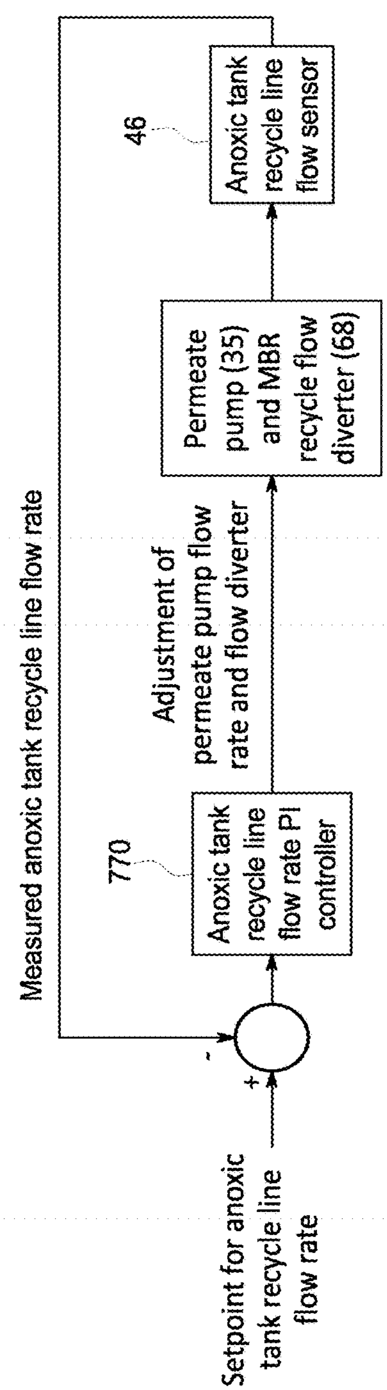

Setpoint for anoxic tank recycle line flow rate
+
-
Measured anoxic tank recycle line flow rate
770
Anoxic tank recycle line flow rate PI controller
Adjustment of permeate pump flow rate and flow diverter
Permeate pump (35) and MBR recycle flow diverter (68)
46
Anoxic tank recycle line flow sensor

FIG. 34

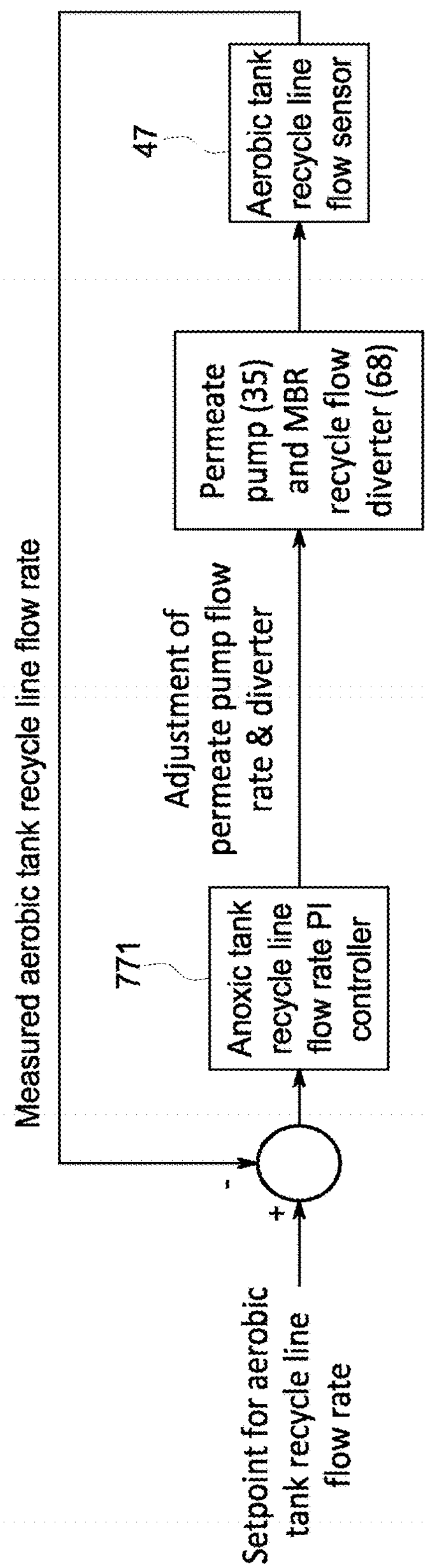

Setpoint for aerobic tank recycle line flow rate
+
-
Measured aerobic tank recycle line flow rate
771
Anoxic tank recycle line flow rate PI controller
Adjustment of permeate pump flow rate & diverter
Permeate pump (35) and MBR recycle flow diverter (68)
47
Aerobic tank recycle line flow sensor

FIG. 35

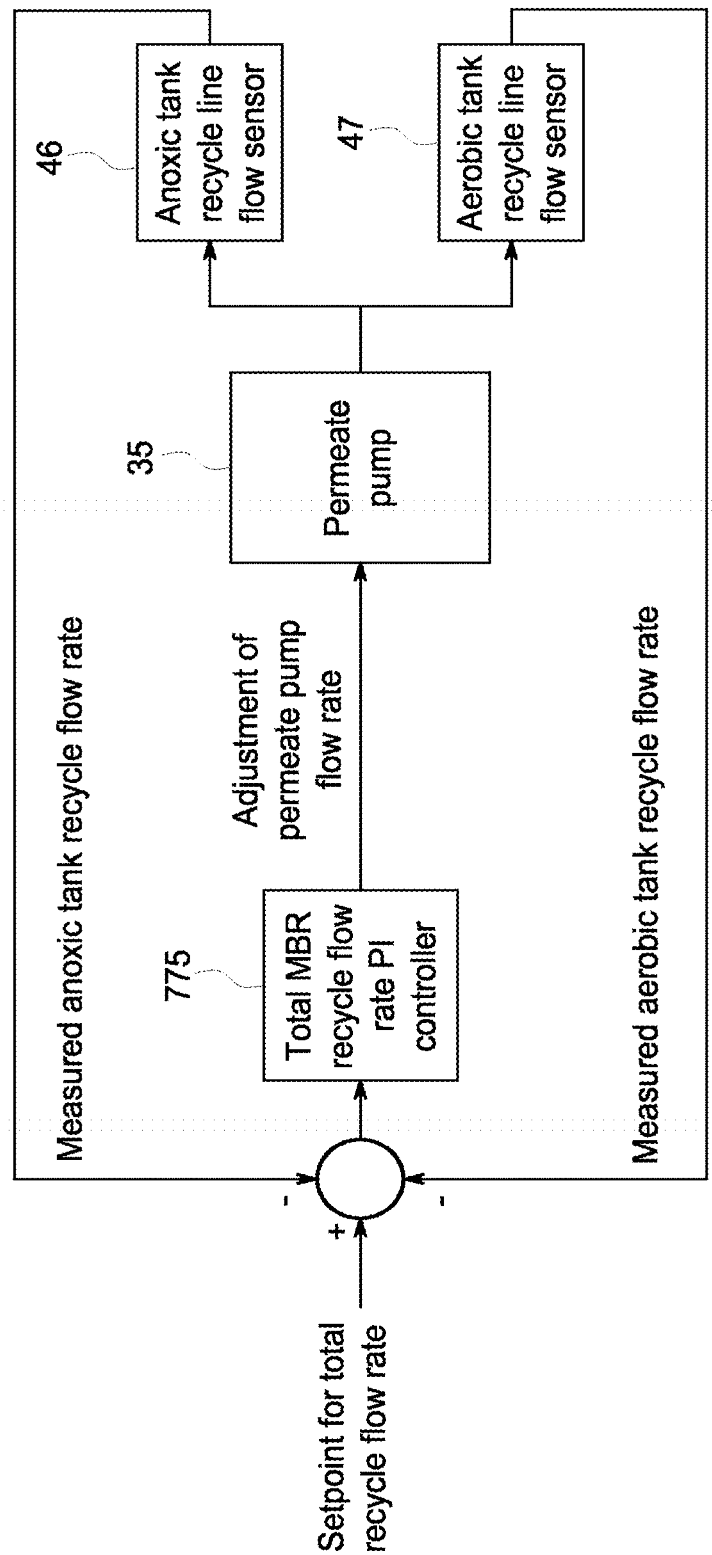

Setpoint for total recycle flow rate
+
-
-
Measured anoxic tank recycle flow rate
Measured aerobic tank recycle flow rate
775
Total MBR recycle flow rate PI controller
Adjustment of permeate pump flow rate
35
Permeate pump
46
Anoxic tank recycle line flow sensor
47
Aerobic tank recycle line flow sensor

FIG. 36

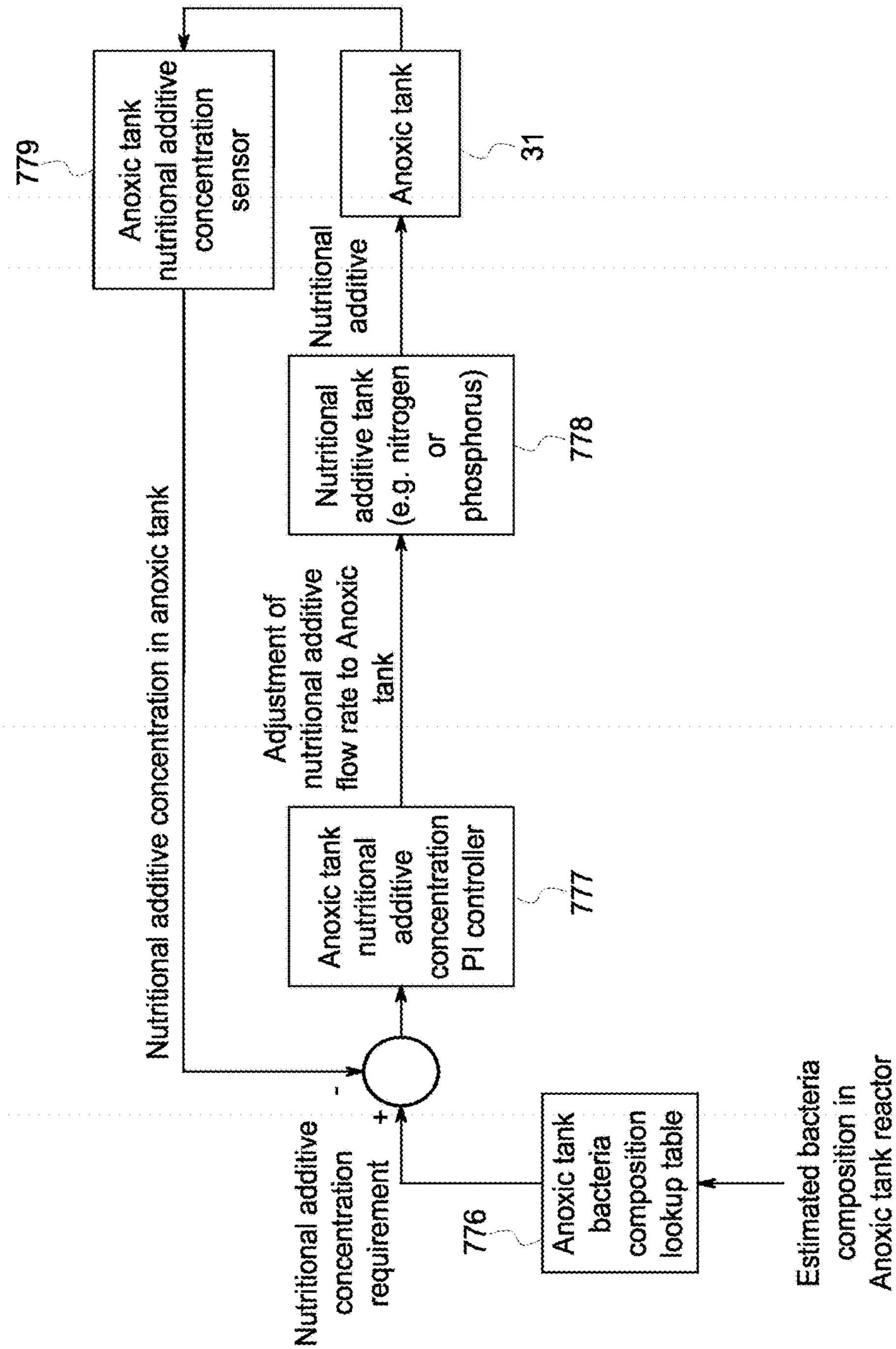

779
Anoxic tank nutritional additive concentration sensor
Anoxic tank
31
Nutritional additive
Nutritional additive tank (e.g. nitrogen or phosphorus)
778
Nutritional additive concentration in anoxic tank
Adjustment of nutritional additive flow rate to Anoxic tank
Anoxic tank nutritional additive concentration PI controller
777
-
+
Nutritional additive concentration requirement
776
Anoxic tank bacteria composition lookup table
Estimated bacteria composition in Anoxic tank reactor

FIG. 37

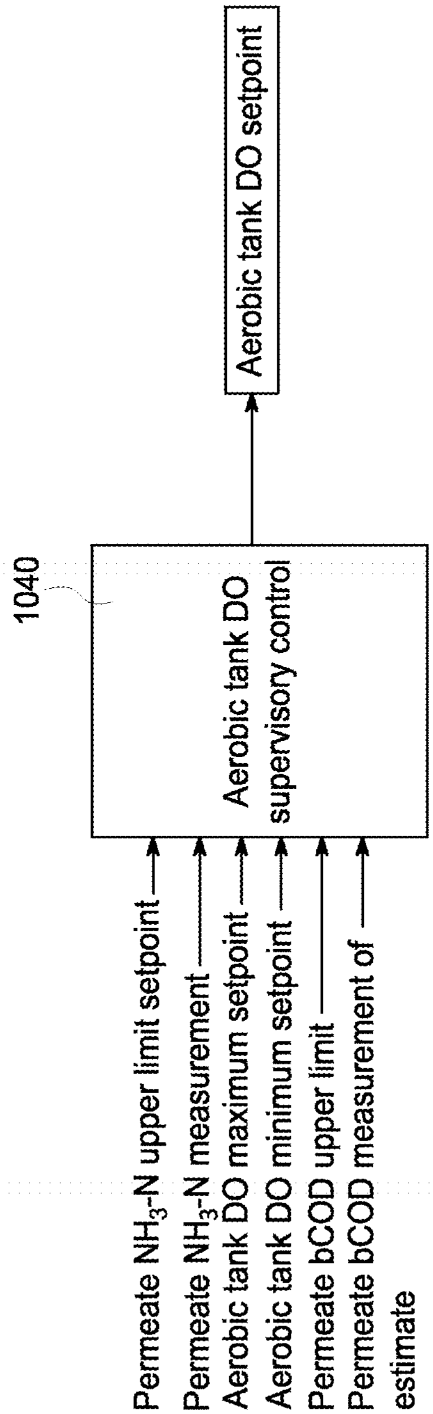

Permeate NH_3-N upper limit setpoint
Permeate NH_3-N measurement
Aerobic tank DO maximum setpoint
Aerobic tank DO minimum setpoint
Permeate bCOD upper limit
Permeate bCOD measurement of estimate
1040
Aerobic tank DO supervisory control
Aerobic tank DO setpoint

FIG. 38

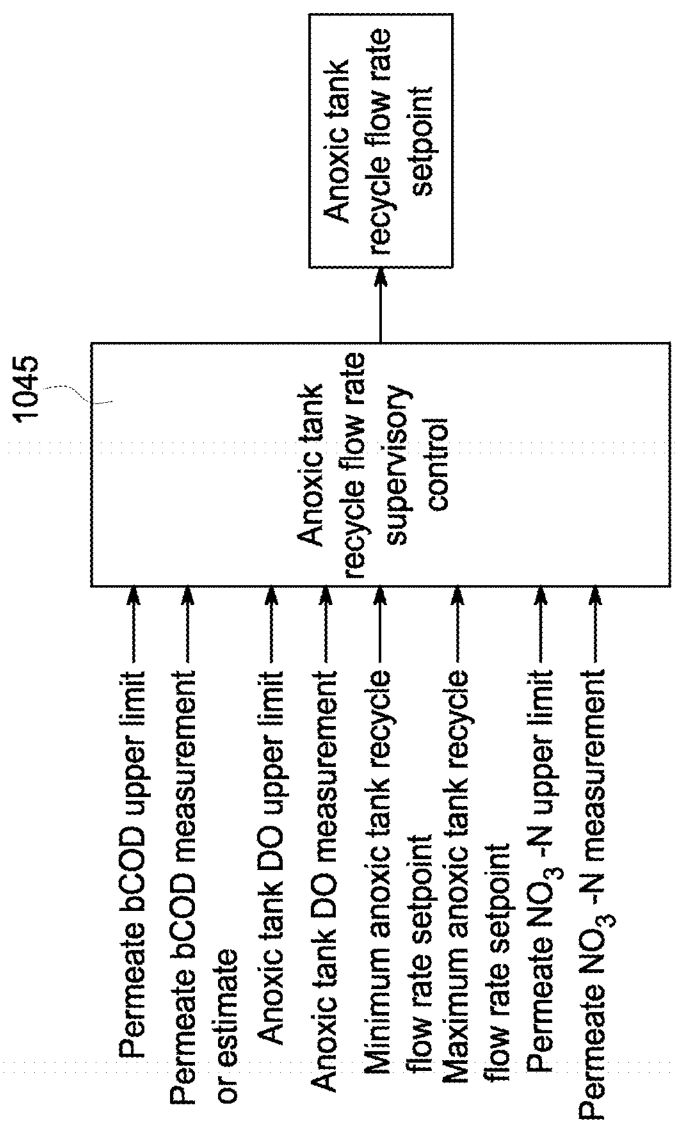

Anoxic tank recycle flow rate setpoint
1045
Anoxic tank recycle flow rate supervisory control
Permeate bCOD upper limit
Permeate bCOD measurement or estimate
Anoxic tank DO upper limit
Anoxic tank DO measurement
Minimum anoxic tank recycle flow rate setpoint
Maximum anoxic tank recycle flow rate setpoint
Permeate NO_3 -N upper limit
Permeate NO_3 -N measurement

FIG. 39

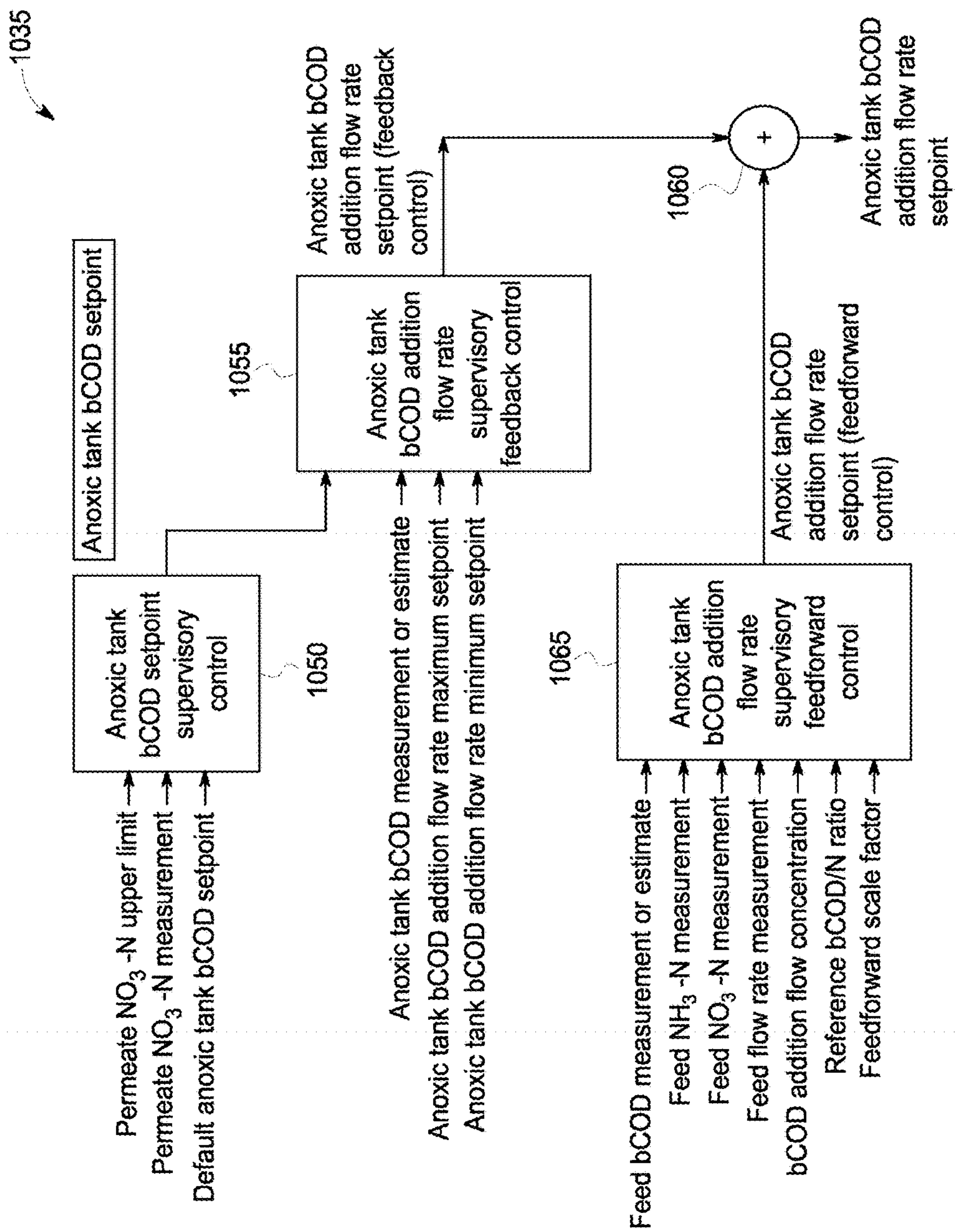

1035
Anoxic tank bCOD setpoint
Permeate NO_3 -N upper limit
Permeate NO_3 -N measurement
Default anoxic tank bCOD setpoint
Anoxic tank bCOD setpoint supervisory control
1050
1055
Anoxic tank bCOD measurement or estimate
Anoxic tank bCOD addition flow rate maximum setpoint
Anoxic tank bCOD addition flow rate minimum setpoint
Anoxic tank bCOD addition flow rate supervisory feedback control
Anoxic tank bCOD addition flow rate setpoint (feedback control)
1060
+
Anoxic tank bCOD addition flow rate setpoint
1065
Feed bCOD measurement or estimate
Feed NH_3 -N measurement
Feed NO_3 -N measurement
Feed flow rate measurement
bCOD addition flow concentration
Reference bCOD/N ratio
Feedforward scale factor
Anoxic tank bCOD addition flow rate supervisory feedforward control
Anoxic tank bCOD addition flow rate setpoint (feedforward control)

FIG. 40

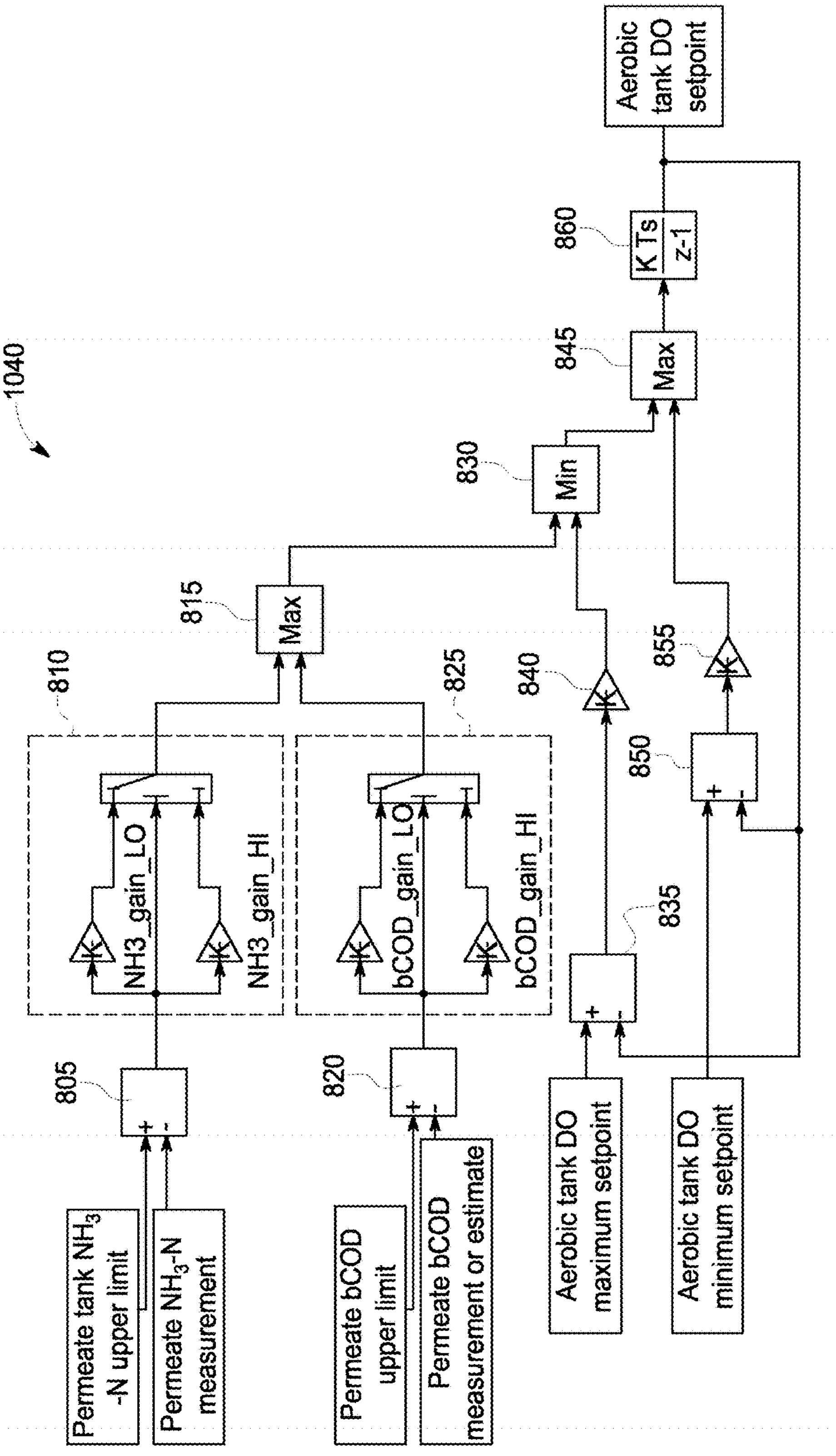

1040
Permeate tank NH_3 -N upper limit
Permeate NH_3-N measurement
805
810
NH3_gain_LO
NH3_gain_HI
815
Max
Permeate bCOD upper limit
Permeate bCOD measurement or estimate
820
825
bCOD_gain_LO
bCOD_gain_HI
Aerobic tank DO maximum setpoint
835
840
830
Min
Aerobic tank DO minimum setpoint
850
855
845
Max
860
K Ts
z-1
Aerobic tank DO setpoint

FIG. 41

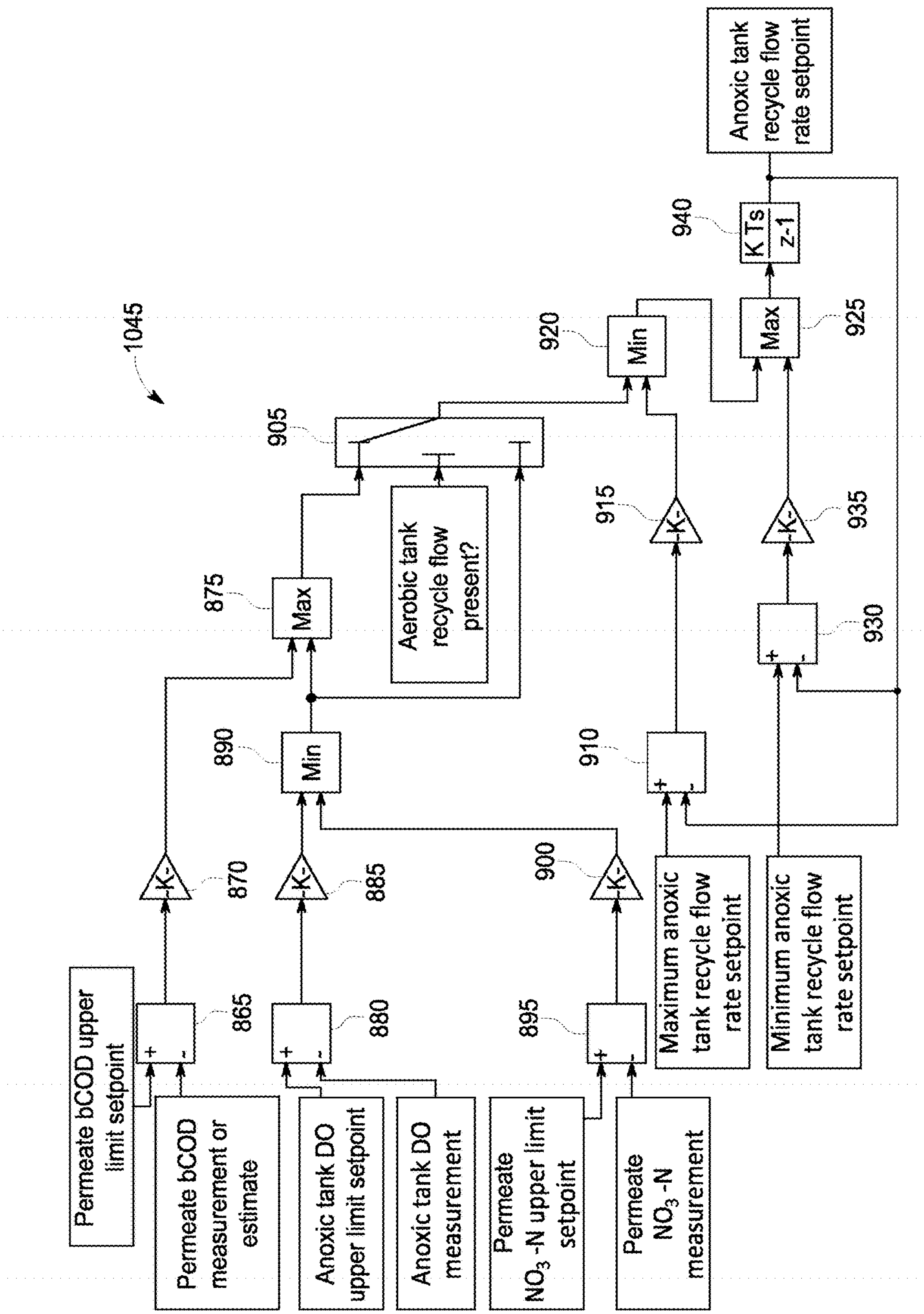

1045
Permeate bCOD upper limit setpoint
Permeate bCOD measurement or estimate
Anoxic tank DO upper limit setpoint
Anoxic tank DO measurement
Permeate NO_3 -N upper limit setpoint
Permeate NO_3 -N measurement
865
880
895
870
885
900
-K-
890
Min
875
Max
Aerobic tank recycle flow present?
905
Maximum anoxic tank recycle flow rate setpoint
Minimum anoxic tank recycle flow rate setpoint
910
915
930
935
920
925
940
K Ts
z-1
Anoxic tank recycle flow rate setpoint

FIG. 42

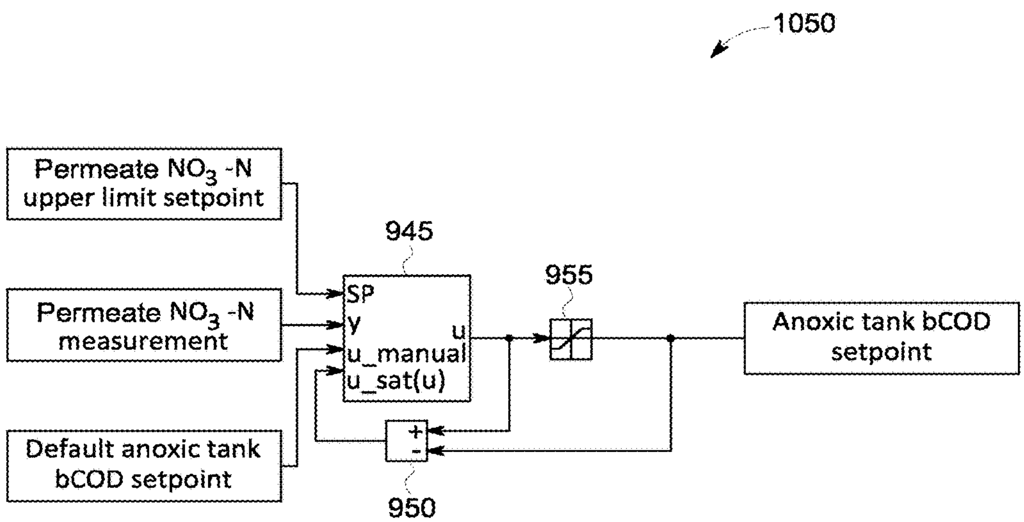

1050
Permeate NO_3 -N upper limit setpoint
Permeate NO_3 -N measurement
Default anoxic tank bCOD setpoint
945
SP
y
u_manual
u_sat(u)
u
955
+
-
950
Anoxic tank bCOD setpoint

FIG. 43

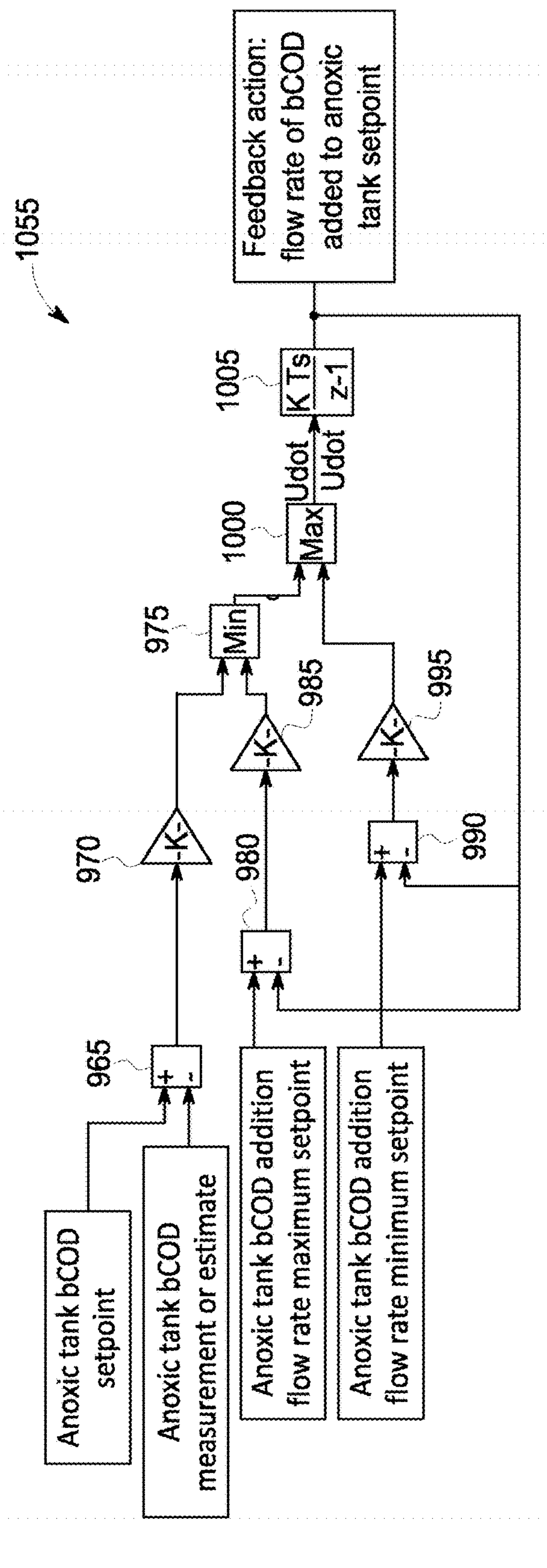

1055
Feedback action: flow rate of bCOD added to anoxic tank setpoint
1005
K Ts
z-1
Udot
Udot
1000
Max
975
Min
985
-K-
995
-K-
970
-K-
980
990
965
Anoxic tank bCOD setpoint
Anoxic tank bCOD measurement or estimate
Anoxic tank bCOD addition flow rate maximum setpoint
Anoxic tank bCOD addition flow rate minimum setpoint

FIG. 44

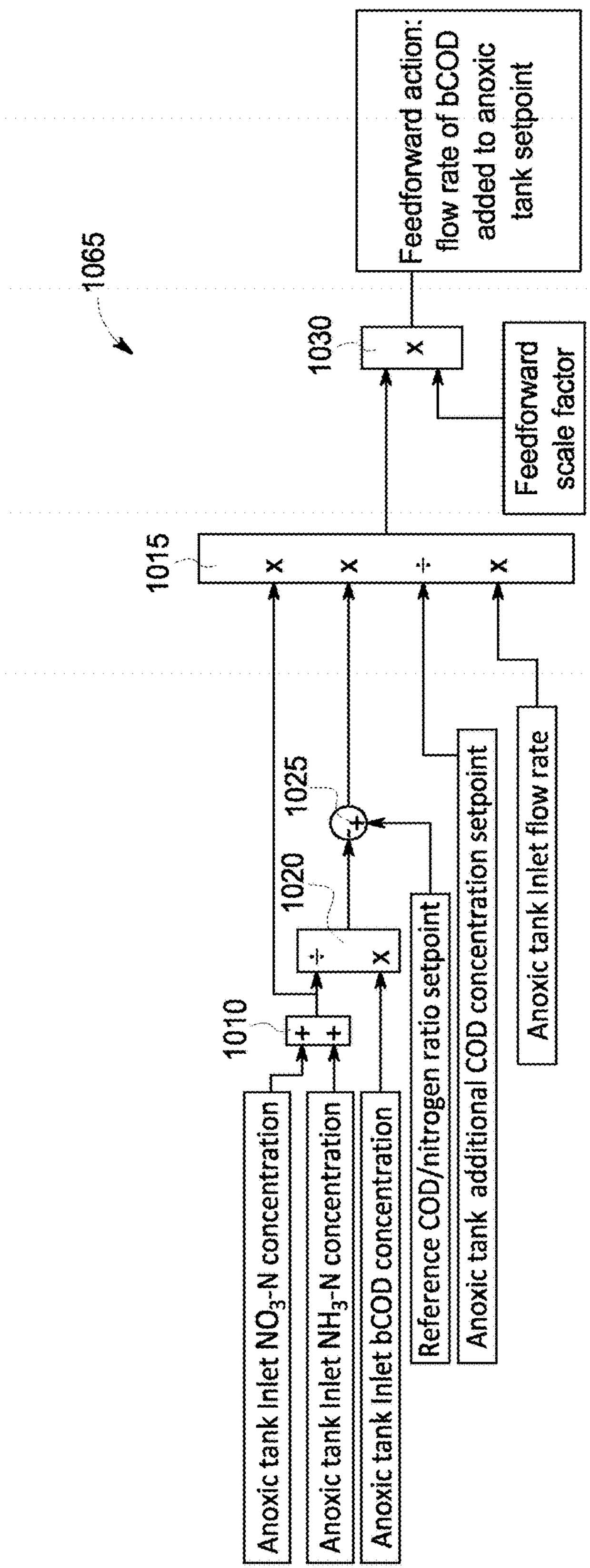

1065
Feedforward action: flow rate of bCOD added to anoxic tank setpoint
1030
x
Feedforward scale factor
1015
x
x
÷
x
1025
+
-
1020
÷
x
1010
+
+
Anoxic tank Inlet NO3-N concentration
Anoxic tank Inlet NH3-N concentration
Anoxic tank Inlet bCOD concentration
Reference COD/nitrogen ratio setpoint
Anoxic tank additional COD concentration setpoint
Anoxic tank Inlet flow rate

FIG. 45

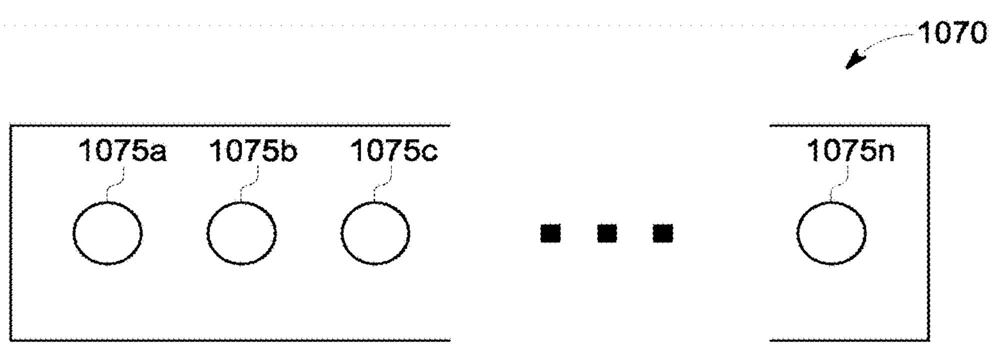


FIG. 46

WASTEWATER TREATMENT PLANT ONLINE MONITORING AND CONTROL

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a divisional of U.S. patent application Ser. No. 14/234,955 filed Apr. 22, 2014, which is the US National Stage entry of PCT/US2012/048163 filed Jul. 25, 2012, and claims priority to U.S. Provisional Patent Application Ser. No. 61/574,017 filed Jul. 26, 2011, all of which are herein incorporated by reference in their entireties.

GOVERNMENT RIGHTS

[0002] This application was funded under Department of Energy Contract DE-FC26-08NT05870. The U.S. Government has certain rights under this application and any patent issuing therefrom.

FIELD OF THE INVENTION

[0003] This application relates to wastewater treatment plants, more particularly to the monitoring and control of the key units of a wastewater treatment plant.

BACKGROUND OF THE INVENTION

[0004] Soaring fuel prices, shrinking water resources, and increased regulation of wastewater treatment plant effluent are forcing wastewater treatment plant operators to manage their key units more efficiently.

[0005] Typically, key units or components of a wastewater treatment plant include a anaerobic digester (AD) and membrane bioreactor (MBR). The AD and MBR operate in a coordinated and an interdependent fashion, hence any upsets or variations in any key unit affect functionality and performance of the rest of the key units. The wastewater feed to the AD, for example, may have significant variations in flow rates, influent chemical oxygen demand (COD), total suspended solids, total soluble COD, temperature, nitrogen, phosphates, sulfates, and pH. The variations in the AD, in turn, impact operations of downstream process units, such as the MBR.

[0006] Conventionally, the variations in the key units are monitored periodic manual sampling and off-line laboratory tests to monitor the system performance, identify any abnormal condition due to variations in the wastewater feed, and decide on appropriate remedial action. Unfortunately, these lab tests are time consuming and infrequent manual sampling are not sufficient to detect potentially adverse changes in a timely manner. Also, manual operation is often inadequate in taking timely corrective actions needed to mitigate effects of variations and avoid any upsets. In particular, upsets in the AD can lead to instabilities which, if undetected or not corrected in a timely manner, can eventually cause a washout condition with loss of active biomass requiring costly shutdown and re-seeding. Also, whenever AD performance is hindered, biogas generation is sacrificed and the load on downstream MBR can become overwhelmingly high leading to violations in MBR effluent water quality.

[0007] These factors often lead to over-design and very conservative operation of the AD and MBR to avoid any potential upsets that can destabilize the AD and MBR. However, a conservative operation often means inefficient operation involving overdosing chemical additives and over-aerating to allow for unknown process variations, and thus unnecessary high operating costs.

[0008] Thus, a need exists for an improved method of operating a wastewater treatment plant through monitoring and controlling the AD and MBR of a wastewater treatment plant.

SUMMARY OF THE INVENTION

[0009] In one aspect of the invention, a method of operating an anaerobic digester (AD) was surprisingly discovered, comprising: providing and monitoring an AD, wherein the monitoring comprises:

[0010] providing an AD offline extended Kalman filter (EKF) having an offline dynamic model of the AD, providing an AD online EKF having an online dynamic model of the AD; wherein the offline and the online dynamic models of the AD are comprised of states, process material balances, energy balances, bio-chemical reaction kinetics, estimated parameters, and adapted model parameters; wherein the adapted model parameters are a subset of the estimated parameters;

[0011] providing historical operation data for the AD, wherein the historical operation data is comprised of historical measured input data, historical measured output data, and historical laboratory analysis data;

[0012] identifying the estimated parameters of the offline dynamic model of the AD using the AD offline EKF and the historical operation data for the AD;

[0013] importing the estimated parameters from the offline dynamic model of the AD into the online dynamic model of the AD;

[0014] providing real time operation data for the AD to the AD online EKF, wherein the real time operational data is comprised of real time measured input data and real time measured output data of the AD;

[0015] updating the adapted model parameters of the online dynamic model of the AD and estimating the model based inferred variables of the AD using the AD online EKF, the online dynamic model of the AD, the real time measured input data of the AD, and the real time measured output data of the AD; and

[0016] providing one or more of the adapted model parameters of the online dynamic model of the AD and the model based inferred variables of the AD to an operator of the AD.

[0017] In another aspect of the method of operating the AD, the AD is comprised of an AD reactor.

[0018] In another aspect of the method of operating the AD, the AD reactor is a CSTR, UASB, EGSB, mixed bed, moving bed, low-rate, or high-rate reactor.

[0019] In another aspect of the method of operating the AD, the AD is further comprised of a pre-acidification (PA) reactor, wherein the AD reactor and the pre-acidification reactor are modeled separately in both of the online and offline dynamic models of the AD.

[0020] In another aspect of the method of operating the AD, the AD is comprised of a mixing stage and at least one recycle line.

[0021] In another aspect of the method of operating the AD, the at least one recycle line of the AD is a pre-acidification reactor recycle line or an AD reactor recycle line.

[0022] In another aspect of the method of operating the AD, materials for the material balances in the online and offline dynamic models of the AD are comprised of insoluble organics, soluble substrates, VFA, biomass, inorganic carbon and alkalinity.

[0023] In another aspect of the method of operating the AD, insoluble organics is comprised of carbohydrates, protein and fat; the soluble substrate and VFA include at least one of sugars, LCFA, amino acids, acetate acid, or propionate acid; and the biomass includes biomass for acedogenesis, acetogenesis, acetoclastic methanogenesis and hydrogen methanogenesis bio-chemical processes.

[0024] In another aspect of the method of operating the AD, the inorganic carbon is comprised of at least one of carbon dioxide, carbonate, or bicarbonate.

[0025] In another aspect of the method of operating the AD, the alkalinity is comprised of alkalinity associated with bicarbonate, VFA, added alkali, and generation of ammonia and hydrogen sulfide.

[0026] In another aspect of the method of operating the AD, the bio-chemical reaction kinetics in the online and offline dynamic models of the AD are comprised of at least one of insoluble organics hydrolysis, acedogenesis, acetogenesis, acetoclastic methanogenesis, or hydrogen methanogenesis process.

[0027] In another aspect of the method of operating the AD, the historical operation data of the AD and the real time operation data of the AD are comprised of at least one of raw influent pH, raw influent temperature, raw influent flow rate, raw influent TOC, raw influent TIC, added alkali flow rate, PA reactor fluid level, AD feed flow rate, raw influent SCOD, raw influent TCOD, raw influent SBOD, raw influent VSS, raw influent TSS, raw influent soluble inorganic nitrogen, raw influent VFA, added alkali concentration, PA reactor pH, PA effluent TOC, PA effluent TIC, AD biogas flow rate, AD biogas CH_4 concentration, AD Biogas CO_2 concentration, AD reactor pH, AD effluent TOC, AD effluent TIC, AD effluent VFA, AD effluent alkalinity, AD reactor MLVSS, AD effluent TCOD, AD effluent SCOD, AD effluent VSS, or AD effluent TSS.

[0028] In another aspect of the method of operating the AD, the estimated parameters and the adapted model parameters of the offline dynamic model of the AD and the online dynamic model of the AD are comprised of at least one of PA reactor composite fraction of carbohydrate, PA reactor composite fraction of fat, PA reactor composite fraction of protein, PA reactor fraction of insoluble convertible to SBOD, PA reactor acedogenthese reaction coefficient, PA reactor biomass decay rate, PA reactor insoluble hydrolysis reaction coefficient, PA reactor insoluble flow out coefficient, PA reactor CO_2 escape coefficient, AD reactor composite fraction of carbohydrate, AD reactor composite fraction of fat, AD reactor composite fraction of protein, AD reactor fraction of insoluble convertible to SBOD, AD reactor acedogenthese reaction coefficient, AD reactor acetogenesis reaction coefficient, AD reactor acetoclastic methanogenesis reaction coefficient, AD reactor hydrogen methanogenesis reaction coefficient, AD reactor biomass decay rate, PA reactor insoluble hydrolysis reaction coefficient, or PA reactor insoluble flow out coefficient.

[0029] In another aspect of the method of operating the AD, at least one of the estimated parameters of the offline dynamic model of the AD and the model based inferred variables of the online dynamic model of the AD are estimated with confidence intervals.

[0030] In another aspect of the method of operating the AD, the model based inferred variables of the online dynamic model of the AD are comprised of at least one of the following unmeasured inputs or outputs of the AD: raw influent insoluble COD, raw influent insoluble inert COD, raw influent soluble inert COD, raw influent SBOD saccharide, raw influent SBOD LCFA, raw influent SBOD amino acid, raw influent propionate acid, raw influent acetate acid, raw influent inorganic carbon content, raw influent alkalinity, raw influent inorganic nitrogen, raw influent SCOD, raw influent TCOD, raw influent SBOD, PA reactor alkalinity, PA reactor VFA, PA reactor temperature, PA reactor SCOD, PA reactor TCOD, PA reactor SBOD, AD reactor alkalinity, AD reactor VFA, AD reactor temperature, AD reactor SCOD, AD reactor SBOD, AD reactor acedogenthese biomass, AD reactor acetogenesis biomass, AD reactor acetoclastic methanogenesis biomass, AD reactor hydrogen methanogenesis biomass, AD reactor insoluble COD, AD reactor insoluble inert COD, AD reactor soluble inert COD, AD reactor SBOD saccharide, AD reactor SBOD LCFA, AD reactor SBOD amino acid, AD reactor propionate acid, AD reactor acetate acid, AD reactor inorganic carbon content, AD reactor alkalinity, AD reactor inorganic nitrogen, AD reactor SCOD, AD reactor TCOD, AD reactor SBOD, SCOD conversion rate, CH_4 conversion efficiency, or recycle flow rate.

[0031] In another aspect of the method of operating the AD, the adapted model parameters of the online dynamic model of the AD are turned using different weights for online measurements and prior knowledge of measurement accuracy.

[0032] In another aspect of the method of operating the AD, limits are applied to one or more of the estimated parameters and the adapted model parameters; wherein constraints are applied to one or more of the model based inferred variables.

[0033] In another aspect of the method of operating the AD, the adapted model parameters of the online dynamic model of the AD are adjusted by one or both of: calculating model predicted outputs of the AD using the AD online EKF, the online dynamic model of the AD, the real time measured input data of the AD, and the real time measured output data of the AD, comparing the measured output data of the AD and the model predicted outputs of the AD, and updating the adapted model parameters of the online dynamic model of the AD such that the real time measured output data of the AD substantially correspond with the model predicted outputs of the AD; or periodically re-identifying the estimated parameters of the offline dynamic model of the AD using the AD offline EKF and the historical operation data for the AD, and importing the estimated parameters from the offline dynamic model of the AD into the online dynamic model of the AD.

[0034] In another aspect of the method of operating the AD, the AD is controlled, wherein the controlling comprises: providing an AD control system; wherein the AD is comprised of an AD reactor and optionally a PA reactor; wherein the AD control system uses one or more of the real time measured input data of the AD, the real time measured output data of the AD, the estimated parameters of the online dynamic model of the AD, or the model based inferred variables of the AD to control at least one of a nutritional additive concentration of the AD reactor, a nutritional additive concentration of the PA reactor, pH of the AD reactor, pH of the PA reactor, biomass concentration of the AD reactor, fluid level of the PA reactor, or a recycle flow rate of the AD.

[0035] In another aspect of the method of operating the AD, at least one of the monitoring the AD or the controlling the AD is performed using a computer.

[0036] In another aspect of the method of operating the AD, controlling the nutritional additive concentration of the AD prevents biomass overfeeding and starvation, controlling the nutritional additive concentration of the PA reactor prevents biomass overfeeding and starvation, controlling the pH of the AD reactor minimizes alkali dosing, wherein controlling the pH of the PA reactor minimizes alkali dosing, controlling the biomass concentration of the AD reactor offsets biomass inhibition and saves alkali, controlling a recycle flow rate of the PA reactor minimizes alkali dosing and maintains fluid level of the PA reactor, and controlling a recycle flow rate of the AD reactor maximizes COD conversion and biogas generation.

[0037] In another aspect of the method of operating the AD, the AD control system is comprised of an AD supervisory control system and an AD low-level control system.

[0038] In another aspect of the method of operating the AD, the AD supervisory control system is comprised of at least one of an AD reactor pH supervisory controller, a PA reactor pH supervisory controller, or an PA:AD overall recycle flow ratio supervisory controller.

[0039] In another aspect of the method of operating the AD, the AD reactor pH supervisory controller is comprised of an AD reactor nonlinear Proportion-Integration (PI) pH controller and an AD reactor Proportion (P) alkalinity controller in a cascaded configuration.

[0040] In another aspect of the method of operating the AD, the PA reactor pH supervisory controller is comprised of a PA reactor nonlinear PI pH controller and a PA reactor P alkalinity controller in a cascaded configuration.

[0041] In another aspect of the method of operating the AD, the PA:AD overall recycle flow ratio supervisory controller is comprised of a PA:AD recycle ratio controller, and a PA reactor and AD reactor recycle flow rate controller.

[0042] In another aspect of the method of operating the AD, the AD low-level control system is comprised of at least one of an AD reactor biomass controller, a PA reactor fluid level controller, a PA reactor nutritional additive concentration controller, or an AD reactor nutritional additive concentration controller.

[0043] In another aspect of the method of operating the AD, at least one of the AD reactor pH supervisory controller or the PA reactor pH supervisory controller uses a model based inferred variable of the AD.

[0044] In another aspect of the method of operating the AD, the model based inferred variable of the AD is PA alkalinity or AD alkalinity.

[0045] In another aspect of the method of operating the AD, at least one of the AD reactor pH supervisory controller or the PA reactor pH supervisory controller has a feedforward control action; wherein the feedforward control action uses a model based inferred variable of the AD.

[0046] In another aspect of the method of operating the AD, the model based inferred variable of the AD is raw influent alkalinity.

[0047] In another aspect of the method of operating the AD, at least one of the AD reactor biomass controller, the PA reactor nutritional additive concentration controller, and the AD reactor nutritional additive concentration controller uses at least one of the estimated parameters of the online dynamic model of the AD or the model based inferred variables of the AD.

[0048] In another aspect of the method of operating the AD, the estimated parameters of the online dynamic model of the AD or the model based inferred variables of the AD is at least one of reaction coefficients and biomass concentrations for hydrolysis, acedogenthese, acetogenesis, acetoclastic methanogenesis, or hydrogen methanogenesis processes.

[0049] In another aspect of the method of operating the AD, the AD reactor pH supervisory controller is comprised of an AD reactor nonlinear PI pH controller and a PA reactor P alkalinity controller in a cascaded configuration.

[0050] In yet another aspect of the invention, a method of operating a membrane bioreactor (MBR) was surprisingly discovered, comprising: providing and monitoring a MBR, wherein the monitoring comprises:

[0051] providing a MBR offline extended Kalman filter (EKF) having an offline dynamic model of the MBR, providing a MBR online EKF having an online dynamic model of the MBR; wherein the offline and the online dynamic models of the MBR are comprised of states, process material balances, energy balances, biochemical reaction kinetics, estimated parameters, and adapted model parameters; wherein the adapted model parameters are a subset of the estimated parameters;

[0052] providing historical operation data for the MBR, wherein the historical operation data is comprised of historical measured input data, historical measured output data, and historical laboratory analysis data;

[0053] identifying the estimated parameters of the offline dynamic model of the MBR using the MBR offline EKF and the historical operation data for the MBR;

[0054] importing the estimated parameters from the offline dynamic model of the MBR into the online dynamic model of the MBR;

[0055] providing real time operation data for the MBR to the MBR online EKF, wherein the real time operational data is comprised of real time measured input data and real time measured output data of the MBR;

[0056] updating the adapted model parameters of the online dynamic model of the MBR and estimating the model based inferred variables of the MBR using the MBR online EKF, the online dynamic model of the MBR, the real time measured input data of the MBR, and the real time measured output data of the MBR; and

[0057] providing one or more of the adapted model parameters of the online dynamic model of the MBR and the model based inferred variables of the MBR to an operator of the MBR.

[0058] In another aspect of the method of operating the MBR, the MBR is comprised of an aerobic tank, a membrane tank, and optionally an anoxic tank; wherein the aerobic tank is located upstream of the membrane tank; wherein the anoxic tank is located either immediately upstream or downstream of the aerobic tank when the anoxic tank is present.

[0059] In another aspect of the method of operating the MBR, the aerobic tank and the anoxic tank are modeled separately in both of the online and offline dynamic models of the MBR when both of the aerobic and the anoxic tanks are present.

[0060] In another aspect of the method of operating the MBR, the MBR is further comprised of a mixer and at least one recycle line.

[0061] In another aspect of the method of operating the MBR, the at least one recycle line of the MBR is an anoxic tank recycle line or an aerobic tank recycle line.

[0062] In another aspect of the method of operating the MBR, materials for the material balances in the online and offline dynamic models of the MBR are comprised of at least one of particulate inert, slowly degradable substrate, heterotrophic biomass, autotrophic biomass, decayed biomass, soluble inert, soluble readily degradable substrate, dissolved oxygen, dissolved nitrate-N(Nitrogen), dissolved ammonia-N, particulate bio-degradable-N, or bicarbonate alkalinity.

[0063] In another aspect of the method of operating the MBR, the bio-chemical reaction kinetics in the online and offline dynamic models of the MBR are comprised of at least one of aerobic heterotroph, anoxic heterotroph, aerobic autotroph, decay of heterotroph, decay of autotroph, ammonification of soluble organic N, hydrolysis of organics, or hydrolysis of organic N.

[0064] In another aspect of the method of operating the MBR, the historical operation data of the MBR and the real time operation data of the MBR are comprised of at least one of raw influent pH, raw influent temperature, raw influent flow rate, raw influent TOC, raw influent TIC, added alkali flow rate, added alkali concentration, effluent flow out rate, raw influent SCOD, raw influent TCOD, raw influent readily biodegradable COD, raw influent slowly biodegradable COD, raw influent VSS, raw influent TSS, raw influent nitrate nitrogen, raw influent ammonia-nitrogen, raw influent soluble biodegradable organic nitrogen, raw influent particulate degradable organic nitrogen, raw influent inorganic inert particulate, membrane permeate flow rate, wasting sludge flow rate, anoxic tank addition biodegradable COD flow, anoxic rank reactor pH, anoxic tank Dissolved Oxygen, anoxic tank temperature, anoxic tank liquid level, anoxic tank MLVSS, anoxic tank MLSS, aerobic rank blower air flow rate, aerobic tank reactor pH, aerobic tank alkalinity, aerobic tank MLVSS, aerobic tank MLSS, aerobic tank Dissolved Oxygen, aerobic tank temperature, aerobic tank liquid level, membrane tank MLSS, membrane tank MLVSS, membrane permeate SCOD, membrane permeate TCOD, membrane permeate TOC, membrane permeate TIC, membrane permeate nitrate nitrogen, membrane permeate ammonia-nitrogen, wasting sludge MLSS, or wasting sludge MLVSS.

[0065] In another aspect of the method of operating the MBR, the estimated parameters and the adapted model parameters of the offline dynamic model of the MBR and the online dynamic model of the MBR are comprised of at least one of hetrotrophic maximum specific growth rate, anoxic/aerobic hetrotroph growth rate, anoxic/aerobic hydrolysis rate fraction, particulate hydrolysis max specific rate constant, autotrophic maximum specific growth rate, decay constant for heterotrophs, decay constant for autotrophs, yield of hetrotrophic biomass, yield of autotrophic biomass, carbon content in soluble substrate, carbon content of particulate substrate, carbon content of soluble inert, carbon content of particulate nondegradable organic, mass transfer coefficient for O_2 removal in aerobic tank, or mass transfer coefficient for CO_2 removal in anoxic tank.

[0066] In another aspect of the method of operating the MBR, at least one of the estimated parameters of the offline dynamic model of the MBR and the model based inferred variables of the online dynamic model of the MBR are estimated with confidence intervals.

[0067] In another aspect of the method of operating the MBR, the model based inferred variables of the online dynamic model of the MBR are comprised of at least one of the following unmeasured inputs or outputs of the MBR: raw influent alkalinity, raw influent nitrate nitrogen, raw influent ammonia-nitrogen, raw influent SCOD, raw influent TCOD, raw influent readily biodegradable COD, raw influent slowly biodegradable COD, raw influent VSS, raw influent TSS, raw influent inorganic inert particulate, anoxic rank SCOD, anoxic tank MLVSS, anoxic tank nitrate nitrogen, anoxic tank ammonia-nitrogen, anoxic tank biodegradable COD, aerobic tank SOCD, aerobic tank MLVSS, aerobic tank nitrate nitrogen, aerobic tank ammonia-nitrogen, aerobic tank biodegradable COD, membrane tank MLVSS, membrane permeate SCOD, membrane permeate biodegradable COD, membrane permeate TCOD, membrane permeate nitrate nitrogen, membrane permeate ammonia-nitrogen, wasting sludge MLVSS, COD removal rate, or nitrogen removal rate.

[0068] In another aspect of the method of operating the MBR, the adapted model parameters of the online dynamic model of the MBR are tuned using different weights for online measurements and prior knowledge of measurement accuracy.

[0069] In another aspect of the method of operating the MBR, limits are applied to one or more of the estimated parameters and the adapted model parameters; wherein constraints are applied to one or more of the model based inferred variables.

[0070] In another aspect of the method of operating the MBR, the adapted model parameters of the online dynamic model of the MBR are adjusted by one or both of: calculating model predicted outputs of the MBR using the MBR online EKF, the online dynamic model of the MBR, the real time measured input data of the MBR, and the real time measured output data of the MBR, comparing the measured output data of the MBR and the model predicted outputs of the MBR, and updating the adapted model parameters of the online dynamic model of the MBR such that the real time measured output data of the MBR substantially correspond with the model predicted outputs of the MBR; or periodically re-identifying the estimated parameters of the offline dynamic model of the MBR using the MBR offline EKF and the historical operation data for the MBR, and importing the estimated parameters from the offline dynamic model of the MBR into the online dynamic model of the MBR.

[0071] In another aspect of the method of operating the MBR, the MBR is controlled, wherein the controlling comprises: providing an MBR control system; wherein the MBR is comprised of an aerobic tank, a membrane tank, and optionally an anoxic tank; wherein the MBR control system uses one or more of the real time measured input data of the MBR, the real time measured output data of the MBR, the estimated parameters of the online dynamic model of the MBR, or the model based inferred variables of the MBR to control at least one of pH of the anoxic tank, pH of the aerobic tank, fluid level of the aerobic tank, DO concentration of the aerobic tank, MLSS concentration of the membrane tank, bCOD addition flow rate setpoint of the anoxic tank, at least one nutritional additive concentration of the anoxic tank, or at least one recycle flow setpoint of the MBR.

[0072] In another aspect of the method of operating the MBR, at least one of the monitoring the MBR or the controlling the MBR is performed using a computer.

[0073] In another aspect of the method of operating the MBR, wherein controlling at least one nutritional additive concentration of the anoxic tank prevents biomass overfeeding and starvation, wherein controlling the pH of the anoxic tank minimizes alkali dosing, wherein controlling the pH of the aerobic tank minimizes alkali dosing, wherein controlling the fluid level of the aerobic tank minimizes the affect of fluid perturbations of the aerobic tank, wherein controlling the DO concentration of the aerobic tank ensures that a proper concentration of DO is present in the aerobic tank, wherein controlling the MLSS concentration of the membrane tank maximizes membrane permeability, wherein controlling the bCOD addition flow rate setpoint of the anoxic tank minimizes bCOD usage, wherein controlling at least one recycle flow setpoint of the MBR helps to maintain flow through the MBR.

[0074] In another aspect of the method of operating the MBR, the MBR control system is comprised of an MBR supervisory control system and an MBR low-level control system.

[0075] In another aspect of the method of operating the MBR, the MBR supervisory control system is comprised of at least one of an aerobic tank DO supervisory controller, an anoxic tank recycle flow supervisory controller, or an anoxic tank bCOD addition flow rate supervisory control scheme.

[0076] In another aspect of the method of operating the MBR, the anoxic tank bCOD addition flow supervisory control scheme of the MBR is comprised of an anoxic tank bCOD setpoint supervisory controller, an anoxic tank bCOD addition flow rate supervisory feedback controller, and an anoxic tank bCOD addition flow rate supervisory feedforward controller.

[0077] In another aspect of the method of operating the MBR, the MBR low-level control system is comprised of at least one of an aerobic tank fluid level PI controller, an aerobic tank pH controller, an anoxic tank pH controller, an anoxic tank recycle line flow rate controller, an aerobic tank DO concentration controller, an anoxic tank nutritional additive concentration controller, aerobic tank recycle line flow rate PI controller, total MBR recycle flow rate PI controller, an aerobic tank recycle flow rate lookup table, or a membrane tank MLSS concentration controller.

[0078] In another aspect of the method of operating the MBR, the MLSS concentration controller uses a model based inferred variable of the MBR.

[0079] In another aspect of the method of operating the MBR, the model based inferred variable of the MBR is MLVSS concentration or MLSS concentration.

[0080] In another aspect of the method of operating the MBR, the aerobic tank DO supervisory controller, the anoxic tank recycle flow supervisory controller, and the anoxic tank bCOD addition flow rate supervisory control scheme satisfy membrane permeate requirements on COD, nitrate, and ammonia, while minimizing aeration, recycle flow, and bCOD addition.

[0081] In another aspect of the method of operating the MBR, at least one of the aerobic tank DO supervisory controller, the anoxic tank recycle flow supervisory controller, or the anoxic tank bCOD addition flow rate supervisory control scheme uses at least one of the estimated parameters of the online dynamic model of the MBR or the model based inferred variables of the MBR.

[0082] In yet another aspect of the invention, a method of operating a wastewater treatment plant (WWTP) was surprisingly discovered, comprising:

[0083] operating an anaerobic digester (AD) comprising: providing an AD and monitoring the AD, wherein the monitoring comprises:

[0084] providing an AD offline extended Kalman filter (EKF) having an offline dynamic model of the AD, providing an AD online EKF having an online dynamic model of the AD; wherein the offline and the online dynamic models of the AD are comprised of states, process material balances, energy balances, bio-chemical reaction kinetics, estimated parameters, and adapted model parameters; wherein the adapted model parameters are a subset of the estimated parameters;

[0085] providing historical operation data for the AD, wherein the historical operation data is comprised of historical measured input data, historical measured output data, and historical laboratory analysis data;

[0086] identifying the estimated parameters of the offline dynamic model of the AD using the AD offline EKF and the historical operation data for the AD;

[0087] importing the estimated parameters from the offline dynamic model of the AD into the online dynamic model of the AD;

[0088] providing real time operation data for the AD to the AD online EKF, wherein the real time operational data is comprised of real time measured input data and real time measured output data of the AD;

[0089] updating the adapted model parameters of the online dynamic model of the AD and estimating the model based inferred variables of the AD using the AD online EKF, the online dynamic model of the AD, the real time measured input data of the AD, and the real time measured output data of the AD; and

[0090] providing one or more of the adapted model parameters of the online dynamic model of the AD and the model based inferred variables of the AD to an operator of the AD.

[0091] operating a membrane bioreactor (MBR), comprising: providing a MBR and monitoring the MBR, wherein the monitoring comprises:

[0092] providing a MBR offline extended Kalman filter (EKF) having an offline dynamic model of the MBR, providing a MBR online EKF having an online dynamic model of the MBR; wherein the offline and the online dynamic models of the MBR are comprised of states, process material balances, energy balances, bio-chemical reaction kinetics, estimated parameters, and adapted model parameters; wherein the adapted model parameters are a subset of the estimated parameters;

[0093] providing historical operation data for the MBR, wherein the historical operation data is comprised of historical measured input data, historical measured output data, and historical laboratory analysis data;

[0094] identifying the estimated parameters of the offline dynamic model of the MBR using the MBR offline EKF and the historical operation data for the MBR;

[0095] importing the estimated parameters from the offline dynamic model of the MBR into the online dynamic model of the MBR;

[0096] providing real time operation data for the MBR to the MBR online EKF, wherein the real time operational data is comprised of real time measured input data and real time measured output data of the MBR;

[0097] updating the adapted model parameters of the online dynamic model of the MBR and estimating the model based inferred variables of the MBR using the MBR online EKF, the online dynamic model of the MBR, the real time measured input data of the MBR, and the real time measured output data of the MBR; and

[0098] providing one or more of the adapted model parameters of the online dynamic model of the MBR and the model based inferred variables of the MBR to an operator of the MBR.

[0099] In another aspect of the method of operating the WWTP, the adapted model parameters of the online dynamic model of the AD are adjusted by one or both of: calculating model predicted outputs of the AD using the AD online EKF, the online dynamic model of the AD, the real time measured input data of the AD, and the real time measured output data of the AD, comparing the measured output data of the AD and the model predicted outputs of the AD, and updating the adapted model parameters of the online dynamic model of the AD such that the real time measured output data of the AD substantially correspond with the model predicted outputs of the AD; or periodically re-identifying the estimated parameters of the offline dynamic model of the AD using the AD offline EKF and the historical operation data for the AD, and importing the estimated parameters from the offline dynamic model of the AD into the online dynamic model of the AD.

[0100] In another aspect of the method of operating the WWTP, the adapted model parameters of the online dynamic model of the MBR are adjusted by one or both of: calculating model predicted outputs of the MBR using the MBR online EKF, the online dynamic model of the MBR, the real time measured input data of the MBR, and the real time measured output data of the MBR, comparing the measured output data of the MBR and the model predicted outputs of the MBR, and updating the adapted model parameters of the online dynamic model of the MBR such that the real time measured output data of the MBR substantially correspond with the model predicted outputs of the MBR; or periodically re-identifying the estimated parameters of the offline dynamic model of the MBR using the MBR offline EKF and the historical operation data for the MBR, and importing the estimated parameters from the offline dynamic model of the MBR into the online dynamic model of the MBR.

[0101] In another aspect of the method of operating the WWTP, the AD is controlled, wherein controlling the AD comprises: providing an AD control system; wherein the AD control system uses one or more of the real time measured input data of the AD, the real time measured output data of the AD, the estimated parameters of the online dynamic model of the AD, or the model based inferred variables of the AD to control at least one of a nutritional additive concentration of the AD reactor, a nutritional additive concentration of the PA reactor, pH of the AD reactor, pH of the PA reactor, biomass concentration of the AD reactor, fluid level of the PA reactor, or a recycle flow rate of the AD.

[0102] In another aspect of the method of operating the WWTP, the MBR is controlled, wherein controlling the MBR comprises: providing an MBR control system; wherein the MBR control system uses one or more of the real time measured input data of the MBR, the real time measured output data of the MBR, the estimated parameters of the online dynamic model of the MBR, or the model based inferred variables of the MBR to control at least one of pH of the anoxic tank, pH of the aerobic tank, fluid level of the aerobic tank, DO concentration of the aerobic tank, MLSS concentration of the membrane tank, bCOD addition flow rate setpoint of the anoxic tank, at least one nutritional additive concentration of the anoxic tank, or at least one recycle flow setpoint of the MBR.

[0103] In another aspect of the method of operating the WWTP, the MBR is located upstream of the AD, wherein the MBR online EKF provides model based inferred variables to the AD, wherein the model based inferred variables provided to the AD comprise the composition and flow rate of the MBR effluent; wherein the model based inferred variables provided to the AD enable feed forward control of the AD.

[0104] In another aspect of the method of operating the WWTP, the AD is located upstream of the MBR, wherein the AD online EKF provides model based inferred variables to the MBR, wherein the model based inferred variables provided to the MBR comprise the composition and flow rate of the AD effluent; wherein the model based inferred variables provided to the MBR enable feed forward control of the MBR.

[0105] In another aspect of the method of operating the WWTP, operating the WWTP is performed using a computer.

[0106] In yet another aspect of the invention, a waste water treatment plant (WWTP) comprised of at least one of an aerobic digester (AD) and a membrane bioreactor (MBR) was discovered:

[0107] wherein the AD is comprised of an AD reactor, an AD control system, and optionally a pre-acidification (PA) reactor; wherein the PA reactor is located upstream of the AD reactor when the PA reactor is present;

[0108] wherein the WWTP is further comprised of an AD online EKF having an online dynamic model of the AD when the AD is present; wherein the online dynamic model of the AD is comprised of states, process material balances, energy balances, and bio-chemical reaction kinetics, estimated parameters, and adapted online model parameters; wherein the adapted model parameters are a subset of the estimated parameters; wherein the AD reactor and the PA reactor are modeled separately when both of the AD reactor and the PA reactor are present;

[0109] wherein the MBR is comprised of an aerobic tank, a membrane tank, an MBR control system, and optionally an anoxic tank; wherein the aerobic tank is located upstream of the membrane tank; wherein the anoxic tank is located either immediately upstream or downstream of the aerobic tank when the anoxic tank is present;

[0110] wherein the WWTP is further comprised of an MBR online EKF having an online dynamic model of the MBR when the MBR is present; wherein the online dynamic model of the MBR is comprised of estimated parameters, adapted model parameters, states, process material balances, energy balances and bio-chemical reaction kinetics; wherein the adapted model parameters are a subset of the estimated parameters; wherein the aerobic tank and the anoxic tank are modeled separately when both of the aerobic and the anoxic tanks are present.

[0111] In another aspect of the WWTP, the AD control system is comprised of an AD supervisory control system and an AD low-level control system.

[0112] In another aspect of the WWTP, the AD supervisory control system is comprised of at least one of an AD reactor pH supervisory controller, a PA reactor pH supervisory controller, or an PA:AD overall recycle flow ratio supervisory controller.

[0113] In another aspect of the WWTP, the AD reactor pH supervisory controller is comprised of an AD reactor nonlinear PI pH controller and an AD reactor P alkalinity controller in a cascaded configuration; wherein the PA reactor pH supervisory controller is comprised of a PA reactor nonlinear PI pH controller and a PA reactor P alkalinity controller in a cascaded configuration; wherein the PA:AD overall recycle flow ratio supervisory controller is comprised of a AD:PA Recycle ratio controller, and a PA reactor and AD reactor recycle flow rate controller.

[0114] In another aspect of the WWTP, the AD low-level control system is comprised of at least one of an AD reactor biomass controller, a PA reactor fluid level controller, a PA reactor nutritional additive concentration controller, or an AD reactor nutritional additive concentration controller.

[0115] In another aspect of the WWTP, the MBR control system is comprised of an MBR supervisory control system and an MBR low-level control system.

[0116] In another aspect of the WWTP, the MBR supervisory control system is comprised of at least one of an aerobic tank DO supervisory controller, anoxic tank recycle flow supervisory controller, or an anoxic tank bCOD addition flow rate supervisory control scheme.

[0117] In another aspect of the WWTP, the anoxic tank bCOD addition flow supervisory control scheme of the MBR is comprised of an anoxic tank bCOD setpoint supervisory controller, an anoxic tank bCOD addition flow rate supervisory feedback controller, and an anoxic tank bCOD addition flow rate supervisory feedforward controller.

[0118] In another aspect of the WWTP, the MBR low-level control system is comprised of at least one of an aerobic tank fluid level PI controller, an aerobic tank pH controller, an anoxic tank pH controller, an anoxic tank recycle line flow rate controller, an aerobic tank DO concentration controller, an anoxic tank nutritional additive concentration controller, an aerobic tank recycle line flow rate PI controller, a total MBR recycle flow rate PI controller, an aerobic tank recycle flow rate lookup table, or a membrane tank MLSS concentration controller.

[0119] In another aspect of the WWTP, the AD is comprised of a mixing stage and at least one recycle line.

[0120] In another aspect of the WWTP, the AD reactor is a CSTR, UASB, EGSB, mixed bed, moving bed, low-rate, or high-rate reactor; wherein the at least one recycle line of the AD is a PA reactor recycle line or an AD reactor recycle line.

[0121] In another aspect of the WWTP, the MBR is further comprised of a mixer and at least one recycle line.

[0122] In another aspect of the WWTP, at least one recycle line of the MBR is an anoxic tank recycle line or an aerobic tank recycle line.

[0123] In another aspect of the WWTP, at least one of the AD online EKF, MBR online EKF, AD control system, or MBR control system is implemented using a computer.

[0124] In yet another aspect of the invention, a system for monitoring and controlling a WWTP comprised of at least one of an AD or an MBR was discovered. The system is comprised of memory and a microprocessor operable connected with the memory. Wherein said microprocessor is configured to when said MBR is present: update adapted model parameters of an online dynamic model of said MBR and estimate model based inferred variables of said MBR using an MBR online EKF, said online dynamic model of said MBR, real time measured input data of said MBR, and real time measured output data of said MBR; wherein said MBR online EKF, and said online dynamic model of said MBR are stored in the memory and executed by the microprocessor; and control said MBR using an MBR control system, one or more of said real time measured input data of said MBR, said real time measured output data of said MBR, said adapted model parameters of said online dynamic model of said MBR, or said model based inferred variables of said MBR. Wherein said microprocessor is further configured to when said AD is present: update adapted model parameters of an online dynamic model of said AD and estimate model based inferred variables of said AD using an AD online EKF, said online dynamic model of said AD, real time measured input data of said AD, and real time measured output data of said AD; wherein said AD online EKF, and said online dynamic model of said AD are stored in the memory and executed by the microprocessor; and control said AD using an AD control system, one or more of said real time measured input data of said AD, said real time measured output data of said AD, said adapted model parameters of said online dynamic model of said AD, or said model based inferred variables of said AD.

[0125] Advantages of the present invention will become more apparent to those skilled in the art from the following description of the embodiments of the invention which have been shown and described by way of illustration. As will be realized, the invention is capable of other and different embodiments, and its details are capable of modification in various respects.

BRIEF DESCRIPTION OF SEVERAL VIEWS OF THE DRAWINGS

[0126] These and other features of the present invention, and their advantages, are illustrated specifically in embodiments of the invention now to be described, by way of example, with reference to the accompanying diagrammatic drawings, in which:

[0127] FIG. **1***a* is a block diagram of an exemplary wastewater treatment plant, in accordance with aspects of the present technique;

[0128] FIG. **1***b* is a block diagram of an exemplary wastewater treatment plant, in accordance with aspects of the present technique;

[0129] FIG. **2** is a block diagram of an exemplary anaerobic digester (AD) in accordance with aspects of the present technique;

[0130] FIG. **3** is a material conversion block diagram in the model of the anaerobic digester to be used for control design and system monitoring accordance with aspects of the present technique;

[0131] FIG. **4***a* is a block diagram of an exemplary membrane bioreactor in accordance with aspects of the present technique;

[0132] FIG. **4***b* is a block diagram of an exemplary membrane bioreactor in accordance with aspects of the present technique;

[0133] FIG. **5** is a plot of TTF variation with time;

[0134] FIG. **6** is a plot of membrane permeability variation with time;

[0135] FIG. **7** is a plot of the dominant variables in PLS and their relative contribution to variations in permeability;

[0136] FIG. **8** is a plot of the cross validation of membrane permeability for PLS;

[0137] FIG. **9** is a block diagram of the overall architecture for an AD having an extended Kalman filter (EKF) and a control system in accordance with aspects of the present technique;

[0138] FIG. **10** is a block diagram of the architecture for an AD having an online EKF and a control system in accordance with aspects of the present technique;

[0139] FIG. **11** is a block diagram of the architecture for an AD having an offline EKF and a control system in accordance with aspects of the present technique;

[0140] FIG. **12***a* is a flow chart depicting a method of operating an AD in accordance with aspects of the present technique;

[0141] FIG. **12***b* is a flow chart depicting a method of operating an AD in accordance with aspects of the present technique;

[0142] FIG. **13** is a block diagram of the overall architecture for an MBR having an extended Kalman filter (EKF) and a control system in accordance with aspects of the present technique;

[0143] FIG. **14** is a block diagram of the architecture for an MBR having an online EKF and a control system in accordance with aspects of the present technique;

[0144] FIG. **15** is a block diagram of the architecture for an MBR having an offline EKF and a control system in accordance with aspects of the present technique;

[0145] FIG. **16***a* is a flow chart depicting a method of operating an MBR in accordance with aspects of the present technique;

[0146] FIG. **16***b* is a flow chart depicting a method of operating an MBR in accordance with aspects of the present technique;

[0147] FIG. **17***a* is a block diagram depicting AD reactor pH supervisory controller for AD reactor with a nonlinear PI control and an alkalinity control in cascade structure in accordance with aspects of the present technique;

[0148] FIG. **17***b* is a block diagram depicting AD reactor pH supervisory controller for AD reactor with a nonlinear PI control and an alkalinity control in cascade structure in accordance with aspects of the present technique;

[0149] FIG. **18** is a block diagram depicting PA reactor pH supervisory controller for PA reactor with a nonlinear PI control and an alkalinity control in cascade structure in accordance with aspects of the present technique;

[0150] FIG. **19***a* is a block diagram depicting a PA:AD overall recycle flow ratio supervisory controller in accordance with aspects of the present technique;

[0151] FIG. **19***b* is a block diagram depicting a PA reactor and AD reactor recycle flow rate controller in accordance with aspects of the present technique;

[0152] FIG. **20** is a block diagram depicting a PA:AD Recycle Ratio controller in accordance with aspects of the present technique;

[0153] FIG. **21** is a block diagram depicting an implementation of AD reactor biomass concentration controller in accordance with aspects of the present technique;

[0154] FIG. **22** is a block diagram depicting an AD reactor biomass concentration controller in accordance with aspects of the present technique;

[0155] FIG. **23** is a flow chart depicting the operations taking place within AD reactor biomass concentration controller in accordance with aspects of the present technique;

[0156] FIG. **24** is a block diagram depicting an implementation of PA fluid level controller in accordance with aspects of the present technique;

[0157] FIG. **25** is a block diagram depicting a PA fluid level controller in accordance with aspects of the present technique;

[0158] FIG. **26** is a flow chart depicting the operations taking place within PA fluid level controller in accordance with aspects of the present technique;

[0159] FIG. **27** is a block diagram depicting a PA reactor nutritional additive concentration controller in accordance with aspects of the present technique;

[0160] FIG. **28** is a block diagram depicting an AD reactor nutritional additive concentration controller in accordance with aspects of the present technique;

[0161] FIG. **29** is a block diagram depicting an aerobic tank DO concentration controller in accordance with aspects of the present technique;

[0162] FIG. **30** is a block diagram depicting an aerobic tank pH controller in accordance with aspects of the present technique;

[0163] FIG. **31** is a block diagram depicting an anoxic tank pH controller in accordance with aspects of the present technique;

[0164] FIG. **32***a* is a block diagram depicting a control scheme for regulating the MLSS concentration within MBR membrane tank in accordance with aspects of the present technique;

[0165] FIG. **32***b* is a block diagram depicting a control scheme for regulating the MLVSS concentration within MBR membrane tank in accordance with aspects of the present technique;

[0166] FIG. **33** is a block diagram depicting an aerobic tank fluid level PI controller in accordance with aspects of the present technique;

[0167] FIG. **34** is a block diagram depicting an anoxic tank recycle line flow rate PI controller in accordance with aspects of the present technique;

[0168] FIG. **35** is a block diagram depicting an aerobic tank recycle line flow rate PI controller in accordance with aspects of the present technique;

[0169] FIG. **36** is a block diagram depicting a total MBR recycle flow rate PI controller in accordance with aspects of the present technique;

[0170] FIG. **37** is a block diagram depicting an anoxic tank nutritional additive concentration controller in accordance with aspects of the present technique;

[0171] FIG. **38** is a block diagram depicting aerobic tank DO supervisory controller in accordance with aspects of the present technique;

[0172] FIG. **39** is a block diagram depicting an anoxic tank recycle flow rate supervisory controller in accordance with aspects of the present technique;

[0173] FIG. **40** is a block diagram depicting an anoxic tank biodegradable COD (bCOD) addition flow rate supervisory control scheme in accordance with aspects of the present technique;

[0174] FIG. **41** is a block diagram depicting an aerobic tank DO supervisory controller in accordance with aspects of the present technique;

[0175] FIG. **42** is a block diagram depicting an anoxic tank recycle flow rate supervisory controller in accordance with aspects of the present technique;

[0176] FIG. **43** is a block diagram depicting an anoxic tank bCOD setpoint supervisory controller in accordance with aspects of the present technique;

[0177] FIG. **44** is a block diagram depicting an anoxic tank bCOD addition flow rate supervisory feedback controller in accordance with aspects of the present technique;

[0178] FIG. **45** is a block diagram depicting an anoxic tank bCOD addition flow rate supervisory feedforward controller in accordance with aspects of the present technique; and

[0179] FIG. **46** depicts an operator control panel in accordance with aspects of the present technique.

[0180] It should be noted that all the drawings are diagrammatic and not drawn to scale. Relative dimensions and proportions of parts of these Figures have been shown exaggerated or reduced in size for the sake of clarity and convenience in the drawings. The same reference numbers are generally used to refer to corresponding or similar features in the different embodiments. Accordingly, the drawing(s) and description are to be regarded as illustrative in nature and not as restrictive.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0181] Approximating language, as used herein throughout the specification and claims, may be applied to modify any quantitative representation that could permissibly vary without resulting in a change in the basic function to which it is related. Accordingly, a value modified by a term or terms, such as “about”, is not limited to the precise value specified. In at least some instances, the approximating language may correspond to the precision of an instrument for measuring the value. Range limitations may be combined and/or interchanged, and such ranges are identified and include all the sub-ranges stated herein unless context or language indicates otherwise. Other than in the operating examples or where otherwise indicated, all numbers or expressions referring to quantities of ingredients, reaction conditions and the like, used in the specification and the claims, are to be understood as modified in all instances by the term “about”.

[0182] “Optional” or “optionally” means that the subsequently described event or circumstance may or may not occur, or that the subsequently identified material may or may not be present, and that the description includes instances where the event or circumstance occurs or where the material is present, and instances where the event or circumstance does not occur or the material is not present.

[0183] As used herein, the terms “comprises”, “comprising”, “includes”, “including”, “has”, “having”, or any other variation thereof, are intended to cover a non-exclusive inclusion. For example, a process, method, article or apparatus that comprises a list of elements is not necessarily limited to only those elements, but may include other elements not expressly listed or inherent to such process, method, article, or apparatus.

[0184] The singular forms “a”, “an”, and “the” include plural referents unless the context clearly dictates otherwise.

[0185] FIG. **1***a* shows a general integrated wastewater treatment plant (WWTP) **10**. The wastewater is fed to the anaerobic digester (AD) **20**, where typically 80-90% of the readily biodegradable COD is converted to biogas. The anaerobic digester effluent is then treated in the membrane bioreactor (MBR) **30** to eliminate the remaining COD through aerobic bio-treatment. For wastewater feeds with high solids content, an entrapped air flotation process **48** is used to remove the particulate solid before feeding to the MBR **30**. Entrapped air flotation process **48** can be located immediately before MBR **30** or immediately inside MBR **30** upstream of aerobic tank **32** and anoxic tank **31**, if present. The MBR **30** removes COD, nitrogen, phosphorus, and total suspended solids (TSS) to yield the clean permeate water. The MBR **30** allows for the recovery of 90-95% of the water in wastewater as cleaned permeate water.

[0186] WWTP **10** is further comprised of a computer **1071** containing microprocessor **1072** and memory **1073**. The AD online EKF **252**, AD offline EKF **251**, AD online dynamic model **262**, AD offline dynamic model **261**, MBR online EKF **352**, MBR offline EKF **351**, MBR online dynamic model **362**, MBR offline dynamic model **361**, and methods for operating AD **20** and MBR **30** are contained in the memory **1073** of computer **1071**. The real time operation data of AD **20** and MBR **30** and offline laboratory testing results for AD **20** and MBR **30** is also stored in the memory **1073** of computer **1071** and used later as historical operation data. Microprocessor **1072** retrieves from memory **1073** and executes the methods of operating AD **20** and MBR **30** discussed below. It is contemplated that computer **1071** can be any device, or devices, deemed suitable by a person having ordinary skill in the art that has microprocessor **1072** and memory **1073**, including, but not limited to, a general purpose computer, a local computer, a remote computer, a cloud based computer, or a PLC. Further, it is also contemplated in some embodiments, computer **1071** also contains operator control panel **1070**.

[0187] FIG. **1***b* shows an alternative embodiment of WWTP **10** in which MBR **30** is located upstream of AD **20**. In this embodiment, AD **20** receives the effluent from membrane tank sludge discharge **43** of MBR **30**. It is contemplated that in some embodiments of WWTP **10**, AD **20** has an AD computer **1071***a* and MBR **30** has an MBR computer **1071***b*, or alternatively only one of AD computer **1071***a* or MBR computer **1071***b* is present in WWTP if only one of AD **20** or MBR **30** is present in WWTP **10**. When both are present, AD computer **1071***a* and MBR computer **1071***b* are networked together to share information. AD computer contains microprocessor **1072***a* and memory **1073***a*. MBR computer contains microprocessor **1072***b* and memory **1073***b*.

[0188] The AD online EKF **252**, AD offline EKF **251**, AD online dynamic model **262**, AD offline dynamic model **261**, method for operating AD **20** is contained in the memory **1073***a* of AD computer **1071***a*. The real time operation data of AD **20** offline laboratory testing results for AD **20** are also stored in the memory **1073***a* of AD computer **1071***a* and used later as historical operation data. Microprocessor **1072***a* retrieves from memory **1073***a* and executes a method of operating AD **20** discussed below.

[0189] The MBR online EKF **352**, MBR offline EKF **351**, MBR online dynamic model **362**, MBR offline dynamic model **361**, and method MBR **30** are contained in the memory **1073***b* of MBR computer **1071***b*. The real time operation data of MBR **30** and offline laboratory testing results for MBR **30** are also stored in the memory **1073** of computer **1071** and used later as historical operation data. Microprocessor **1072***b* retrieves from memory **1073***b* and executes a method of operating MBR **30** discussed below.

[0190] It is contemplated that AD computer **1071***a* and MBR computer **1071***b* can be any device, or devices, deemed suitable by a person having ordinary skill in the art that has microprocessor **1072** and memory **1073**, including, but not limited to, a general purpose computer, a local computer, a remote computer, a could based computer, a PLC. Further, it is also contemplated in some embodiments, one or both of AD computer **1071***a* and MBR computer **1071***b* also contain operator control panel **1070**.

[0191] In one embodiment, said computer **1071** and said WWTP **10** form a system for monitoring and controlling the WWTP **10** comprised of at least one of an AD **20** or an MBR **30**, a memory **1073**, and a microprocessor **1072** operable connected with the memory **1073**, wherein said microprocessor **1072** is configured to, when said MBR **30** is present, update adapted model parameters of an online dynamic model **362** of said MBR **30** and estimate model based inferred variables of said MBR **30**: using an MBR online EKF **352**, said online dynamic model **362** of said MBR **30**, real time measured input data of said MBR **30**, and real time measured output data of said MBR **30**. Said MBR online EKF **352**, and said online dynamic model **362** of said MBR **30** are stored in the memory **1073** and executed by the microprocessor **1072**. Microprocessor **1072** is further configured to, when said MBR **30** is present, to control said MBR **30** using an MBR control system **300**, and one or more of: said real time measured input data of said MBR **30**, said real time measured output data of said MBR **30**, said adapted model parameters of said online dynamic model of said MBR **30**, or said model based inferred variables of said MBR **30**.

[0192] Wherein said microprocessor **1072** is further configured to, when said AD **20** is present, update adapted model parameters of an online dynamic model **262** of said AD **20** and estimate model based inferred variables of said AD **20** using: an AD online EKF **252**, said online dynamic model **262** of said AD **20**, real time measured input data of said AD **20**, and real time measured output data of said AD **20**. Said AD online EKF **252**, and said online dynamic model **262** of said AD **20** are stored in the memory **1073** and executed by the microprocessor **1072**. Said microprocessor **1072** is further configured to, when said AD **20** is present, control said AD **20** using an AD control system **200**, and one or more of: said real time measured input data of said AD, said real time measured output data of said AD, said adapted model parameters of said online dynamic model of said AD, or said model based inferred variables of said AD.

[0193] In another embodiment, one or both of AD computer **1071***a* and MBR computer **1071***b*, and said WWTP **10** form a system for monitoring and controlling the WWTP **10**. The system is comprised of at least one of an AD **20** or an MBR **30**. The system has an AD computer **1071***a* if said AD **20** is present, and an MBR computer **1071***b* if said MBR **30** is present. If present, said AD computer **1071***a* is comprised of memory **1073***a* and a microprocessor **1072***a* operable connected with the memory **1073***a*. If present, said MBR computer **1071***b* is comprised of memory **1073***b* and a microprocessor **1072***b* operable connected with the memory **1073***b*.

[0194] Wherein, when said MBR **30** and said MBR computer **1071***b* are present, said microprocessor **1072***b* is configured to update adapted model parameters of an online dynamic model **362** of said MBR **30** and estimate model based inferred variables of said MBR **30**: using an MBR online EKF **352**, said online dynamic model **362** of said MBR **30**, real time measured input data of said MBR **30**, and real time measured output data of said MBR **30**. Said MBR online EKF **352** and said online dynamic model **362** of said MBR **30** are stored in the memory **1073***b* and executed by the microprocessor **1072***b*. MBR microprocessor **1072***b* is further configured to control said MBR **30** using an MBR control system **300**, and one or more of: said real time measured input data of said MBR **30**, said real time measured output data of said MBR **30**, said adapted model parameters of said online dynamic model of said MBR **30**, or said model based inferred variables of said MBR **30**.

[0195] Wherein, when said AD **20** and said AD computer **1071***a* are present, said microprocessor **1072***a* is further configured to update adapted model parameters of an online dynamic model **262** of said AD **20** and estimate model based inferred variables of said AD **20** using: an AD online EKF **252**, said online dynamic model **262** of said AD **20**, real time measured input data of said AD **20**, and real time measured output data of said AD **20**. Said AD online EKF **252** and said online dynamic model **262** of said AD **20** are stored in the memory **1073***a* and executed by the microprocessor **1072***a*. AD microprocessor **1072***a* is further configured to control said AD **20** using an AD control system **200**, and one or more of: said real time measured input data of said AD, said real time measured output data of said AD, said adapted model parameters of said online dynamic model of said AD, or said model based inferred variables of said AD.

[0196] One challenge for operating the AD **20** and MBR **30** in a unified and seamless manner is the presence of variations in the wastewater feed flow and composition. For example, operation of AD **20** is sensitive to temperature and pH variations and could go unstable in the presence of sustained excursions in these parameters beyond normal operations conditions. Thus, typically, pH is regulated in an AD **20**. Additional controls sometimes found in an AD include active regulation of wastewater feed and effluent flow rates and nutrient addition, and in some cases regulation of AD temperature. However, there is no direct control of COD conversion and often the biogas flow rate and composition are not monitored or regulated.

[0197] FIG. **2** shows a general anaerobic digester **20** having a pre-acidification (PA) reactor **22**, PA reactor mixing stage **21**, AD reactor mixing stage **23** and AD reactor **24**. The wastewater is fed to AD **20** first enters the PA reactor mixing stage **21** where additives are mixed with the wastewater before it enters the PA reactor **22**. The PA effluent enters the AD reactor mixing stage **23** where additives are mixed with the PA effluent before it enters the AD reactor **24**. PA reactor **22** acts as an equalization tank and allows a partial acidification of the soluble (primary carbohydrate) COD to yield volatile fatty acids (VFA)s, thus also acting as a pre-acidification tank. The mixed carbohydrate and VFA feed is converted to methane in the AD reactor **24**. Due to the acidification and buildup of VFA, the PA reactor **22** operates at a fairly low pH (about 6.0), which is not suitable for methanogenesis. The AD reactor **24** is operated at a higher pH (between about 6.5 to 7.5) to favor the methanogenesis. The pH in the PA reactor **22** and AD reactor **24** are regulated by addition of suitable alkali addition at AD reactor mixing stage **23** and PA reactor mixing stage **21**, or PA reactor **22** and AD reactor **24** if the AD reactor mixing stage **23** and PA reactor mixing stage **21** are not present. Such suitable alkali addition may include, but is not limited to, one or more of caustic, sodium bicarbonate, and magnesium hydroxide. It is contemplated that AD reactor pH supervisory controller **700** will control the flow rate of alkali from AD alkali tank **702** to AD reactor **24**, either directly to AD reactor **24** or via AD reactor mixing stage **23**. Further, it is contemplated that PA reactor pH supervisory controller **701** will control the flow rate of alkali from PA alkali tank **703** to PA reactor **22**, either directly to PA reactor **22** or via PA reactor mixing stage **21**. In some embodiments, an AD feed pump **27** is present. In some embodiments of AD **20**, nutritional additives are provided to PA reactor **22** and AD reactor **24**, either directly to PA reactor **22** and AD reactor **24** or via PA reactor mixing stage **21** and AD reactor mixing stage **23**. The nutritional additives provided to PA reactor **22** are provided from PA reactor nutritional additive tank **52**, whose flow rate is controlled by PA reactor nutritional additive concentration controller **51**. The nutritional additives provided to AD reactor **24** are provided from AD reactor nutritional additive tank **62**, whose flow rate is controlled by AD reactor nutritional additive concentration controller **61**.

[0198] It is understood that in some embodiments of AD **20** each nutritional additive for PA reactor **22** will have a PA reactor nutritional additive tank **52** and PA reactor nutritional additive concentration controller **51**. Along the same lines, each nutritional additive for AD reactor **24** will have a PA reactor nutritional additive tank **52** and PA reactor nutritional additive concentration controller **51**.

[0199] However, in other embodiments of AD **20**, all of the nutritional additives for PA reactor **22** are combined in a single PA reactor nutritional additive tank **52** and all of the nutritional additives for AD reactor **24** are combined in a single AD reactor nutritional additive tank **62**. Accordingly, only one PA reactor nutritional additive tank **52** and corresponding PA reactor nutritional additive concentration controller **51** are present, and only one AD reactor nutritional additive tank **62** and corresponding AD reactor nutritional additive concentration controller **61** are present.

[0200] In some embodiments, an PA recycle line **25** having a PA recycle pump **28** is located between the AD reactor **24** and PA reactor **22** to mix a portion of effluent from AD reactor **24** into the influent of PA reactor **22**, thereby allowing regulation for hydraulic load variations and also dilution of the incoming wastewater. In one embodiment, this is accomplished by placing a recycle line from the AD reactor **24** effluent to PA reactor mixing stage **21**. Further, in some embodiments, such as those using an EGSB AD reactor **24**, an AD recycle line **26** having an AD recycle pump **29** is present around the AD reactor **24** itself. In one embodiment, this is accomplished by placing a recycle line from AD reactor **24** effluent to AD reactor mixing stage **23**.

[0201] PA reactor mixing stage **21** and PA reactor **22** are optional. However, they are often present when AD reactor **24** is a high-rate digester. It is contemplated that AD reactor **24** can be one of several types of reactors, including, but not limited to a be a continuously stirred tank reactor (CSTR), upflow anaerobic sludge blanket reactor (UASB), expanded granular sludge bed reactor (EGSB), mixed bed, moving bed, low-rate, or high-rate reactor.

[0202] Anaerobic digesters have been studied quite extensively over the last several decades and have recently attracted efforts on modeling, focusing primarily on offline simulation studies. There is a highly detailed model available for anaerobic digesters, Anaerobic Digesters Model 1 (ADM1), developed by the International Water Association, and is used as a reference standard for describing the dynamic operation of anaerobic digesters. The ADM1 is a comprehensive and detailed model with seven reaction paths, 19 reactions, and 3 inhibition effects, designed for very general waste content and broad operation conditions. While the ADM1 has broad applicability, it is complex and not readily useable for online monitoring and control. In particular, it includes detailed dynamics in liquid and gas phases spanning multiple time-scales leading to a very stiff model with some fast dynamics that are not practically important for the overall bioprocess operation.

[0203] In contrast to the detailed ADM1, a "6-state" simple model (6th order model—includes 6 dynamic components) has been proposed and used by Bernard in a paper, *Dynamical Model Development and Parameter Identification for an Anaerobic Wastewater Treatment Process*, Biotechnology and Bioengineering, Vol. 75, pp 424-438, 2001. The 6-state model simplifies the AD process as acidification and methanation in two sequential reaction steps with acidogenesis and methanogenesis microbes converting from COD to volatile fatty acids (VFA), and from VFA to methane, respectively. The six components modeled dynamically are: COD, VFA, inorganic carbon, alkalinity, acidogenesis microbes and methanogenesis microbes. While this model is very simple, it is too restricted in applicability to primary soluble carbohydrates in the wastewater feed COD, and does not account for nitrogen balance or acid-base equilibrium for pH calculations and effects on pH on the bioprocess.

[0204] A more reasonable "10-state" model (10th order model—includes 10 dynamic components) of intermediate complexity has been proposed and used as a starting point. This model is described in Dochain, *Dynamical modelling, analysis, monitoring, and control design for nonlinear bioprocesses, survey chapter in Advances in Biochemical Engineering*, Vol. 56, Springer-Verlag Berlin Heidelberg, 1997; Dochain, *Adaptive control of the hydrogen concentration in anaerobic digestion*, Industrial and Engineering Chemistry Research, 1991, 30, 129-136; and Mosey, *Mathematical Modelling of the Anaerobic Digestion Process: Regulatory Mechanisms for the Formation of Short-Chain Volatile Acids from Glucose*, Water Science Technology, 1983, 15, 209-232.

[0205] The 10-state model has a little more detail on the bioprocess compared to the 6-state model—modeling in more detail the reaction pathways for acedogenesis, acetogenesis and the final methanogenesis. It assumes the process to start with simple carbohydrate (e.g. glucose), and identifies 4 reaction paths: 2 for acidification and 2 for methanation. The 10 components modeled dynamically are: COD, propionate, acetate, hydrogen, inorganic carbon, acidogenic biomass, OHPA (Obligate Hydrogen Producing Acidogens), acetoclastic methanogenic biomass, hydrogenophilic methanogenic biomass, and methane. In total, 26 parameters are used for the bio-reaction kinetics and the yield coefficients. However, this model captures most, but not all, of the important processes and the important components. We have found that it is also necessary to extend the 10-state model to include additional detail to allow more general applicability to ADs beyond brewery/winery applications. In particular, the 10-state model has been extended to (i) include fats (LCFA) and proteins (amino acids) in addition to carbohydrates (glucose) as soluble COD, (ii) include particulate or insoluble biodegradable and non-biodegradable/inert (i.e. refractory) COD, (iii) include biomass decay, (iv) include nitrogen balance, and (v) include alkalinity and inorganic carbon balance for pH calculation and its effect on the bioprocess kinetics. The overall material conversion scheme in the final model used is shown in FIG. **3**, and the dynamic material balance is shown in Eq. 3.

[0206] As can be seen, the scheme of FIG. **3** has been extended to include soluble and insoluble, as well as biodegradable and inert (refractory) COD. Further, insoluble (particulate) COD with first order kinetics for decomposition and hydrolysis has been added to the model. Decomposition yields insoluble inert and insoluble bCOD. Insoluble bCOD undergoes hydrolysis to Sol bCOD. Additionally, decomposition and hydrolysis are both first order reactions—combined together (hydrolysis is an order of magnitude faster than decomposition). Further, bCOD is biodegradable COD, a mixture of carbohydrates (glucose), fat (LCFA) and protein (amino acids)—COD fractions f_c, f_f, and f_p.

[0207] Further, in the scheme of FIG. **3**, all higher order (than acetic) fatty acids are combined into propionic acid, and biomass decay was added to reduce active biomass. As can be seen in FIG. **3**, biomass in the diagram denotes active biomass only. Accordantly, the scheme of FIG. **3** can also include N-balance.

[0208] The bio-chemical reactions in AD reactor **24** are modeled starting from soluble biodegradable COD (denoted as SbCOD), the four reactions R1-R4 show below are modeled:

Eq 1

SbCOD→Prop acid+Acet acid+H_2+CO_2 R1:

Prop acid→Acet acid+CO_2+H_2 R2:

Acet acid→Methane+CO_2 R3:

CO_2+H_2→Methane R4:

[0209] SbCOD=mix of glucose, LCFA/alcohol, amino acid

[0210] In the above simplified reaction scheme, R1 denotes the acedogenesis reaction from a mixed soluble bCOD, R2 denotes the acetogenesis reaction, R3 denotes the acetoclastic methanogenesis and R4 denotes the methanogenesis from hydrogen. In general, the substrate for the first reaction will be a mix of carbohydrates (glucose), fats (long chain fatty acids—LCFA and alcohol) and proteins (amino acid). To allow the applicability for general processes, the carbohydrates, fats and proteins are modeled distinctly with the respective individual reactions (alcohol can be lumped together with fats owing to similar reaction stoichiometry):

Eq 2

Glucose→Prop acid+Acet acid+H_2+CO_2 R1a:

LCFA/Ethanol→Acet acid+H_2 R1b:

Amino acid→Prop acid+Acet acid+H_2+CO_2(+IN) R1c:

[0211] The separate modeling for the carbohydrates, fats and proteins was also important to allow a more accurate total carbon balance, which in turn, is used in the inorganic carbon balance for calculation of alkalinity, CO_2 and pH. Finally, the model was updated to include the decay of the active biomass, as a first order reaction, wherein the active biomass decays to yield insoluble COD. The insoluble or particulate COD, in turn, undergoes a slow decomposition and hydrolysis through a first order reaction to yield insoluble inert COD and soluble biodegradable COD.

[0212] For the above-mentioned bioprocess the overall dynamic model of the digester is given by:

$$\dot{X}_C = D(X_{C,in} - \alpha X_C) + b(X_1 + X_2 + X_3 + X_4) - hX_C \qquad \text{Eq 3}$$

$$\dot{X}_I = D(X_{I,in} - \alpha X_I) + (1 - f_B)hX_C$$

$$\dot{X}_1 = D(X_{1,in} - \alpha X_1) + k_1 r_1 X_1 - bX_1$$

$$\dot{X}_2 = D(X_{2,in} - \alpha X_2) + k_2 r_2 X_2 - bX_2$$

$$\dot{X}_3 = D(X_{3,in} - \alpha X_3) + k_3 r_3 X_3 - bX_3$$

$$\dot{X}_4 = D(X_{4,in} - \alpha X_4) + k_4 r_4 X_4 - bX_4$$

$$\dot{S}_I = D(S_{I,in} - S_I)$$

$$\dot{S}_1 = D(S_{1,in} - S_1) - r_1 X_1 + f_B h X_C$$

$$\dot{S}_2 = D(S_{2,in} - S_2) + k_5 r_1 X_1 - r_2 X_2$$

$$\dot{S}_3 = D(S_{3,in} - S_3) + k_6 r_1 X_1 + k_7 r_2 X_2 - r_3 X_3$$

$$\dot{S}_4 = D(S_{4,in} - S_4) + (k_8 r_1 X_1 + k_9 r_2 X_2 - r_4 X_4 - q_{H_2}) * (10^6/\mathrm{MW}_{H_2})$$

$$\dot{S}_5 = D(S_{5,in} - S_5) + (k_{10} r_1 X_1 + k_{11} r_2 X_2 + k_{12} r_3 X_3 - k_{13} r_4 X_4 - q_{CO_2})/\mathrm{MW}_{CO_2})$$

$$\dot{Z} = D(Z_{in} - Z) + Z_{gen}$$

$$\dot{S}_{IN} = D(S_{IN,in} - S_{IN}) + N_{gen} - N_{bac}\left(\sum_{i-1}^{4} k_i \mu_i X_i\right)$$

[0213] In the above model, X_C denotes the insoluble COD concentration, X denotes the insoluble inert COD concentration, X_i (i=1, . . . , 4) denotes the concentration of the biomass for the i^{th} reaction, S_1 denotes the soluble inert COD concentration, S_1 denotes the soluble biodegradable COD, S_2 denotes propionic acid concentration (higher order VFA are ignored and lumped into propionic acid), S_3 denotes acetic acid concentration, S_4 denotes dissolved H_2 concentration, S_5 denotes the total inorganic carbon concentration, Z denotes the total alkalinity and S_{IN} denotes the total inorganic nitrogen concentration. All concentrations in the model are expressed in gCOD/l, except S_4 is in micromol/l, while S_5 and S_{IN} are in mol/l, and Z is expressed as equivalent g $CaCO_3$/l. The variable D denotes the dilution rate, or the inverse of the hydraulic retention time (HRT), the parameter b denotes the rate constant for biomass decay, h denotes the net first-order reaction rate constant for decomposition/hydrolysis, while f_B denotes the fraction of insoluble COD that yields soluble biodegradable COD upon decomposition/hydrolysis—the remaining fraction is insoluble inert COD.

[0214] The total inorganic carbon consists of dissolved CO_2 and bicarbonate—at the operating pH range of 6.5-7.5 (or lower in the PA reactor) the carbonate concentration is ignored. The total alkalinity includes alkalinity due to dissolved bicarbonate, and due to ionized VFA. At operating pH above 6.5, it is assumed that all VFA is ionized, whereas at lower pH conditions in the PA reactor, VFA is partially ionized depending on the dissociation equilibrium. Finally, total inorganic nitrogen is the nitrogen as NH_3/NH_4^+ in the reactor. At pH below 7.5, all inorganic nitrogen is present as NH_4^+. The inorganic nitrogen is accumulated in the reactor due to generation from uptake of proteinaceous COD, and simultaneously removed by assimilation into the biomass during their growth (N_{bac} denotes the specific nitrogen uptake during biomass growth). The terms r_iX_i denote the uptake rate of the key substrate in the respective reaction, and the corresponding biomass growth rates are given by $k_ir_iX_i$. Note that the parameter a denotes the ratio of concentration of the biomass/particulate matter in the effluent stream to the concentration in the reactor. For a mixed CSTR, with perfect mixing, this ratio is nominally 1. On the other hand for high-throughput digesters like UASB and EGSB, with preferential retention of biomass and particulate matter, this ratio is less than 1. This parameter allows adapting for varying AD design, and can be also interpreted as the ratio of HRT and solid retention time (SRT), i.e., α=HRT/SRT, a critical design and operation parameter for digester performance. This parameter can be adjusted/adapted for varying design/operating conditions.

[0215] The reaction stoichiometry parameters k_i, and the reaction rates r_i can also be adjusted/adapted for varying feed and operation conditions. In particular, the reaction rate r_i is given by a standard monod-expression with multiplicative terms for inhibition effects due to pH and H_2 concentrations:

$$r_i = r_{i,max}(T)\frac{S_i}{KS_i + S_i} I_{pH} \cdot I_{H_2} \qquad \text{Eq 4}$$

$$r_{i,max}(T) = \bar{r}_{i,max} b_3 (T - T_{min})^2 (1 - \exp(c_3(T - T_{max})))$$

[0216] In the above relation, the max reaction rate for each substrate and the corresponding biomass growth rate is a function of the operating temperature. For mesophillic bacteria, the optimum temperature is about 35° C., and the peak reaction rate drops gradually at lower temperatures, and very sharply at higher temperatures as given by the two-term function in the above equation. The peak reaction rate parameter $\bar{r}_{i,max}$ can be adapted/adjusted. The inhibition terms I_{pH} and I_{H2} range from 1 (un-inhibited) to 0 (completely inhibited) over respective pH and dissolved H_2 concentration ranges, and they are modeled the same as in ADM1.

[0217] As mentioned above, the soluble biodegradable COD (S_1) is composed of the individual carbohydrates (S_{1c}), fats (including alcohol) (S_{1f}) and proteins (S_{1p}), i.e.,

$$S_1 = S_{1c} + S_{1f} + S_{1p} \qquad \text{Eq 5}$$

and the corresponding reaction rate for R1 is given as:

$$r_1 = r_{1c} + r_{1f} + r_{1p} \qquad \text{Eq 6}$$

$$r_{1c} = r_{1c,max}(T)\frac{S_{1c}}{KS_{1c} + S_{1c}} I_{pH} \cdot I_{H_2}$$

$$r_{1f} = r_{1f,max}(T)\frac{S_{1f}}{KS_{1f} + S_{1f}} I_{pH} \cdot I_{H_2}$$

$$r_{1p} = r_{1p,max}(T)\frac{S_{1p}}{KS_{1p} + S_{1p}} I_{pH} \cdot I_{H_2}$$

[0218] In the above model, the terms q_{CO_2} and q_{H_2} denote the mass transfer rate of CO_2 and H_2 from liquid phase to the gas phase. Due to the fast consumption of H_2 in the reaction R4, the concentration of dissolved H_2 is nominally very low, and thus, q_{H_2} is also low and is ignored. On the other hand, q_{CO_2} needs to be calculated to complete the inorganic carbon balance. This is accomplished by calculating the mass transfer of methane as:

$$q_{CH_4} = \frac{k_{14} r_3 X_3 + k_{15} r_4 X_4}{\mathrm{MW}_{CH_4} COD2M_{CH_4}} \ (\text{mol/}l\text{/day}) \qquad \text{Eq 7}$$

i.e., all methane produced in R3 and R4 is assumed to transfer to gas phase due to the very low solubility of methane in water, and imposing vapor-liquid equilibrium. Assuming the gas phase is a mixture of methane, water vapor, and CO_2, and the partial pressure for CO_2 is given by Henry's law:

$$p_{CO_2} = k_H(T) CO_{2,aq} \ (\text{atm}) \qquad \text{Eq 8}$$

$$CO_{2,aq} = (S_5 - B) \ (\text{mol/}l)$$

$$B = \left[\frac{2Z}{\mathrm{MW}_{CaCO_3}} - \frac{S_2}{COD2M_{S_2}\mathrm{MW}_{S_2}} - \frac{S_3}{COD2M_{S_3}\mathrm{MW}_{S_3}}\right]$$

the mass transfer rate for CO_2 can be calculated as:

$$q_{CH_4} = \left[\frac{P_{CO_2}(q_{CH_4}/\mathrm{MW}_{CH_4})}{P_{CO_2} - P_{H_2O}}\right] \qquad \text{Eq 9}$$

[0219] Finally, an important output for the digester model is the operating pH, which needs to be regulated in the desired operating range 6.5-7.5. In this operation range, the bicarbonate equilibrium is the dominant equilibrium that determines the buffer capacity of the holdup and the resulting pH given by:

$$\mathrm{pH} = \mathrm{p}K_1 + \log_{10}(B) — \log_{10}(CO_{2,aq}) \qquad \text{Eq 10}$$

where B denotes the concentration of dissolved bicarbonate (in mol/l). The above set of equations complete the model for the AD reactor. However, this model is very stiff, necessitating the use of variable step-size stiff solvers for numerical computation. This is not desirable for real-time implementation in a PLC for monitoring and control. A key source of the stiffness is the fast kinetics for the consumption of dissolved H_2 in R4, yielding very low concentration of H_2. In essence H_2 is an intermediate product from R1 & R2, which is consumed in R4 as fast as it is produced. This fast reaction and corresponding dynamics can be approximated by a quasi-steady-state condition:

$$0=(k_8 r_1 X_1+k_9 r_2 X_2-r_4 X_4) \qquad \text{Eq 11}$$

which is solved iteratively for S_4.

[0220] The PA reactor model is similar to the AD model described above, except that R2, R3 and R4 are eliminated—these reactions are suppressed at the low operation pH in the PA reactor. Also, due to the suppressed methanogenesis reaction, the reaction stoichiometry for R1 is modified to convert all the H_2 COD into propionic acid COD—this is to account for the fact that owing to suppression of the H_2 consuming methanogenesis reaction, the acidification reactions will yield higher order VFAs. Additionally, owing to the typical operation pH of the PA reactor below 6, the inorganic carbon balance, and alkalinity, pH calculation is modified to include partial ionization of the VFAs. The ionization of the VFAs is given by the respective equilibriums for their dissociation, which is a function of pH, i.e.,

$$CO_{2,aq} = (S_S - B)\ (\mathrm{mol}/l) \qquad \text{Eq 12}$$

$$B = \left[\frac{2Z}{\mathrm{MW}_{CaCO_3}} - \left(\frac{Ka_2}{Ka_2 - 10^{-pH}}\right)\frac{S_2}{COD2M_{S_2}\mathrm{MW}_{S_2}} - \left(\frac{Ka_3}{Ka_3 - 10^{-pH}}\right)\frac{S_3}{COD2M_{S_3}\mathrm{MW}_{S_3}}\right] (\mathrm{mol}/l)$$

[0221] This leads to an iterative calculation for pH unlike in the digester, where at pH above 6.5, all of the VFA is assumed to be completely ionized. Also, the mass transfer of CO_2 from liquid to gas phase is calculated through a mass transfer correlation:

$$q_{CO_2}=k_{la}(CO_{2,aq}-CO^*_2)(\mathrm{mol/l/day}) \qquad \text{Eq 13}$$

where CO^*_2 denotes the equilibrium composition of dissolved CO_2 in gas phase corresponding to the off-gas from the PA reactor consisting primarily of CO_2.

[0222] Finally, the model includes chemical additives like NaOH, Na_2CO_3, $NaHCO_3$, NH_3, NH_4Cl, $Mg(OH)_2$. Each of these chemical additives is modeled as equivalent (in molar concentration) addition of inorganic carbon, alkalinity and/or inorganic nitrogen.

[0223] As can be seen, PA reactor **22** and AD reactor **24** are modeled separately in dynamic model **260** of AD **20**, which serves as the basis for offline dynamic AD model **261** and online dynamic AD model **262**. Accordingly, PA reactor **22** and AD reactor **24** are modeled separately in offline dynamic AD model **261** and online dynamic AD model **262**.

[0224] FIGS. **4***a-b* show a general MBR **30** having an anoxic tank **31**, aerobic tank **32** and membrane tank **33** connected in series. The anoxic tank **31** is optional for feeds with high nitrogen. Aerobic tank **32** is for aerobic biochemical reactions to remove biodegradable COD in the waste water, and membrane tank **33** is for solids and liquids separation, and retains the biomass in the system. This configuration of MBR **30** largely represents the majority of MBR systems. MBR **30** is an aerobic/anoxic bioprocess used to remove remaining unconverted COD and nitrogen in the effluent of AD **20** if it is used to follow the AD **20** as shown in FIG. **1***a*. For wastewater feeds with high solids content, an entrapped air flotation process **48** is used to remove the particulate solid before feeding to the MBR **30**. As can be seen, aerobic tank **32** is located upstream of membrane tank **33**. Further, optional anoxic tank **31** is located either immediately upstream or downstream of said aerobic tank **32**.

[0225] As can be seen, in a typical MBR **30**, membrane tank **33** is at a higher elevation than anoxic tank **31** and aerobic tank **32**. Recycle from membrane tank **33** flows back into anoxic tank **31** by overflow and gravity through the membrane tank to anoxic tank recycle line **34** and optional aerobic tank recycle line **36**. In embodiments in which a stand along anoxic tank **31** is not present, recycle from membrane tank **33** is provided to aerobic tank **32** through aerobic tank recycle line **36**. In some embodiments, an MBR recycle line flow diverter **68** is present, which changes the ratio of fluid flowing between anoxic tank recycle line **34** and aerobic tank recycle line **36**.

[0226] The return activated sludge pump (RAS) **40** operates at R+1 times the feed-rate of influent into MBR **30**, with R being the recycle ratio. The liquid level in the aerobic tank **32** is controlled at a desired level by the aerobic tank fluid level PI controller **765**, described below, and an aerobic tank fluid level sensor **37** to detect the level of fluid in aerobic tank **32**, which manipulate the flow rate of permeate pump **35** to maintain the fluid level in aerobic tank **32** at a predetermined level. Similarly, the dissolved oxygen DO concentration in the aerobic tank **32** is regulated by varying the speed of aerobic tank blower of aerobic and membrane tank aeration system **38** and **39**, while the pH in the aerobic tank **32** is controlled by varying the alkali addition to aerobic tank **32**. Aeration may also be applied to membrane tank. Anoxic tank **31** has a mixer **41**. It is also contemplated that some embodiments of MBR **30** include an MBR feed pump **42** and a membrane tank sludge discharge **43**.

[0227] In some embodiments of MBR **30**, the pH of anoxic tank **31** is controlled by alkali addition from anoxic tank alkali tank **45**, whose flow rate is controlled by anoxic tank pH controller **755**. In some embodiments, anoxic tank pH controller **755** is a PI controller. Further, in some embodiments of MBR **30**, the pH of aerobic tank **32** is controlled by alkali addition from aerobic tank alkali tank **49**, whose flow rate is controlled by anoxic tank pH controller **755**.

[0228] In some embodiments of MBR **30**, nutritional additives are provided to anoxic tank **31**. The nutritional additives provided to anoxic tank **31** are provided from anoxic tank additive tank **778**, whose flow rate is controlled by anoxic tank nutritional additive concentration PI controller **777**. It is understood that each nutritional additive for anoxic tank **31** will have a anoxic tank additive tank **778** and anoxic tank nutritional additive concentration PI controller **777**. It is understood that each nutritional additive for anoxic tank **31** will have an anoxic tank additive tank **778** and an anoxic tank nutritional additive concentration PI controller **777**.

[0229] However, in other embodiments of MBR **30**, all of the nutritional additives for anoxic tank **31** are combined in a single anoxic tank additive tank **778**. Accordingly, only one anoxic tank additive tank **778** and corresponding anoxic tank nutritional additive concentration PI controller **777** are present.

[0230] In embodiments in which a standalone anoxic tank **31** is not present, aerobic tank **32** will have both an anoxic zone and an aerobic zone. Anoxic zone acts as a pseudo anoxic tank **31** and aerobic zone acts as a pseudo aerobic tank **32**. Accordingly, the nutritional requirements of aerobic tank **32** will be analyzed and any needed nutritional additives will be provided to aerobic tank **32**.

[0231] Further, some embodiments of MBR **30** include a bCOD tank **1066** for providing additional bCOD to anoxic tank **31** if the feed has high concentration of Nitrogen and low concentration of COD. The flow rate of bCOD from bCOD tank **1066** into anoxic tank **31** is determined by anoxic tank bCOD addition flow rate supervisory control scheme **1035**, discussed below. In embodiments in which a stand alone anoxic tank **31** is not present, the bCOD from bCOD tank **1066** will be added to aerobic tank **32**.

[0232] FIG. **4*b*** shows an embodiment in which anoxic tank **31** is not present, in which aerobic tank **32** has both an anoxic zone and an aerobic zone, which act as both anoxic tank **31** and aerobic tank **32**.

[0233] The bioprocess operation in the anoxic tank **31** and aerobic tank **32** of MBR **30** is modeled by Activated Sludge Model No. 1 (ASM1), as proposed by Metcalf and Eddy in **2002**. However, the ASM1 model has been extended to include the calculation of Mixed Liquor Suspended Solids (MLSS), oxygen mass transfer, dissolved oxygen (DO) concentration, inorganic carbon balance for alkalinity, and pH calculation.

[0234] The bioprocess operation model for MBR **30**, which is duplicated for the individual anoxic tank **31** and aerobic tank **32**, is given as:

Eq 14

Particulate Inert (mgCOD/l):

$$\frac{dI}{dt} = [Q*(I_{in} - I)]/V$$

Slowly $degr.\ Sustr.$ (mgCOD/l):

$$\frac{dX_S}{dt} = [Q*(X_{S,in} - X_S) + R_{X_S}*V]/V$$

Hetrorophic biomass (mgCOD/l):

$$\frac{dX_{bh}}{dt} = [Q*(X_{bh,in} - X_{bh}) + R_{X_{bh}}*V]/V$$

Autotrophic biomass (mgCOD/l):

$$\frac{dX_{ba}}{dt} = [Q*(X_{ba,in} - X_{ba}) + R_{X_{ba}}*V]/V$$

Decayed biomass (mgCOD/l):

$$\frac{dX_d}{dt} = [Q*(X_{d,in} - X_d) + R_{X_d}*V]/V$$

Soluble Inert (mgCOD/l):

$$\frac{dS_I}{dt} = [Q*(S_{I,in} - S_I)]/V$$

Soluble readily $degr.\ Substr.$ (mgCOD/l):

$$\frac{dS_S}{dt} = [Q*(S_{S,in} - S_S) + R_{S_S}*V]/V$$

Dissolved oxygen (mg/l):

$$\frac{dS_O}{dt} = [Q*(S_{O,in} - S_O) + K_{la}*V*(S_{O,sat} - S_O) + V*R_O]/V$$

-continued

Dissolved nitrate-N (mg/l):

$$\frac{dS_{NO}}{dt} = [Q*(S_{NO,in} - S_{NO}) + R_{S_{NO}}*V]/V$$

Dissolved ammonia-N (mg/l):

$$\frac{dS_{NO}}{dt} = [Q*(S_{NO,in} - S_{NO}) + R_{S_{NO}}*V]/V$$

Soluble $bio\text{-}degr.\ N$ (mg/l):

$$\frac{dS_{NS}}{dt} = [Q*(S_{NS,in} - S_{NS}) + R_{S_{NS}}*V]/V$$

Particulate $bio\text{-}degr.\ N$ (mg/l):

$$\frac{dX_{NS}}{dt} = [Q*(X_{NS,in} - X_{NS}) + R_{X_{NS}}*V]/V$$

Bicarb alkalinity (mmol/l):

$$\frac{dS_{alk}}{dt} = [Q*(S_{alk,in} - alk) + R_{alk}*V]/V$$

[0235] ASM1 only includes organic COD (classified as biodegradable or non-biodegradable/inert/refractory, as well as particulate/insoluble and soluble). The particulate COD is included in the MLVSS calculation along with the biomass concentration. However, total MLSS also includes particulate inorganic matter from the feed—to accommodate this, the particulate inorganic matter is also included as a separate state with a simple accumulation based on inlet and outlet and no reaction. The bioprocess model includes the following reactions:

Eq 15

$R1$-Aerobic growth of heterotrophy:

$$SBOD + O_2 \xrightarrow{X_{bh}} X_{bh} + CO_2$$

$R2$-Anoxic growth of heterotrophy:

$$SBOD + NO_{32} \xrightarrow{X_{bh}} X_{bh} + N_2 \ \text{(De-nitrifaction)}$$

$R3$-Aerobic growth of autotroph:

$$O_2 + NH_3 + \text{(light)} \xrightarrow{X_{ba}} X_{ba} + NO_3 \ \text{(Nitrification)}$$

$R4$-Decay of heterotrophy:

$$X_{bh} \to \text{Debris } (X_d) + InsBOD(X_S) + InsOrgN(X_{NS})$$

$R5$-Decay of autotroph:

$$X_{ba} \to \text{Debris } (X_d) + InsBOD(X_S) + InsOrgN(X_{NS})$$

$R6$-Ammonification of $sol.\ Org.\ N$:

$$SolOrgN \xrightarrow{X_{bh}} NH_3$$

$R7$-Hydrolysis of organics:

$$InsBOD \xrightarrow{X_{bh}} SBOD$$

$R8$-Hydrolysis of organic N:

$$InsOrgN \xrightarrow{X_{bh}} SolOrgN$$

[0236] The reaction rates for these reactions are given by:

Aerobic growth of heterotrophy: $R_1=\alpha*\mu_H*(S_S/(K_S+S_S))*(S_O/(K_{OH}+S_O))*X_{bh}$ Eq 16

Anoxic growth of heterotroph: $R_2=(1-\alpha)*\mu_H*(S_S/(K_S+S_S))*(K_{OH}/(K_{OH}+S_O))*(S_{NO}/(S_{NO}+K_{NO}))*\eta_g*X_{bh}$

Aerobic growth of autotroph: $R_3=\mu_A*(S_{NH}/(S_{NH}+K_{NH}))*(S_O/(K_{OH}+S_O))*X_{ba}$

Decay of heterotrophy: $R_4=b_H*X_{bh}$

Decay of autotroph: $R_5=b_A*X_{ba}$

Ammonification of sol. Org. N: $R_6=k_a*S_{NS}*X_{bh}$

Hydrolysis of organics: $R_7=k_h\{(X_S/X_{bh})/[k_x+(X_S/X_{bh})]\}*X_{bh}\{[S_O/(K_{OH}+S_O)]+\eta_h[K_{OH}/(K_{OH}+S_O)]*[S_{NO}/(K_{NO}+S_{N0})]\}$

Hydrolysis of organic N: $R_8=R_7*X_{NS}/(X_S+10^{-1})$ (10^{-} 10 included to avoid divide by zero)

Net generation of slowly *degr.* Particulate: Eq 17

$$R_{XS} = R_4(1-f_P) + R_5(1-f_P) - R_7$$

Net Growth rate of hetrotroph:

$$R_{X_{bh}} = R_1 + R_2 - R_4$$

Net Growth rate of autotroph:

$$R_{X_{ba}} = R_3 - R_5$$

Generation of soluble readily *degr. substr*:

$$R_{S_s} = -\frac{(R_1-R_2)}{Y_h} + R_7$$

Consumption rate of oxygen:

$$R_O = -(1-Y_h)*\frac{R_1}{Y_h} - (4.57-Y_a)*\frac{R_3}{Y_a}$$

Net generation of nitrate-N:

$$R_{S_{NO}} = -R_2\left[\frac{(1-Y_h)}{(2.86*Y_h)}\right] + \frac{R_3}{Y_a}$$

Net generation of ammonia-N:

$$R_{S_{NH}} = -ixbn(R_1+R_2) - R_3\left(ixbn + \frac{1}{Y_a}\right) + R_6$$

Net generation of soluble organic N:

$$R_{S_{NS}} = -R_6 + R_8$$

Net generation of particulate organic N:

$$R_{X_{NS}} = (ixbn - f_p * ixun) * (R_4 + R_5) - R_8$$

Net generation of bicarbonate alkalinity:

$$R_{alk} = \left(ixbn * \frac{R_1}{14}\right) + R_2\left\{[(1-Y_h)/(14*2.86*Y_h)] - \left(\frac{ixbn}{14}\right)\right\} - R_3\left[\frac{ixbn}{14} + \frac{1}{(7Y_a)}\right] + \frac{R_6}{14}$$

Generation of debris from biomass decay:

$$R_{X_d} = f_p(R_4 + R_5)$$

Generation of CO_2 (mol/m^3/d):

$$R_{CO_2} = (R_1+R_2)*\left(\frac{IC_{S_S}}{Y_h} - IC_{X_B}\right) - R_3 IC_{X_B} + (R_4+R_5)*[IC_{X_B} - f_p IC_{X_I} - (1-f_p)IC_{X_S}] + R_7(IC_{S_S} - IC_{X_S})$$

[0237] In addition to the above bioprocess model, additional equations were included to model the oxygen mass transfer, alkalinity and pH.

[0238] Estimating dissolved oxygen requires the air flow rate, saturated oxygen concentration, and oxygen mass transfer coefficient. Subsequently, the model estimates dependency of all these parameters for different temperature and MLSS. The saturation oxygen concentration is a function of temperature. The estimated oxygen mass transfer coefficient includes temperature correction, MLSS correction, factors due to diffuser density and the air velocity and is given by:

$$K_l\alpha=(1.024^{T-20})D\alpha(U)^{k4} \quad \text{Eq 18}$$

where

$$U = \frac{Q_{air}}{A},\ Q_{air}$$

is the flow rate of air in m^3/day and A is the cross sectional area of the bioreactor. The exponential dependence on U is captured with k_4=0.8198. For the oxygen mass transfer, the mixed liquor solids concentration offers resistance and hence reduces the effective mass transfer by the factor $\alpha=e^{-k3(MLSS)}$ where k_3=0.0771. Finally, D denotes a correction factor depending on diffuser density. The model uses diffuser density of 2 to 35%. For a diffuser density of 2% and temperature of 25° C., the above figure shows relation between superficial velocity and mass transfer coefficient. The correction factor due to diffuser density is given by:

$$D=k_1(DD)^{0.25}+k_2$$

where k_1=2.5656, k_2=0.0432 and DD denotes the diffuser density.

[0239] The pH in the aerobic and anoxic tanks **32** and **31** also has to be calculated since it is an operation parameter for monitoring and control. This is done similar to the AD model, by including a dynamic balance on the total dissolved inorganic carbon (IC) and calculation of pH from bicarbonate equilibrium relationship, since the MBR **30** is typically operated at close to pH 7.

[0240] More specifically, a dynamic balance for total IC (bicarbonate+dissolved CO_2) is given as:

$$\frac{d(S_{IC})}{dt} = Q(S_{IC,in} - S_{IC}) + R_{CO_2} - \frac{R_{CO_2,stripping}}{V} \quad \text{Eq 19}$$

where S_{IC} denotes the molar concentration of inorganic carbon in the water, R_{CO_2} denotes the specific reaction rate for generation of CO_2, and $R_{CO_2,stripping}$ denotes the molar rate of removal of CO_2 from the liquid phase to the gas phase. The model already includes a balance for bicarbonate alkalinity, denoted as S_{alk}, which allows a calculation of the dissolved CO_2 concentration as $S_{CO_2}=S_{IC}-S_b$. Thereafter, the pH in the aerobic reactor is calculated from the bicarbonate equilibrium relationship as:

$$\text{pH}=-\log_{10}(S_H)=\log_{10}(K_a)+\log_{10}(S_{alk})-\log_{10}(S_{CO_2}) \quad \text{Eq 20}$$

[0241] The CO_2 removal rate from liquid to gas phase, $R_{CO_2,stripping}$, is calculated in the aerobic tank **32** by using the Henry relationship for gas-liquid equilibrium, and a mass balance on CO_2 between the incoming and exhaust air. In the anoxic tank **31**, it is calculated by using a mass transfer relation.

[0242] Finally, the bioprocess model in the aerobic tank **32** and anoxic tank **31** was coupled with a static separation model in the membrane tank **33**, ignoring the relatively faster dynamics due to the much lower holdup volume compared to the aerobic/anoxic tanks **32** and **31**.

[0243] As can be seen, anoxic tank **31** and aerobic tank **32** are modeled separately in dynamic MBR model **360**, which serves as the basis for offline dynamic MBR model **361** online dynamic MBR model **362**. Accordingly, anoxic tank **31** and aerobic tank **32** are modeled separately in offline dynamic MBR model **361** and online dynamic MBR model **362**.

[0244] While the discussion of the MBR model above has been directed to the bioprocess operation, another critical aspect is the membrane fouling—which has a direct impact on operation costs in terms of aeration for scouring and chemicals for cleaning. Motivated by this, a data-based empirical model was sought using plant operation data to describe changes in permeability of the membrane in membrane tank **33** over time as a function of upstream bioprocess and membrane tank operation parameters.

[0245] Data analysis for membrane fouling or permeability has been conducted using plant operation data. In one case, standardized time-to-filter (TTF) data was available, which is indicative of the filterability of the sludge and is directly related to the inverse of the membrane permeability. FIG. **5** shows a comparison of measured TTF and predicted (estimated) TTF obtained for an embodiment of MBR **30** by fitting a correlation for TTF variation with respect to available parameters measured in the MBR operation. FIG. **5**, is a plot of TTF vs. time.

[0246] Preliminary data regression analysis indicated that for this account, there are three factors that have a large impact membrane permeability. They are system temperature, reactor MLSS, and % Total Kejeldahl Nitrogen (TKN) removal. The empirical correlation identified for the embodiment of MBR **30** was TTF=240.6+0.008*ReactorMLS S+818*(1−TKN %)−2.57*Temp (F), R^2=60%.

	Coefficient	Standard Error	t Stat	P-value
Intercept	240.6	78.0	3.085	0.004
Reactor MLSS	0.0	0.0	2.051	0.048
1-TKN %	817.6	126.6	6.457	0.000
Temp	−2.6	1.0	−2.514	0.017

[0247] The coefficients identified are all statistically significant (i.e. p-value<0.05). The higher the reactor MLSS and the lower % TKN removal and system water temperature, the higher the TTF, therefore, the lower the membrane permeability. The impacts of reactor MLSS and system water temperature on membrane permeability are as expected. The rate-limiting step in the reactor is autotrophic reaction, and % TKN removal is an indication of how autotrophic bacteria perform in the reactor. A lower % TKN removal indicates likelihood that the autotrophic bacteria are stressed, which may secrete exocellular biopolymer to protect themselves and lead to decreasing sludge filterability. Moreover, the absolute TKN removal is also strongly correlated to MLVSS/(SRT/HRT) in the following empirical correlation identified for the embodiment of MBR **30**: MLVSS/(SRT/HRT)=111.1+16.5*(TKN_in−TKN_out).

	Coefficient	Standard Error	t Stat	P-value
Intercept	111.11	210.6	0.528	0.600
TKN_in − TKN_out	16.5	5.8	2.825	0.007

[0248] In the above embodiment of MBR **30**, SRT/HRT is approximated by (MLSS-MLVSS)/TSS_in with the assumption that influent VSS/TSS ratio is constant. The fact that it is statistically significant that TKN removal variation relates well with both membrane permeability variation and MLVSS variation highlights the need for TKN monitoring and its control (by SRT, HRT) to reduce system TKN variation, and therefore its impact on membrane performance.

[0249] In another embodiment of MBR **30**, very detailed operation data was recorded over a long period of several months. This data, along with variation in the membrane permeability was analyzed to identify the correlation between the two. A key challenge in this analysis is that several of the variables that are used as factors for predicting the permeability, are themselves highly correlated (e.g. dissolved oxygen and blower rates, pH and alkalinity etc.). Partial least squares (PLS) is an advanced multivariate statistical analysis tool that works very well with these challenges. A dynamic first-order model was postulated to describe the slow variation in membrane permeability over several months of operation. To this end, all the recorded variables were also averaged to get daily average data—any faster variation is not important to predict long-term variation in permeability.

[0250] FIG. **6**, a plot of membrane permeability vs. time, clearly shows non-stationary behavior of permeability. Hence, it was modeled as a first order system by augmenting lagged output vector with the other inputs. Thus if Y_k represents the permeability/response vector, the corresponding predictor block is constructed as $Z_k=[Y_{k-1}\ X_{k-1}]$, where X_{k-1} denote the extensive set of recorded variables for bioprocess and influent conditions.

[0251] PLS was used to fit a first-order dynamic model mentioned above. It was observed that a single loading vector (the dominant combination of all predictor variables that is most correlated with the output) explains a significant portion of the output variation. Analysis of this first loading vector revealed the relative importance of the variables obtained from the PLS model, which is based on their predictive ability, as shown in FIG. **7**—Dominant variables and their relative contribution to variation in permeability.

[0252] It can be seen in FIG. **7** that if the lagged output (Y_{k-1}) is ignored, the other influential variables are Blower rate, pH, Tank level, COD/TKN ratio, process water temperature, TKN, TN, DO, Conductivity and Alkalinity. The figure shows ability of the PLS model to pick-up the same variables measured at different locations (tanks). For instance, 12 and 13th variables both refer to the blower rate, which are identified as the two variables having maximum impact on the fouling rate. It could be seen that contribution of other variables drop from 12.6% predictive power to less than 2%, the latter of which is used as a cut-off threshold.

[0253] Using the alternate samples in dynamic data block for model building, the remaining section of the data was used for validation. It can be seen in FIG. **8** that the derived dynamic model can predict the permeability data quite satisfactorily.

[0254] The developed dynamic models of the AD **20** and MBR **30** are used as the basis for a method of operating AD **20** and MBR **30** through online monitoring and control of one or both of AD **20** and MBR **30** of wastewater treatment plant **10**.

[0255] More specifically, for online monitoring of the AD **20**, a set of online sensors are used along with model-based estimation of variables not measured directly through the use of a constrained Extended Kalman Filter. FIG. **9** shows the overall architecture for monitoring an embodiment of AD **20** with control system **200**, using a combination of online sensors that measure the measured input data and measured output data of AD **20**. An extended Kalman filter **250** containing the dynamic model **260** of AD **20** discussed above uses the measured input data and measured output data of AD **20** to estimate the following items: estimated parameters, states, adapted model parameters, model predicted (estimated) outputs, and model based inferred variables. AD control system **200** interfaces with AD extended Kalman filter **250** and has a supervisory control system **201** and a low level control system **202**.

[0256] The comparison of the estimated and actual values of the measured output data, offline laboratory testing data and estimated values of model predicted outputs and model based inferred variables by extended Kalman filter **350** estimate values for the estimated parameters, states, and adapted model parameters of dynamic model **360** of MBR **30**.

[0257] Further extended Kalman filter **250** containing the dynamic model **260** of AD **20** discussed above uses the measured input data and measured output data of AD **20** to calculate model predicted outputs and model based inferred variables (also sometimes called virtual sensors). A similar architecture is used for the MBR **30** as well. Extended Kalman Filter (EKF) is a standard online model-based estimation algorithm to estimate unknown variables (states, parameters) in the model and match the model outputs to measured variables from online sensors.

[0258] Below are exemplary lists of measured output data, measured input data, estimated parameters, adapted model parameters, model predicted outputs, and model based inferred variables for AD **20** of WWTP **10**. AD **20** has an AD control system **200**, AD online EKF **251**, and AD offline EKF **252**.

Estimated Parameters and Adapted Model Parameters	Updated By Online EKF (Adapted Model Parameters)	Estimated By Offline EKF (Estimated Parameters
PA Reactor Composite Fraction of Carbohydrate	X	X
PA Reactor Composite Fraction of Fat	X	X
PA Reactor Composite Fraction of Protein	X	X
PA Reactor Fraction of Insoluble Convertible to SBOD	X	X
PA Reactor Acedogenthese Reaction Coefficient	X	X
PA Reactor Biomass Decay Rate		X
PA Reactor Insoluble Hydrolysis Reaction Coefficient		X

-continued

Estimated Parameters and Adapted Model Parameters	Updated By Online EKF (Adapted Model Parameters)	Estimated By Offline EKF (Estimated Parameters
PA Reactor Insoluble Flow out Coefficient	X	X
PA Reactor CO_2 Escape Coefficient		X
AD Reactor Composite Fraction of Carbohydrate	X	X
AD Reactor Composite Fraction of Fat	X	X
AD Reactor Composite Fraction of Protein	X	X
AD Reactor Fraction of Insoluble Convertible to SBOD	X	X
AD Reactor Acedogenthese Reaction Coefficient		X
AD Reactor Acetogenesis Reaction Coefficient		X
AD Reactor Acetoclastic Methanogenesis Reaction Coefficient	X	X
AD Reactor Hydrogen Methanogenesis Reaction Coefficient		X
AD Reactor Biomass Decay Rate		X
PA Reactor Insoluble Hydrolysis Reaction Coefficient		X
PA Reactor Insoluble Flow out Coefficient	X	X

Model Based Inferred Variables

Outputs	Inputs
PA Reactor Alkalinity	Raw Influent Insoluble COD
PA Reactor VFA	Raw Influent Insoluble Inert COD
PA Reactor Temperature	Raw Influent Soluble Inert COD
PA Reactor SCOD	Raw Influent SBOD Saccharide
PA Reactor TCOD	Raw Influent SBOD LCFA
PA Reactor SBOD	Raw Influent SBOD Amino Acid
AD Reactor Alkalinity	Raw Influent Propionate Acid
AD Reactor VFA	Raw Influent Acetate Acid
AD Reactor Temperature	Raw Influent Inorganic Carbon Content
AD Reactor SCOD	Raw Influent Alkalinity
AD Reactor SBOD	Raw Influent Inorganic Nitrogen
AD Reactor Acedogenthese Biomass	Raw Influent SCOD
AD Reactor Acetogenesis Biomass	Raw Influent TCOD
AD Reactor Acetoclastic Methanogenesis Biomass	Raw Influent SBOD
AD Reactor Hydrogen Methanogenesis Biomass	
AD Reactor Insoluble COD	
AD Reactor Insoluble Inert COD	
AD Reactor Soluble Inert COD	
AD Reactor SBOD Saccharide	
AD Reactor SBOD LCFA	
AD Reactor SBOD Amino Acid	
AD Reactor Propionate Acid	
AD Reactor Acetate Acid	
AD Reactor Inorganic Carbon Content	
AD Reactor Alkalinity	
AD Reactor Inorganic Nitrogen	
AD Reactor SCOD	
AD Reactor TCOD	
AD Reactor SBOD	
SCOD Conversion Rate	
CH_4 Conversion Efficiency	
Recycle Flow Rate	

Measured Input Data	Online	Offline
Raw Influent pH	X	X
Raw Influent Temperature	X	X
Raw Influent Flow Rate	X	X
Raw Influent TOC	X	X
Raw Influent TIC	X	X
Added Alkali Flow Rate	X	X
PA Reactor Level	X	X
AD Feed Flow Rate	X	X
Raw Influent SCOD		X
Raw Influent TCOD		X
Raw Influent SBOD		X
Raw Influent VSS		X
Raw Influent TSS		X
Raw Influent Soluble Inorganic Nitrogen		X
Raw Influent VFA		X
Added Alkali concentration		X

Measured Output Data & Model Predicted Outputs	Online	Offline
PA Reactor pH	X	X
PA Effluent TOC	X	X
PA Effluent TIC	X	X
AD Biogas Flow Rate	X	X
AD Biogas CH_4 Concentration	X	X
AD Biogas CO_2 Concentration	X	X
AD Reactor pH	X	X
AD Effluent TOC	X	X
AD Effluent TIC	X	X
AD Effluent VFA		X
AD Effluent Alkalinity		X
AD Reactor MLVSS		X
AD Effluent TCOD		X
AD Effluent SCOD		X
AD Effluent VSS		X
AD Effluent TSS		X

[0259] It is understood that the lists above of measured output data, measured input data, estimated parameters, adapted model parameters, model predicted outputs, and model based inferred variables are exemplary, can vary from one application to another application, and can be established by a person having ordinary skill in the art based on the person's knowledge of the process and application. Further, it is understood that the adapted model parameters are a subset of the estimated parameters, which are more extensive. Additionally, it is understood that the model based inferred variables include both unmeasured inputs and outputs for AD **20**.

[0260] More specifically, FIG. **10** shows the overall architecture for the AD offline EKF **251** containing an offline dynamic model **261** of AD **20** for identifying estimated parameters and states of offline dynamic model **261** of an embodiment of AD **20** having control system **200**. AD offline EKF **251** identifies the estimated parameters and states of offline dynamic model **261** by using historical measured input data, historical measured output data, and historical offline laboratory testing data for AD **20**.

[0261] FIG. **11** shows the overall architecture of an AD online EKF **252** containing an online dynamic model **262** of AD **20** for real-time monitoring/virtual sensing/controlling of an embodiment of AD **20** having control system **200**. Control system **200** has a supervisory control system **201** and a low level control system **202**. AD online EKF **252** calculates model predicted outputs and model based inferred variables for AD **20** and updates the adapted model parameters of the online dynamic model **262** of AD **20** using real time measured output data and real time measured input data for AD **20**, and the online dynamic model **262** of AD **20** containing estimated parameters. The adapted model parameters of the online dynamic model **262** of AD **20** are a subset of the estimated parameters that were identified in the offline dynamic model **261** of AD **20** using AD offline EKF **251** as was discussed above.

[0262] The raw feed composition listed in the model based inferred variables above can include one or more of carbohydrates, protein, fat, sCOD, insCOD, propionate, acetate, and alkalinity.

[0263] Additionally, it is understood that in some embodiments of WWTP **10**, if an AD **20** is located upstream of MBR **30**, some of the model based inferred variables calculated by online dynamic model **262** of AD **20** located in AD online EKF **252**, such as the composition of AD effluent, are provided to MBR **30** by AD online EKF **252**, therefore enabling feed forward control of MBR **30** by MBR control system **300** which uses the provided data as inputs. It is understood that the information provided regarding the composition of the effluent includes multiple pieces of information, such as the individual amounts of elements and compounds contained in the effluent (e.g. Nitrogen, Oxygen, etc.).

[0264] Additionally, it is understood that in some embodiments of WWTP **10**, if an MBR **30** is located upstream of AD **20**, some of the model based inferred variables calculated by online dynamic model **362** of MBR **30** located in MBR online EKF **352**, such as the composition of MBR effluent, are provided to AD **20** by MBR online EKF **352**, therefore enabling feed forward control of AD **20** by AD control system **200** which uses the provided data as inputs. It is understood that the information provided regarding the composition of the effluent includes multiple pieces of information, such as the individual amounts of elements and compounds contained in the effluent (e.g. Nitrogen, Oxygen, etc.).

[0265] Further, the states for offline dynamic model **261** of AD offline EKF **251** and online dynamic model **262** of AD online EKF **252**, are defined above in equations 3 and 7-10.

[0266] Further, it is understood that both offline dynamic model **261** of AD **20** and online dynamic model **262** of AD **20** both contain estimated parameters and adapted model parameters, a subset of the adapted model parameters. Accordingly, the structures of offline dynamic model **261** of AD **20** and online dynamic model **262** of AD **20** are the same. However, all of the estimated parameters are identified by AD offline EKF **251** in offline dynamic model **261** of AD **20**. Meanwhile, only the adapted model parameters are identified (updated) in the online dynamic model **262** of AD **20** by AD online EKF **252**. Further, it is understood that the offline dynamic model **261** of AD **20** and online dynamic model **262** of AD **20** are based on first principles with physical meanings for the respective estimated parameters and adapted model parameters with unknown values (e.g., the reaction rate kinetic parameter) whose values are estimated by best fitting.

[0267] It is understood that the measured input data and measured output data is data obtained from physical sensors of AD **20**. Further, model based inferred variables are virtual sensors that have traditionally only been available through periodic offline testing. A model based inferred variable of AD **20** is a "virtual sensed" variable that is estimated by the AD online EKF **252** using the online dynamic model **262** of AD **20**, real time measured input data of AD **20**, and real time measured output data of AD **20**. The model based inferred variables of AD **20** are first developed by the AD online EKF **251** using offline dynamic model **261** of AD **20**, historical measured input data of AD **20**, historical measured output data of AD **20**, and historical offline testing data of AD **20**. It is understood that the model based inferred variables include both unmeasured inputs and outputs of AD **20**.

[0268] A model predicted output is an output of AD **20** that is estimated by the AD offline EKF **251** and AD online EKF **252**. The AD offline EKF **251** estimates the model predicted outputs of AD **20** using offline dynamic model **261** of AD **20**, historical measured input data of AD **20**, historical measured output data of AD **20**, and historical offline testing data of AD **20**. The AD online EKF **252** estimates the model predicted outputs of AD **20** using the online dynamic model **262** of AD **20**, real time measured input data, and real time measured output data. It is understood that each model predicted output of AD **20** corresponds to a measured output of AD **20**.

[0269] Estimated parameters are parameters that are identified in the offline dynamic model **261** of AD **20** located in AD offline EKF **251**, such that for a given historical input data value, the predicted historical output data value or model based inferred variable value matches the corresponding actual historical output data value or actual offline laboratory testing value. The estimated parameters from the offline dynamic model **261** of AD **20** located in AD offline EKF **251** are imported into the online dynamic model **262** of AD **20** located in AD online EKF **252**. The adapted model parameters are a subset of the estimated parameters, which are updated in the AD online EKF **252**. The AD online EKF **252** is used to generate real time estimated values for the model predicted outputs and model based inferred variables of AD **20**.

[0270] In one embodiment of a method of monitoring and controlling AD **20**, initially an AD offline EKF **251**, such as the one shown in FIG. **10**, is used to identify estimated parameters (e.g. reaction kinetics) and states for the offline dynamic model **261** of AD **20** to match historical operation data from AD **20**. During this offline phase, extensive data, both available historical measured output data, historical measured input data, as well as historical offline lab-analysis data from over a period of operation are used to identify the states and estimated parameters of the offline dynamic model **261** of AD **20**. Once the estimated model parameters and states of offline dynamic model **261** of AD **20** are identified, they are imported from offline dynamic model **261** of AD **20** into the online dynamic model **262** of AD **20**. The online dynamic model **262** of AD **20** is used in AD online EKF **252**, such as the one shown in FIG. **11**, for online monitoring, wherein real time measured output data and real time measured input data from AD **20** online sensor data is used to estimate model predicted outputs and model based inferred variables of AD **20**. In the online estimation, one unknown is the variation in the feed composition to AD **20**, e.g. mix of carbohydrates, fats and proteins, alkalinity, and VFA. The AD online EKF **252** is used to estimate the unknown/varying feed compositions along with any adapted model parameters that are likely to vary frequently and are prudent for monitoring, such as the inhibition of methanogenesis kinetics due to a toxic ingredient in the feed. Once the unknown feed composition is identified correctly, the model based inferred variables (e.g. biomass concentration, alkalinity, VFA, etc.) provides a "virtual" estimate of these unmeasured variables for more complete online monitoring. Traditionally, these model based inferred variables were ascertained via offline laboratory testing and not available in real time through actual real time sensors. Accordingly, AD online EKF **252** provides a real time estimated value for these model based inferred variables.

[0271] FIG. **12*a*** is a flow chart of a method of operating AD **20** through online monitoring and control of AD **20** using the AD offline and online EKFs **251** and **252** and control system **200**. Steps **100-135** and **145-150** are monitoring steps of AD **20** and step **140** is a controlling step of AD **20**.

[0272] In step **100**, the monitoring of AD **20** is commenced by AD offline EKF **251** having an offline dynamic model **261** of AD **20**, providing an AD online EKF **252** having an online dynamic model **262** of AD **20**. The online and offline dynamic models **261** and **262** of AD **20** have states, process material balances, energy balances and biochemical reaction kinetics. The offline dynamic model **251** and online dynamic model **252** of AD **20** have both estimated parameters and adapted model parameters. The adapted model parameters are a subset of the estimated parameters.

[0273] The estimated parameters of offline dynamic model **261** of AD **20** and adapted model parameters of online dynamic model **262** of AD **20** are comprised of kinetic parameters and stoichiometric coefficients for reactions of at least one of insoluble organics hydrolysis, acedogenesis, acetogenesis, acetoclastic methanogenesis, hydrogen methanogenesis, and biomass growth.

[0274] The material balances in said online and offline dynamic models **261** and **262** of AD **20** are comprised of insoluble organics, soluble substrates, VFA, organic carbon, inorganic carbon and alkalinity. The insoluble organics is comprised of carbohydrates, protein and fat. Further, soluble substrate and VFA include at least one of glucose, LCFA, amino acid, acetate acid, propionate acid and biomass for acedogenesis, acetogenesis, acetoclastic methanogenesis and hydrogen methanogenesis bio-chemical processes. Additionally, organic carbon is comprised of organics and methane from biogas. Further, inorganic carbon is comprised of at least one of carbon dioxide, carbonate and bicarbonate. Additionally, alkalinity is comprised of alkalinity associated with bicarbonate, VFA, added alkali, and generation of ammonia and hydrogen sulfide.

[0275] The bio-chemical reaction kinetics in online and offline dynamic models **261** and **262** of AD **20** are comprised of at least one of insoluble organics hydrolysis, acedogenesis, acetogenesis, acetoclastic methanogenesis, hydrogen methanogenesis, and biomass growth.

[0276] In some embodiments, limits are applied to one or more of the estimated parameters, adapted model parameters, and states. Further, in some embodiments, constraints are applied to one or more of the model-predicted outputs and model based inferred variables. These limits and constraints can be lower and upper limits specified by a person having ordinary skill in the art based on the person's knowledge of the process and application.

[0277] In step **105**, historical operation data for AD **20** is obtained. The historical operation data includes measured input data, measured output data, and laboratory analysis data. More specifically, historical operation data of AD **20** may include at least one of liquid flow rates, gas flow rates, biogas compositions, TOC in liquid streams, TIC in liquid streams, AD pH, and ammonia in AD effluent. Further, biogas compositions include one or more of methane, carbon dioxide, and hydrogen sulfide

[0278] In step **110**, estimated parameters and states of the offline dynamic model **261** of AD **20** are identified using the AD offline EKF **251** and the historical operation data for AD **20**. At least one of the estimated parameters of offline dynamic model **261** of AD **20** is estimated with confidence intervals, which are the estimated variances corresponding to the estimated parameters of offline dynamic model **261** of AD **20**. Stated alternatively, the confidence intervals are determined by their corresponding variances, normally assumed as Normal distribution, therefore 95% confidence intervals are approximate four times of the standard deviations.

[0279] The estimated parameters of the offline dynamic model **261** are identified by AD offline EKF **251** simulating one time step of the historical operation data for AD **20** to update values for the estimated parameters, model predicted outputs, states, and covariance estimates and develop model based inferred variables. In one embodiment, a dynamic nonlinear model of AD **20** and measured input data are used to simulate and update the estimated parameters, model predicted outputs, states, and model based inferred variables. A linearized dynamic model of AD **20** is used to simulate and update the covariance estimate.

[0280] Once estimated, the values for the model predicted outputs and model based inferred variables are compared to the actual historical values, if available. Based on the comparison, the model predicted outputs, model based inferred variables, and covariance values are adjusted, if necessary for the estimated values to agree with the actual values. AD offline EKF **251** then simulates the next historical data time step.

[0281] The method progresses to step **115** once AD offline EKF **251** simulates all of the historical data time steps or a user intervenes.

[0282] In step **115**, the estimated parameters of the offline dynamic model **261** of said AD **20** are imported into the online dynamic model **262** of AD **20**.

[0283] In step **120**, real time operation data for AD **20** is provided to AD online EKF **252**. The real time operation data is comprised of measured input data and measured output data of AD **20**. More specifically, real time operation data of AD **20** may include at least one of liquid flow rates, gas flow rates, biogas compositions, TOC in liquid streams, TIC in liquid streams, AD pH, and ammonia in AD effluent. Further, biogas compositions include one or more of methane, carbon dioxide, and hydrogen sulfide

[0284] In step **125**, model based inferred variables of AD **20** are updated using AD online EKF **252**, the online dynamic model **262** of AD **20**, measured input data of AD **20**, and measured output data of AD **20**. Optionally, in step **125**, model predicted outputs are calculated using AD online EKF **252**, the online dynamic model **262** of AD **20**, measured input data of AD **20**, and measured output data of AD **20**. At least one of the model based inferred variables of online dynamic model **262** of AD **20** is estimated with confidence intervals, which are the estimated variances corresponding to the model based inferred variables of online dynamic model **262** of AD **20**. Stated alternatively, the confidence intervals are determined by their corresponding variances, normally assumed as Normal distribution, therefore 95% confidence intervals are approximate four times of the standard deviations. The model based inferred variables of online dynamic model **262** of AD **20** are comprised of at least one of feed composition, biomass activity, and biomass concentration.

[0285] In step **130**, one or more adapted model parameters and model based inferred variables of AD **20** are provided to an operator of AD **20**. It is understood that offline laboratory testing providing results corresponding to some of the model based inferred variables of AD **20** will still take place and be recorded for use as historical operation data for tuning purposes, and provided to the operator.

[0286] In step **135**, the adapted model parameters of the online dynamic model **262** of AD **20** are tuned by comparing the measured output data of AD **20** and model predicted outputs of AD **20**, and adjusting the adapted model parameters of the online dynamic model **262** of AD **20**, such that the measured output data of AD **20** substantially corresponds with the model predicted outputs of AD **20**. It is contemplated that in some embodiments, the adapted model parameters of online dynamic model **262** of AD **20** can be further turned using different weights for online measurements and prior knowledge of measurement accuracy.

[0287] In step **140**, control system **200** is provided with measured input data of AD **20**, measured output data of AD **20**, estimated parameters of online dynamic model **262** of the AD **20**, adapted model parameters of online dynamic model **262** of the AD **20**, and model based inferred variables of AD **20** to control at least one of a nutritional additive concentration of AD reactor **24**, a nutritional additive concentration of PA reactor **22**, pH of AD reactor **24**, pH of PA reactor **22**, biomass concentration of AD reactor **24**, fluid level of said PA reactor **22**, and a recycle flow rate of said AD **20**.

[0288] Control system **200** has an AD supervisory control system **201** and an AD low level control system **202**. AD supervisory control system **201** is comprised of at least one of an AD reactor pH supervisory controller **700**, a PA reactor pH supervisory controller **701**, and an PA:AD overall recycle flow ratio supervisory controller **720**.

[0289] AD reactor pH supervisory controller **700** is comprised of an AD reactor nonlinear PI pH controller **705** and an AD reactor P alkalinity controller **710** in a cascaded configuration. PA reactor pH supervisory controller **701** is comprised of a PA reactor nonlinear PI pH controller **706** and a PA reactor P alkalinity controller **711** in a cascaded configuration.

[0290] PA:AD overall recycle flow ratio supervisory controller **720** is comprised of a PA:AD recycle ratio controller **725** and a PA reactor and AD reactor recycle flow rate controller **730**.

[0291] AD low-level control system **202** is comprised of at least one of an AD reactor biomass concentration controller **735**, a PA reactor fluid level controller **737**, a PA reactor nutritional additive concentration controller **51**, and an AD reactor nutritional additive concentration controller **61**.

[0292] In step **145**, normally the method progresses to step **120** for the next time point operation. However, if the adapted model parameters of online dynamic model **262** of AD **20** need to be adjusted after operating for a period of time (e.g. reporting incorrect or inconsistent values for model predicted outputs and model based inferred variables), historical data for AD **20** is obtained and the method returns to step **110**. Optionally, in some embodiments of step **145**, the adapted model parameters are imported from online dynamic model **262** of AD **20** into offline dynamic model **261** of AD **20** before the method returns to step **110**. This importing of the adapted model parameters from online dynamic model **262** of AD **20** into offline dynamic model **261** of AD **20** helps the estimated parameters converge faster when they are re-identified in the offline dynamic model **261** using AD offline EKF **251**.

[0293] FIG. **12***b* is a flow chart of another embodiment of a method of operating AD **20** through monitoring and control of AD **20** using the AD offline and online EKFs **251** and **252** and control system **200**. Steps **160**-**172** and **176** are monitoring steps of AD **20** and step **174** is a controlling step of AD **20**.

[0294] As can be seen, AD **20** is comprised of AD offline and online EKFs **251** and **252** and control system **200**. AD **20** further has an AD reactor **24**, which can be a CSTR, UASB, EGSB, mixed bed, moving bed, low-rate, or high-rate reactor. In some embodiments, AD **20** also has a PA reactor **22**. When both are present, the AD reactor **24** and PA reactor **22** are modeled separately in both of the online and offline models **261** and **262** of AD **20**. Further, in some embodiments, AD **20** has a mixing stage and at least one recycle line. The recycle line can be a PA reactor recycle line or an AD reactor recycle line.

[0295] In step **160** of a method of operating AD **20**, AD offline extended Kalman filter (EKF) **251** having an offline dynamic model **261** of AD **20** is provided, and AD online EKF **252** having online dynamic model **262** of AD **20** is provided. The offline and the online dynamic models **261** and **262** of AD **20** are comprised of states, process material balances, energy balances, bio-chemical reaction kinetics, estimated parameters, and adapted model parameters. The adapted model parameters are a subset of the estimated parameters.

[0296] The materials for the process materials balances of the online and offline dynamic models **261** and **262** of AD **20** are comprised of insoluble organics, soluble substrates, VFA, biomass, inorganic carbon and alkalinity. The insoluble organics is comprised of carbohydrates, protein and fat. The soluble substrate and VFA include at least one of sugars, LCFA, amino acids, acetate acid, or propionate acid. The biomass includes biomass for acedogenesis, acetogenesis, acetoclastic methanogenesis and hydrogen methanogenesis bio-chemical processes. The inorganic carbon is comprised of at least one of carbon dioxide, carbonate, or bicarbonate. The alkalinity is comprised of alkalinity associated with bicarbonate, VFA, added alkali, and generation of ammonia and hydrogen sulfide. The bio-chemical reaction kinetics in said online and offline dynamic models of said AD are comprised of at least one of insoluble organics hydrolysis, acedogenesis, acetogenesis, acetoclastic methanogenesis, or hydrogen methanogenesis process.

[0297] Additionally, the estimated parameters and adapted model parameters of the offline dynamic model **261** of AD **20** and the online dynamic model **262** of AD **20** are comprised of at least one of PA reactor composite fraction of carbohydrate, PA reactor composite fraction of fat, PA reactor composite fraction of protein, PA reactor fraction of insoluble convertible to SBOD, PA reactor acedogenthese reaction coefficient, PA reactor biomass decay rate, PA reactor insoluble hydrolysis reaction coefficient, PA reactor insoluble flow out coefficient, PA reactor CO_2 escape coefficient, AD reactor composite fraction of carbohydrate, AD reactor composite fraction of fat, AD reactor composite fraction of protein, AD reactor fraction of insoluble convertible to SBOD, AD reactor acedogenthese reaction coefficient, AD reactor acetogenesis reaction coefficient, AD reactor acetoclastic methanogenesis reaction coefficient, AD reactor hydrogen methanogenesis reaction coefficient, AD reactor biomass decay rate, PA reactor insoluble hydrolysis reaction coefficient, or PA reactor insoluble flow out coefficient. At least one of the estimated parameters of the offline dynamic model **261** of AD **20** and the model based inferred variables of the online dynamic model **262** of AD **20** are estimated with confidence intervals.

[0298] In step **162**, historical operation data of AD **20** is provided. The historical operation data is comprised of historical measured input data, historical measured output data, and historical laboratory analysis data. More specifically, in some embodiments, the historical operation data of AD **20** is comprised of at least one of raw influent pH, raw influent temperature, raw influent flow rate, raw influent TOC, raw influent TIC, added alkali flow rate, PA reactor fluid level, AD feed flow rate, raw influent SCOD, raw influent TCOD, raw influent SBOD, raw influent VSS, raw influent TSS, raw influent soluble inorganic nitrogen, raw influent VFA, added alkali concentration, PA reactor pH, PA effluent TOC, PA effluent TIC, AD biogas flow rate, AD biogas CH_4 concentration, AD Biogas CO_2 concentration, AD reactor pH, AD effluent TOC, AD effluent TIC, AD effluent VFA, AD effluent alkalinity, AD reactor MLVSS, AD effluent TCOD, AD effluent SCOD, AD effluent VSS, or AD effluent TSS.

[0299] In step **164**, estimated parameters of offline dynamic model **261** of AD **20** are identified using AD offline EKF **251** and the historical operation data for AD **20**.

[0300] In step **166**, the estimated parameters identified in step **164** are imported from the offline dynamic model **261** of AD **20** into the online dynamic model **262** of AD **20**.

[0301] In step **168**, real time operation data for AD **20** is provided to AD online EKF **252**. The real time operation data is comprised of real time measured input data and real time measured output data of AD **20**. More specifically, in some embodiments of AD **20**, the real time operation data of AD **20** is comprised of at least one of raw influent pH, raw influent temperature, raw influent flow rate, raw influent TOC, raw influent TIC, added alkali flow rate, PA reactor fluid level, AD feed flow rate, raw influent SCOD, raw influent TCOD, raw influent SBOD, raw influent VSS, raw influent TSS, raw influent soluble inorganic nitrogen, raw influent VFA, added alkali concentration, PA reactor pH, PA effluent TOC, PA effluent TIC, AD biogas flow rate, AD biogas CH_4 concentration, AD Biogas CO_2 concentration, AD reactor pH, AD effluent TOC, AD effluent TIC, AD effluent VFA, AD effluent alkalinity, AD reactor MLVSS, AD effluent TCOD, AD effluent SCOD, AD effluent VSS, or AD effluent TSS.

[0302] In step **170**, the adapted model parameters of the online dynamic model **262** of AD **20** are updated and the model based inferred variables of AD **20** are estimated using the AD online EKF **252**, the online dynamic model of AD **20**, the real time measured input data of AD **20**, and the real time measured output data of AD **20**.

[0303] The model based inferred variables of the online dynamic model **262** of AD **20** are comprised of at least one of the following unmeasured inputs or outputs of AD **20**: raw influent insoluble COD, raw influent insoluble inert COD, raw influent soluble inert COD, raw influent SBOD saccharide, raw influent SBOD LCFA, raw influent SBOD amino acid, raw influent propionate acid, raw influent acetate acid, raw influent inorganic carbon content, raw influent alkalinity, raw influent inorganic nitrogen, raw influent SCOD, raw influent TCOD, raw influent SBOD, PA reactor alkalinity, PA reactor VFA, PA reactor temperature, PA reactor SCOD, PA reactor TCOD, PA reactor SBOD, AD reactor alkalinity, AD reactor VFA, AD reactor temperature, AD reactor SCOD, AD reactor SBOD, AD reactor acedogenthese biomass, AD reactor acetogenesis biomass, AD reactor acetoclastic methanogenesis biomass, AD reactor hydrogen methanogenesis biomass, AD reactor insoluble COD, AD reactor insoluble inert COD, AD reactor soluble inert COD, AD reactor SBOD saccharide, AD reactor SBOD LCFA, AD reactor SBOD amino acid, AD reactor propionate acid, AD reactor acetate acid, AD reactor inorganic carbon content, AD reactor alkalinity, AD reactor inorganic nitrogen, AD reactor SCOD, AD reactor TCOD, AD reactor SBOD, SCOD conversion rate, CH_4 conversion efficiency, or recycle flow rate.

[0304] In step **172**, one or more of the adapted model parameters of the online dynamic model **262** of AD **20** and one or more of the model based inferred variables of AD **20** are provided to an operator of AD **20**.

[0305] In step **174**, control system **200** of AD **20** is provided with one or more of the real time measured input data of AD **20**, real time measured output data of AD **20**, estimated parameters of the online dynamic model of AD **20**, or model based inferred variables of AD **20**. AD control system **200** uses this information to control at least one of a nutritional additive concentration of said AD reactor **24**, a nutritional additive concentration of said PA reactor **22**, pH of said AD reactor **24**, pH of said PA reactor **22**, biomass concentration of said AD reactor **24**, fluid level of said PA reactor **22**, or a recycle flow rate of said AD **20**.

[0306] Wherein controlling said nutritional additive concentration of said AD **20** prevents biomass overfeeding and starvation, wherein controlling said nutritional additive concentration of said PA reactor **22** prevents biomass overfeeding and starvation, wherein controlling said pH of said AD reactor **24** minimizes alkali dosing, wherein controlling said pH of said PA reactor **22** minimizes alkali dosing, wherein controlling said biomass concentration of said AD reactor **24** offsets biomass inhibition and saves alkali, wherein controlling a recycle flow rate to said PA reactor **22** minimizes alkali dosing and maintains fluid level of said PA reactor **22**, and wherein controlling a recycle flow rate of said AD reactor **24** maximizes COD conversion and biogas generation.

[0307] AD control system **200** is comprised of an AD supervisory control system **201** and an AD low-level control system **202**. The AD supervisory control system **201** is comprised of at least one of an AD reactor pH supervisory controller **700**, a PA reactor pH supervisory controller **701**, or an PA:AD overall recycle flow ratio supervisory controller **720**.

[0308] AD reactor pH supervisory controller **700** is comprised of an AD reactor nonlinear Proportion-Integration (PI) pH controller **705** and an AD reactor Proportion (P) alkalinity controller **710** in a cascaded configuration. PA reactor pH supervisory controller **701** is comprised of a PA reactor nonlinear PI pH controller **706** and a PA reactor P alkalinity controller **711** in a cascaded configuration. The PA:AD overall recycle flow ratio supervisory controller **720** is comprised of a PA:AD recycle ratio controller **725**, and a PA reactor and AD reactor recycle flow rate controller **730**.

[0309] In some embodiments, at least one of AD reactor pH supervisory controller **700** or PA reactor pH supervisory controller **701** uses a model based inferred variable of AD **20**, including, but not limited to, the alkalinity of PA reactor **22** or AD reactor **24**. Further, in some embodiments, at least one of said AD reactor pH supervisory controller **700** or PA reactor pH supervisory controller **701** has a feedforward control action which uses a model based inferred variable of said AD **20**, including, but not limited to, raw influent alkalinity.

[0310] AD low-level control system **202** is comprised of at least one of an AD reactor biomass concentration controller **735**, a PA reactor fluid level controller **737**, a PA reactor nutritional additive concentration controller **51**, or an AD reactor nutritional additive concentration controller **61**.

[0311] In some embodiments, at least one of the AD reactor biomass concentration controller **735**, PA reactor nutritional additive concentration controller **51**, or said AD reactor nutritional additive concentration controller **61** uses at least one of the estimated parameters of the online dynamic model **262** of AD **20** or a model based inferred variable of AD **20**, including, but not limited to, at least one of reaction coefficients and biomass concentrations for hydrolysis, acedogenthese, acetogenesis, acetoclastic methanogenesis, or hydrogen methanogenesis processes.

[0312] In step **176**, the AD operator, or an automated system such as computer **1071**, decides whether it is necessary to adjust the adapted model parameters of the online dynamic model **262** of AD **20** (e.g. reporting incorrect or inconsistent values for model predicted outputs or model based inferred variables). If it is not necessary to adjust the adapted model parameters, the method returns to step **168**.

[0313] In some embodiments, the decision of whether or not to adjust the adapted model parameters is determined by elapsed time, such as an adjustment of the adapted model parameters using the online EKF approach is performed about every 30 minutes to once a day, and an adjustment of the adapted model parameters using the offline EKF approach is performed about every few weeks to few months.

[0314] If it is necessary to adjust the adapted model parameters, the operator can choose to use one or both of an online EKF approach or an offline EKF approach to update the adapted model parameters of the online dynamic model **262**. Traditionally, the offline EKF approach is only used periodically, in some embodiments about every few weeks or months. The online EKF approach is used more frequently, in some embodiments as frequently as about every 30 minutes.

[0315] In the online EKF approach, model predicted outputs of AD **20** are calculated using AD online EKF **252**, online dynamic model **262** of AD **20**, real time measured input data of AD **20**, and real time measured output data of AD **20**. The measured output data of AD **20** and the model predicted outputs of AD **20** are then compared, and the adapted model parameters of online dynamic model **262** of AD **20** are updated such that the real time measured output data of AD **20** substantially correspond with the model predicted outputs of AD **20**.

[0316] In the offline EKF approach, the estimated parameters of the offline dynamic model **261** of AD **20** are re-identified using the AD offline EKF **251** and the historic operation data for AD **20**. The estimated parameters of offline dynamic model **261**, which contain the updated adapted model parameters as a subset, are then imported into the online dynamic model **262**.

[0317] In some embodiments of the offline EKF approach, the adapted model parameters of the online dynamic model **262** of AD **20** are imported into the offline dynamic model **261** of AD **20** before the estimated parameters of the offline dynamic model **261** of AD **20** are re-identified. This allows the estimated parameters of the offline dynamic model **261** to converge faster when they are re-identified by AD offline EKF **251**.

[0318] After step **176**, the method returns to step **168** to provide more real time operation data of AD **20** for the next time point to the AD online EKF **252**.

[0319] It is contemplated that in some embodiments of this method, the adapted model parameters of the online dynamic model **262** of AD **20** can be tuned using different weights for online measurements and prior knowledge of measurement accuracy. Further, it is contemplated that in some embodiments of the method described above, limits are applied to one or more of said estimated parameters and said adapted model parameters; wherein constraints are applied to one or more of said model based inferred variables.

[0320] It is contemplated that in some embodiments, at least one of monitoring AD **20** or controlling AD **20** is performed using a computer.

[0321] It is contemplated that the method of operating AD **20** includes variations of the methods depicted in FIGS. **12***a-b*. Some embodiments of such methods may be arrived at by substituting steps or underlying details of one of **12***a* or **12***b*, and using the steps or underlying details in the other of **12***a* or **12***b*.

[0322] Further, it is contemplated that the method of operating AD **20** depicted in FIGS. **12***a-b* can be combined with the method of operating MBR **30** depicted in FIGS. **16***a-b* to arrive at a method for operating WWTP **10** having one or both of AD **20** and MBR **30**.

[0323] As was previously stated, the developed model of MBR **30** is used as the basis for a method of online monitoring and control of the MBR **30** of wastewater treatment plant **10**. More specifically, for online monitoring of the MBR **30**, a set of online sensors are used along with model-based estimation of variables not measured directly, but estimated through the use of a constrained Extended Kalman Filter. FIG. **13** shows the overall architecture for monitoring an embodiment of MBR **30** with control system **300**, using a combination of online sensors that measure the measured input data and measured output data of MBR **30**. An extended Kalman filter **350** containing the dynamic model **360** of MBR **30** discussed above uses the measured input data and measured output data of MBR **30** to estimate model parameters, model states, adapted model parameters, model predicted outputs, and model based inferred variables of dynamic model **360**.

[0324] The comparison of the estimated and actual values of the measured output data, offline laboratory testing data and estimated values of model predicted outputs and model based inferred variables by extended Kalman filter **350** estimate values for the estimated parameters, states, and adapted model parameters of dynamic model **360** of MBR **30**.

[0325] Below are exemplary lists of measured output data, measured input data, estimated parameters, adapted model parameters, model predicted outputs, and model based inferred variables for MBR **30** of WWTP **10**. MBR **30** has an MBR control system **300**, MBR online EKF **352**, and MBR offline EKF **351**.

Model Based Inferred Variables	
Outputs	**Inputs**
Anoxic Tank SCOD	Raw Influent Alkalinity
Anoxic Tank MLVSS	Raw Influent Nitrate nitrogen
Anoxic Tank Nitrate nitrogen	Raw Influent Ammonia-nitrogen
Anoxic Tank Ammonia-nitrogen	Raw Influent SCOD
Anoxic Tank Biodegradable COD	Raw Influent TCOD
Aerobic Tank SOCD	Raw Influent Readily Biodegradable COD
Aerobic Tank MLVSS	Raw Influent Slowly Biodegradable COD
Aerobic Tank Nitrate nitrogen	Raw Influent VSS
Aerobic Tank Ammonia-nitrogen	Raw Influent TSS
Aerobic Tank Biodegradable COD	Raw Influent Inorganic Inert Particulate
Membrane Tank MLVSS	
Membrane Permeate SCOD	
Membrane Permeate Biodegradable COD	
Membrane Permeate TCOD	
Membrane Permeate Nitrate nitrogen	
Membrane Permeate Ammonia-nitrogen	
Wasting Sludge MLVSS	
COD Removal Rate	
Nitrogen Removal Rate	

Estimated Parameters and Adapted Model Parameters	Updated By Online EKF (Adapted Model Parameters)	Estimated By Offline EKF (Estimated Parameters)
Hetrotrophic maximum specific growth rate	X	X
Anoxic/Aerobic hetrotroph growth rate	X	X
Anoxic/Aerobic hydrolysis rate fraction		X
Particulate hydrolysis max specific rate constant		X
Autotrophic maximum specific growth rate	X	X
Decay constant for hetrotrophs		X
Decay constant for autotrophs		X
Yield of hetrotrophic biomass	X	X
Yield of autotrophic biomass	X	X
Carbon content in soluble substrate		X
Carbon content of particulate substrate		X
Carbon content of soluble inert		X
Carbon content of particulate nondegradable organic		X

-continued

Estimated Parameters and Adapted Model Parameters	Updated By Online EKF (Adapted Model Parameters)	Estimated By Offline EKF (Estimated Parameters)
Mass transfer coeff for O_2 removal in Aerobic tank		X
Mass transfer coeff for CO_2 removal in Anoxic tank		X

Measured Input Data	Online	Offline
Raw Influent pH	X	X
Raw Influent Temperature	X	X
Raw Influent Flow Rate	X	X
Raw Influent TOC	X	X
Raw Influent TIC	X	X
Added Alkali Flow Rate	X	X
Added Alkali concentration		X
Effluent Flow Out Rate	X	X
Raw Influent SCOD		X
Raw Influent TCOD		X
Raw Influent Readily Biodegradable COD		X
Raw Influent Slowely Biodegradable COD		X
Raw Influent VSS		X
Raw Influent TSS		X
Raw Influent Nitrate nitrogen		X
Raw Influent Ammonia-nitrogen		X
Raw Influent Soluble Biodegradable Organic Nitrogen		X
Raw Influent Particulate Degradable Organic Nitrogen		X
Raw Influent Inorganic Inert Particulate		X
Membrane Permeate Flow Rate	X	X
Wasting Sludge Flow Rate	X	X
Anoxic Tank Addition Biodegradable COD Flow	X	X

Measured Output Data & Model Predicted Outputs	Online	Offline
Anoxic Tank Reactor pH	X	X
Anoxic Tank Dissolved Oxygen	X	X
Anoxic Tank Temperature	X	X
Anoxic Tank Liquid Level	X	X
Anoxic Tank MLVSS		X
Anoxic Tank MLSS	X	X
Aerobic Tank Blower Air Flow Rate	X	X
Aerobic Tank Reactor pH	X	X
Aerobic Tank Alkalinity	X	X
Aerobic Tank MLVSS		X
Aerobic Tank MLSS	X	X
Aerobic Tank Dissolved Oxygen	X	X
Aerobic Tank Temperature	X	X
Aerobic Tank Liquid Level	X	X
Membrane Tank MLSS	X	X
Membrane Tank MLVSS		X
Membrane Permeate SCOD		X
Membrane Permeate TCOD		X
Membrane Permeate TOC	X	X
Membrane Permeate TIC	X	X
Membrane Permeate Nitrate nitrogen	X	X
Membrane Permeate Ammonia-nitrogen	X	X
Wasting Sludge MLSS	X	X
Wasting Sludge MLVSS		X

[0326] It is understood that the lists above of measured output data, measured input data, estimated parameters, adapted model parameters, model predicted outputs, and model based inferred variables are exemplary, can vary from one application to another application, and can be established by a person having ordinary skill in the art when examining a particular MBR of interest based on the person's knowledge of the process and application. Further, it is understood that the adapted model parameters are a subset of the estimated parameters, which are more extensive. Additionally, it is understood that the model based inferred variables include both unmeasured inputs and outputs for MBR **30**.

[0327] FIG. **14** shows the overall architecture for the MBR offline EKF **351** containing a model **360** of MBR **30** for parameter identification and adaption of an embodiment of MBR **30** having control system **300**. Control system **300** has a supervisory control system **301** and a low-level control system **302**.

[0328] FIG. **15** shows the overall architecture of an MBR online EKF **352** containing a model of MBR **30** for real-time monitoring/virtual sensing/controlling of an embodiment of MBR **30** having control system **300**.

[0329] Additionally, it is understood that in some embodiments of WWTP **10**, if an MBR **30** is located upstream of AD **20**, some of the model based inferred variables calculated by MBR online EKF **352** using online dynamic model **362** of MBR **30**, such as the composition and flow rate of MBR effluent, are provided to AD **20** by MBR online EKF **352**, therefore enabling feed forward control of AD **20** by AD control system **200** which uses the provided data as inputs. It is understood that the information provided regarding the composition of the effluent includes multiple pieces of information, such as the individual amounts of elements and compounds contained in the effluent (e.g. Nitrogen, Oxygen, etc.).

[0330] Additionally, it is understood that in some embodiments of WWTP **10**, if an AD **20** is located upstream of MBR **30**, some of the model based inferred variables calculated by AD online EKF **252** using AD online model **262** of AD **20**, such as the composition and flow rate of AD effluent, are provided to MBR **30** by AD online EKF **252**, therefore enabling feed forward control of MBR **30** by MBR control system **300** which uses the provided data as inputs. It is understood that the information provided regarding the composition of the effluent includes multiple pieces of information, such as the individual amounts of elements and compounds contained in the effluent (e.g. Nitrogen, Oxygen, etc.).

[0331] Further, the states for offline dynamic model **361** of MBR **30** in MBR offline EKF **351** and online dynamic model **362** of MBR **30** in MBR online EKF **352**, are defined above in equation 14.

[0332] Further, it is understood that both offline dynamic model **361** of MBR **30** and online dynamic model **362** of MBR **30** both contain estimated parameters and adapted model parameters, a subset of the adapted model parameters. Accordingly, the structures of offline dynamic model **361** of MBR **30** and online dynamic model **362** of MBR **30** are the same. However, all of the estimated parameters are identified by MBR offline EKF **351** in offline dynamic model **361** of MBR **30**. Meanwhile, only the adapted model parameters are identified (updated) in the online dynamic model **362** of MBR **30** by MBR online EKF **352**. Further, it is understood that the offline dynamic model **361** of MBR **30** and online dynamic model **362** of MBR **30** are based on first principles with physical meanings for the respective estimated parameters and adapted model parameters with unknown values (e.g., the reaction rate kinetic parameter) whose values are estimated by best fitting.

[0333] It is understood that the measured input data and measured output data is data obtained from physical sensors of MBR **30**. Further, model based inferred variables are virtual sensors that have traditionally only been available through periodic offline testing. A model based inferred variable of MBR **30** is a "virtual sensed" variable that is estimated by the MBR online EKF **352** using the online dynamic model **362** of MBR **30**, real time measured input data of MBR **30**, and real time measured output data of MBR **30**. The model based inferred variables of MBR **30** are first developed by the MBR online EKF **351** using offline dynamic model **361** of MBR **30**, historical measured input data of MBR **30**, historical measured output data of MBR **30**, and historical offline testing data of MBR **30**. It is understood that the model based inferred variables include both unmeasured inputs and outputs of MBR **30**.

[0334] A model predicted output is an output of MBR **30** that is estimated by the MBR offline EKF **351** and MBR online EKF **352**. The MBR offline EKF **351** estimates the model predicted outputs of MBR **30** using offline dynamic model **361** of MBR **30**, historical measured input data of MBR **30**, historical measured output data of MBR **30**, and historical offline testing data of MBR **30**. The MBR online EKF **352** estimates the model predicted outputs of MBR **30** using the online dynamic model **362** of MBR **30**, real time measured input data, and real time measured output data. It is understood that each model predicted output of MBR **30** corresponds to a measured output of MBR **30**. Estimated parameters are parameters that are identified in the offline dynamic model **361** of MBR **30** located in MBR offline EKF **351**, such that for a given historical input data value, the predicted historical output data value or model based inferred variable value matches the corresponding actual historical output data value or actual offline laboratory testing value. The estimated parameters from the offline dynamic model **361** of MBR **30** located in MBR offline EKF **351** are imported into the online dynamic model **362** of MBR **30** located in MBR online EKF **352**. The adapted model parameters are a subset of the estimated parameters, which are updated in the MBR online EKF **352**. The MBR online EKF **352** is used to generate real time estimated values for the model predicted outputs and model based inferred variables of MBR **30**.

[0335] In one embodiment of a method of monitoring and controlling MBR **30**, initially an MBR offline EKF **351**, such as the one shown in FIG. **14**, is used to identify estimated parameters (e.g. reaction kinetics) and states for the offline dynamic model **361** of MBR **30** to match historical operation data from MBR **30**. During this offline phase, extensive data, both available historical measured output data, measured input data, as well as offline lab-analysis data from over a period of operation are used to identify the states and estimated parameters of the offline dynamic model **361** of MBR **30**. Once the model parameters of offline dynamic model **361** of MBR **30** are identified, the estimated parameters are imported from offline dynamic model **361** of MBR **30** into the online dynamic model **362** of MBR **30**. The adapted model parameters, a subset of the estimated parameters, are updated by the online EKF **352** of MBR **30**. The online dynamic model **362** of MBR **30** is used in MBR online EKF **352**, such as the one shown in FIG. **15**, for online monitoring, wherein real time measured output data and measured input data from MBR **30** online sensor data is used. In the online estimation, one unknown is the variation in the feed composition to MBR **30**. The MBR online EKF **352** is used to estimate the unknown/varying feed compositions along with any adapted model parameters that are likely to vary frequently and are prudent for monitoring, such as the inhibition of aerobic bio-chemical reaction kinetics due to a toxic ingredient in the feed. Once the unknown feed composition is identified correctly, the model based inferred variables (e.g. biomass concentration, alkalinity, VFA, etc.) provides a "virtual" estimate of these unmeasured variables for more complete online monitoring. Traditionally, these model based inferred variables were ascertained via offline laboratory testing and not available in real time through actual real time sensors. Accordingly, MBR online EKF **352** provides a real-time estimated value for these model based inferred variables.

[0336] FIG. **16*a*** is a flow chart of a method of operating MBR **30** through online monitoring and control of MBR **30** using the MBR offline and online EKFs **351** and **352** and control system **300**. Steps **400-435** and **445-450** are monitoring steps of MBR **30** and step **440** is a controlling step of MBR **30**.

[0337] In step **400**, the monitoring of MBR **30** is commenced by MBR offline EKF **351** having an offline dynamic model **361** of MBR **30**, providing an MBR online EKF **352** having an online dynamic model **362** of MBR **30**. The online and offline dynamic models **361** and **362** of MBR **30** have states, process material balances, energy balances and bio-chemical reaction kinetics. The offline dynamic model **351** and online dynamic model **352** of MBR **30** both have estimated parameters and adapted model parameters. The adapted model parameters are a subset of the estimated parameters.

[0338] The estimated parameters of offline dynamic model **361** of MBR **30** and adapted model parameters of online dynamic model **362** of MBR **30** are comprised of kinetic parameters and stoichiometric coefficients for reactions of at least one of insoluble organics hydrolysis, heterotrophic, autotrophic, ammonification, biomass decay, and biomass growth.

[0339] The material balances in said online and offline dynamic models **361** and **362** of MBR **30** are comprised of particulate inert, slowly degradable substrate, heterotrophic biomass, autotrophic biomass, decayed biomass, soluble inert, soluble readily degradable substrate, dissolved oxygen, dissolved nitrate-N(Nitrogen), dissolved ammonia-N, particulate bio-degradable-N, and bicarbonate alkalinity. The insoluble organics are converted to soluble COD via hydrolysis process. The organic nitrogen is also converted into soluble nitrogen by hydrolysis. Other bio-chemical reactions include material aerobic heterotroph, anoxic heterotroph, aerobic autotroph, decay of heterotroph, decay of autotroph, and ammonification of soluble organic N. The inorganic carbon is comprised of at least one of carbon dioxide, carbonate and bicarbonate. Additionally, alkalinity is comprised of alkalinity associated with bicarbonate, VFA, added alkali, and generation of ammonia.

[0340] In some embodiments, limits are applied to one or more of the estimated parameters, adapted model parameters, and states. Further, in some embodiments, constraints are applied to one or more of the model-predicted outputs and model based inferred variables. These limits and constraints can be lower and upper limits specified by a person having ordinary skill in the art based on the person's knowledge of the process and application.

[0341] In step **405**, historical operation data for MBR **30** is obtained. The historical operation data includes measured input data, measured output data, and laboratory analysis data. More specifically, historical operation data of MBR **30** may include at least one of liquid flow rates, aeration flow rate, TOC in liquid streams, TIC in liquid streams, MBR pH, anoxic tank pH, aerobic tank pH, membrane tank pH, anoxic tank bCOD, bCOD in MBR feed, NH3-N in MBR feed, NO3-N in MBR feed, NH3-N in MBR effluent, NO3-N in MBR effluent, DO in MBR effluent, and bCOD in MBR effluent.

[0342] In step **410**, estimated parameters of the offline dynamic model **361** of MBR **30** are identified using the MBR offline EKF **351** and the historical operation data for MBR **30**. At least one of the estimated parameters of offline dynamic model **361** of MBR **30** is estimated with confidence intervals, which are the estimated variances corresponding to the estimated parameters of offline dynamic model **361** of MBR **30**. Stated alternatively, the confidence intervals are determined by their corresponding variances, normally assumed as Normal distribution, therefore 95% confidence intervals are approximate four times of the standard deviations.

[0343] The estimated parameters of the offline dynamic model **361** are identified by MBR offline EKF **351** simulating one time step of the historical operation data for MBR **30** to update values for the estimated parameters, model predicted outputs, states, and covariance estimates and develop model based inferred variables. In one embodiment, a dynamic nonlinear model of MBR **30** and measured input data are used to simulate and update the estimated parameters, model predicted outputs, states, and model based inferred variables. A linearized dynamic model of MBR **30** is used to simulate and update the covariance estimate.

[0344] The method progresses to step **415** once MBR offline EKF **351** simulates all of the historical data time steps or a user intervenes.

[0345] In step **415**, the estimated parameters of the offline dynamic model **361** of said MBR **30** are imported into the online dynamic model **362** of MBR **30**.

[0346] In step **420**, real time operation data for MBR **30** is provided to MBR online EKF **352**. The real time operation data is comprised of measured input data and measured output data of MBR **30**. More specifically, real time operation data of MBR **30** may include at least one of liquid flow rates, aeration flow rates, TOC in liquid streams, TIC in liquid streams, MBR pH, anoxic tank pH, aerobic tank pH, membrane tank pH, anoxic tank bCOD, bCOD in MBR feed, NH_3—N in MBR feed, NO_3—N in MBR feed, NH_3—N in MBR effluent, NO_3—N in MBR effluent, DO in MBR effluent, and bCOD in MBR effluent.

[0347] In step **425**, model based inferred variables of MBR **30** are calculated using MBR online EKF **352**, the online dynamic model **362** of MBR **30**, measured input data of MBR **30**, and measured output data of MBR **30**. Model predicted outputs of MBR **30** are calculated using MBR online EKF **352**, the online dynamic model **362** of MBR **30**, measured input data of MBR **30**, and measured output data of MBR **30**. At least one of the model based inferred variables of online dynamic model **362** of MBR **30** is estimated with confidence intervals, which are the estimated variances corresponding to the model based inferred variables of online dynamic model **362** of MBR **30**. Stated alternatively, the confidence intervals are determined by their corresponding variances, normally assumed as Normal distribution, therefore 95% confidence intervals are approximate four times of the standard deviations. The model based inferred variables of online dynamic model **362** of MBR **30** are comprised of at least one of feed composition, biomass activity, biomass concentration, COD, MLSS, MLVSS, HRT, SRT, and reduction in O_2 mass transfer coefficient due to biomass quality changes.

[0348] In step **430**, one or more adapted model parameters and model based inferred variables of MBR **30** are provided to an operator of MBR **30**. It is understood that offline laboratory testing providing results corresponding to some of the model based inferred variables of MBR **30** will still take place and the results are recorded for use as historical operation data and are provided to the operator.

[0349] In step **435**, the adapted model parameters of the online dynamic model **362** of MBR **30** are updated by comparing the measured output data of MBR **30** and model predicted outputs of MBR **30**, and adjusting the adapted model parameters of the online dynamic model **362** of MBR **30**, such that the measured output data of MBR **30** substantially corresponds with the model predicted outputs of MBR **30**. It is contemplated that in some embodiments, the adapted model parameters of online dynamic model **362** of MBR **30** can be further tuned using different weights for online measurements and prior knowledge of measurement accuracy.

[0350] In step **440**, control system **300** is provided with measured input data of MBR **30**, measured output data of MBR **30**, estimated parameters of online dynamic model **362** of MBR **30**, adapted model parameters of online dynamic model **362** of MBR **30**, and model based inferred variables of MBR **30** to control at least one of pH of said optional anoxic tank **31**, pH of said aerobic tank **32**, fluid level of said aerobic tank **32**, DO of said aerobic tank **32**, MLSS concentration of said membrane tank **33**, bCOD addition flow rate setpoint of said anoxic tank **31**, at least one nutritional additive concentration of said optional anoxic tank **31**, and at least one recycle flow setpoint of said MBR **30**.

[0351] Control system **300** has an MBR supervisory control system **301** and an MBR low level control system **302**. MBR supervisory control system **301** is comprised of at least one of aerobic tank DO supervisory controller **1040**, anoxic tank recycle flow supervisory controller **1045**, and an anoxic tank bCOD addition flow rate supervisory control scheme **1035**.

[0352] Anoxic tank bCOD addition flow supervisory control scheme **1035** is comprised of an anoxic tank bCOD setpoint supervisory controller **1050**, an anoxic tank bCOD addition flow rate supervisory feedback controller **1055**, and an anoxic tank bCOD addition flow rate supervisory feedforward controller **1065**.

[0353] MBR low-level control system **302** is comprised of at least one of an aerobic tank fluid level PI controller **765**, an aerobic tank pH controller **750**, an anoxic tank pH controller **755**, an anoxic tank recycle line flow rate controller **770**, an aerobic tank DO concentration controller **745**, an anoxic tank nutritional additive concentration controller **777**, an aerobic tank recycle line flow rate PI controller **771**, a total MBR recycle flow rate PI controller **775**, and a membrane tank MLSS concentration controller **760**.

[0354] In step **445**, normally, the MBR online EKF **352** performs the operations of method step **420** for the next time point operation. However, if the MBR adapted model parameters of online dynamic model **362** of MBR **30** need to be adjusted after a period of time (e.g. reporting incorrect or inconsistent values for model predicted outputs), the historical data for MBR **30** is obtained, and the method returns to step **410**. Optionally, in some embodiments of step **445**, the adapted model parameters are imported from online dynamic model **362** of MBR **30** into offline dynamic model **361** of MBR **30** before the method returns to step **410**. This importing of the adapted model parameters from online dynamic model **362** of MBR **30** into offline dynamic model **361** of MBR **30** helps the estimated parameters converge faster when they are re-identified in the offline dynamic model **361** using MBR offline EKF **351**.

[0355] FIG. **16*b*** is a flow chart of another embodiment of a method of operating MBR **30** through monitoring and control of MBR **30** using the MBR offline and online EKFs **351** and **352** and control system **300**. Steps **460-472** and **476** are monitoring steps of MBR **30** and step **474** is a controlling step of MBR **30**.

[0356] As can be seen, MBR **30** is comprised of MBR offline and online EKFs **351** and **352** and control system **300**. Further, MBR **30** has an aerobic tank **32**, a membrane tank **33**, and optionally an anoxic tank **31**. Aerobic tank **32** is located upstream of membrane tank **33**, and anoxic tank **31** is located either immediately upstream or downstream of said aerobic tank **32** when said anoxic tank **31** is present. In some embodiments, MBR **30** is further comprised of a mixer **41** and at least one recycle line. The recycle line may be one or both of anoxic tank recycle line **34** or aerobic tank recycle line **36**.

[0357] In step **460** of a method of operating MBR **30**, MBR offline EKF **351** having an offline dynamic model **361** of MBR **30** is provided, and MBR online EKF **352** having online dynamic model **362** of MBR **30** is provided. The offline and the online dynamic models **361** and **362** of MBR **30** are comprised of states, process material balances, energy balances, bio-chemical reaction kinetics, estimated parameters, and adapted model parameters. The adapted model parameters are a subset of the estimated parameters. Aerobic tank **32** and said anoxic tank **31** are modeled separately in both of the online and offline dynamic models **361** and **362** of MBR **30** when both aerobic and said anoxic tanks **32** and **31** are present.

[0358] More specifically, in some embodiments, the materials for the process material balances in the online and offline dynamic models **362** and **361** of MBR **30** are comprised of at least one of particulate inert, slowly degradable substrate, heterotrophic biomass, autotrophic biomass, decayed biomass, soluble inert, soluble readily degradable substrate, dissolved oxygen, dissolved nitrate-N(Nitrogen), dissolved ammonia-N, particulate bio-degradable-N, or bicarbonate alkalinity. Further, in some embodiments, the bio-chemical reaction kinetics in the online and offline dynamic models **362** and **361** of the MBR **30** are comprised of at least one of aerobic heterotroph, anoxic heterotroph, aerobic autotroph, decay of heterotroph, decay of autotroph, ammonification of soluble organic N, hydrolysis of organics, or hydrolysis of organic N.

[0359] In some embodiments, the estimated parameters and adapted model parameters of the offline dynamic model **361** of MBR **30** and the online dynamic model **362** of MBR **30** are comprised of at least one of hetrotrophic maximum specific growth rate, anoxic/aerobic hetrotroph growth rate, anoxic/aerobic hydrolysis rate fraction, particulate hydrolysis max specific rate constant, autotrophic maximum specific growth rate, decay constant for heterotrophs, decay constant for autotrophs, yield of hetrotrophic biomass, yield of autotrophic biomass, carbon content in soluble substrate, carbon content of particulate substrate, carbon content of soluble inert, carbon content of particulate nondegradable organic, mass transfer coefficient for O_2 removal in aerobic tank, or mass transfer coefficient for CO_2 removal in anoxic tank.

[0360] In step **462**, historical operation data of MBR **30** is provided. The historical operation data is comprised of historical measured input data, historical measured output data, and historical laboratory analysis data.

[0361] In some embodiments, the historical operation data of MBR **30** is comprised of at least one of raw influent pH, raw influent temperature, raw influent flow rate, raw influent TOC, raw influent TIC, added alkali flow rate, added alkali concentration, effluent flow out rate, raw influent SCOD, raw influent TCOD, raw influent readily biodegradable COD, raw influent slowly biodegradable COD, raw influent VSS, raw influent TSS, raw influent nitrate nitrogen, raw influent ammonia-nitrogen, raw influent soluble biodegradable organic nitrogen, raw influent particulate degradable organic nitrogen, raw influent inorganic inert particulate, membrane permeate flow rate, wasting sludge flow rate, anoxic tank addition biodegradable COD flow, anoxic rank reactor pH, anoxic tank Dissolved Oxygen, anoxic tank temperature, anoxic tank liquid level, anoxic tank MLVSS, anoxic tank MLSS, aerobic rank blower air flow rate, aerobic tank reactor pH, aerobic tank alkalinity, aerobic tank MLVSS, aerobic tank MLSS, aerobic tank Dissolved Oxygen, aerobic tank temperature, aerobic tank liquid level, membrane tank MLSS, membrane tank MLVSS, membrane permeate SCOD, membrane permeate TCOD, membrane permeate TOC, membrane permeate TIC, membrane permeate nitrate nitrogen, membrane permeate ammonia-nitrogen, wasting sludge MLSS, or wasting sludge MLVSS.

[0362] In step **464**, estimated parameters of offline dynamic model **361** of MBR **30** are identified using MBR offline EKF **351** and the historical operation data for MBR **30**.

[0363] In step **466**, the estimated parameters identified in step **464** are imported from the offline dynamic model **361** of MBR **30** into the online dynamic model **362** of MBR **30**.

[0364] In step **468**, real time operation data for MBR **30** is provided to MBR online EKF **352**. The real time operation data is comprised of real time measured input data and real time measured output data of MBR **30**.

[0365] In some embodiments, the real time operation data of MBR **30** is comprised of at least one of raw influent pH, raw influent temperature, raw influent flow rate, raw influent TOC, raw influent TIC, added alkali flow rate, added alkali concentration, effluent flow out rate, raw influent SCOD, raw influent TCOD, raw influent readily biodegradable COD, raw influent slowly biodegradable COD, raw influent VSS, raw influent TSS, raw influent nitrate nitrogen, raw influent ammonia-nitrogen, raw influent soluble biodegradable organic nitrogen, raw influent particulate degradable organic nitrogen, raw influent inorganic inert particulate, membrane permeate flow rate, wasting sludge flow rate, anoxic tank addition biodegradable COD flow, anoxic rank reactor pH, anoxic tank Dissolved Oxygen, anoxic tank temperature, anoxic tank liquid level, anoxic tank MLVSS, anoxic tank MLSS, aerobic rank blower air flow rate, aerobic tank reactor pH, aerobic tank alkalinity, aerobic tank MLVSS, aerobic tank MLSS, aerobic tank Dissolved Oxygen, aerobic tank temperature, aerobic tank liquid level, membrane tank MLSS, membrane tank MLVSS, membrane permeate SCOD, membrane permeate TCOD, membrane permeate TOC, membrane permeate TIC, membrane permeate nitrate nitrogen, membrane permeate ammonia-nitrogen, wasting sludge MLSS, or wasting sludge MLVSS.

[0366] In step **470**, the adapted model parameters of the online dynamic model **362** of MBR **30** are updated and the model based inferred variables of MBR **30** are estimated using the MBR online EKF **352**, the online dynamic model of MBR **30**, the real time measured input data of MBR **30**, and the real time measured output data of MBR **30**.

[0367] In some embodiments, the model based inferred variables of online dynamic model **362** of MBR **30** are comprised of at least one of the following unmeasured inputs or outputs of said MBR: raw influent alkalinity, raw influent nitrate nitrogen, raw influent ammonia-nitrogen, raw influent SCOD, raw influent TCOD, raw influent readily biodegradable COD, raw influent slowly biodegradable COD, raw influent VSS, raw influent TSS, raw influent inorganic inert particulate, anoxic rank SCOD, anoxic tank MLVSS, anoxic tank nitrate nitrogen, anoxic tank ammonia-nitrogen, anoxic tank biodegradable COD, aerobic tank SOCD, aerobic tank MLVSS, aerobic tank nitrate nitrogen, aerobic tank ammonia-nitrogen, aerobic tank biodegradable COD, membrane tank MLVSS, membrane permeate SCOD, membrane permeate biodegradable COD, membrane permeate TCOD, membrane permeate nitrate nitrogen, membrane permeate ammonia-nitrogen, wasting sludge MLVSS, COD removal rate, or nitrogen removal rate.

[0368] In step **472**, one or more of the adapted model parameters of the online dynamic model **362** of MBR **30** and one or more of the model based inferred variables of MBR **30** are provided to an operator of MBR **30**.

[0369] In step **474**, MBR control system **300** is provided with one or more of the real time measured input data of MBR **30**, real time measured output data of MBR **30**, estimated parameters of the online dynamic model of MBR **30**, or model based inferred variables of MBR **30**. MBR control system **300** uses this information to control at least one of pH of anoxic tank **31**, pH of aerobic tank **32**, fluid level of aerobic tank **32**, DO concentration of aerobic tank **32**, MLSS concentration of membrane tank **33**, bCOD addition flow rate setpoint of anoxic tank **31**, at least one nutritional additive concentration of anoxic tank **31**, or at least one recycle flow setpoint of MBR **30**.

[0370] Wherein controlling at least one nutritional additive concentration of anoxic tank **31** prevents biomass overfeeding and starvation, wherein controlling the pH of anoxic tank **31** minimizes alkali dosing, wherein controlling the pH of aerobic tank **32** minimizes alkali dosing, wherein controlling the fluid level of aerobic tank **32** minimizes the affect of fluid perturbations of aerobic tank **32**, wherein controlling the DO concentration of aerobic tank **32** ensures that a proper concentration of DO is present in aerobic tank **32**, wherein controlling the MLSS concentration of membrane tank **33** maximizes membrane permeability, wherein controlling the bCOD addition flow rate setpoint of said anoxic tank **31** minimizes bCOD usage, wherein controlling at least one recycle flow setpoint of MBR **30** helps to maintain flow through MBR **30**.

[0371] MBR control system **300** is comprised of an MBR supervisory control system **301** and an MBR low-level control system **302**. MBR supervisory control system **301** is comprised of at least one of an aerobic tank DO supervisory controller **1040**, an anoxic tank recycle flow supervisory controller **1045**, or an anoxic tank bCOD addition flow rate supervisory control scheme **1035**.

[0372] In some embodiments, anoxic tank bCOD addition flow supervisory control scheme **1035** of MBR **30** is comprised of anoxic tank bCOD setpoint supervisory controller **1050**, anoxic tank bCOD addition flow rate supervisory feedback controller **1055**, and an anoxic tank bCOD addition flow rate supervisory feedforward controller **1065**. Further, in some embodiments, the aerobic tank DO supervisory controller **1040**, anoxic tank recycle flow supervisory controller **1045**, and anoxic tank bCOD addition flow rate supervisory control scheme **1035** work together to satisfy membrane permeate requirements on COD, nitrate, and ammonia, while minimizing aeration, recycle flow, and bCOD addition, which are established by government entities.

[0373] Further, in some embodiments, at least one of the aerobic tank DO supervisory controller **1040**, anoxic tank recycle flow supervisory controller **1045**, or anoxic tank bCOD addition flow rate supervisory control scheme **1035** uses at least one of an estimated parameter of online dynamic model **362** of MBR **30** or a model based inferred variable of MBR **30**.

[0374] Additionally, in some embodiments, MBR low-level control system **302** is comprised of at least one of an aerobic tank fluid level PI controller **765**, an aerobic tank pH controller **750**, an anoxic tank pH controller **755**, an anoxic tank recycle line flow rate controller **770**, an aerobic tank DO concentration controller **745**, an anoxic tank nutritional additive concentration controller **777**, an aerobic tank recycle line flow rate PI controller **771**, a total MBR recycle flow rate PI controller **775**, or a membrane tank MLSS concentration controller **760**.

[0375] In some embodiments, membrane tank MLSS concentration controller **760** uses a model based inferred variable of said MBR. In some embodiments, the model based inferred variable is MLVSS concentration or MLSS concentration.

[0376] In step **476**, the MBR operator, or an automated system such as computer **1071**, decides whether it is necessary to adjust the adapted model parameters of the online dynamic model **362** of MBR **30** (e.g. reporting incorrect or inconsistent values for model predicted outputs or model based inferred variables). If it is not necessary to adjust the adapted model parameters, the method returns to step **468**.

[0377] If it is necessary to adjust the adapted model parameters, the operator or computer **1071** can choose to use one or both of an online EKF approach or an offline EKF approach to update the adapted model parameters of the online dynamic model **362**. Traditionally, the offline EKF approach is only used periodically, in some embodiments about every few weeks or months. The online EKF approach is used more frequently, in some embodiments as frequently as about every 30 minutes.

[0378] In some embodiments, the decision of whether or not to adjust the adapted model parameters is determined by elapsed time, such as an adjustment of the adapted model parameters using the online EKF approach is performed about every 30 minutes to once a day, and an adjustment of the adapted model parameters using the offline EKF approach is performed about every few weeks to few months.

[0379] In the online EKF approach, model predicted outputs of MBR **30** are calculated using MBR online EKF **352**, online dynamic model **362** of MBR **30**, real time measured input data of MBR **30**, and real time measured output data of MBR **30**. The measured output data of MBR **30** and the model predicted outputs of MBR **30** are then compared, and the adapted model parameters of online dynamic model **362** of MBR **30** are updated such that the real time measured output data of MBR **30** substantially correspond with the model predicted outputs of MBR **30**.

[0380] In the offline EKF approach, the estimated parameters of the offline dynamic model **361** of MBR **30** are re-identified using the MBR offline EKF **351** and the historic operation data for MBR **30**. The estimated parameters of offline dynamic model **361**, which contain the updated adapted model parameters as a subset, are then imported into the online dynamic model **362**.

[0381] In some embodiments of the offline EKF approach, the adapted model parameters of the online dynamic model **362** of MBR **30** are imported into the offline dynamic model **361** of MBR **30** before the estimated parameters of the offline dynamic model **361** of MBR **30** are re-identified. This allows the estimated parameters of the offline dynamic model **361** to converge faster when they are re-identified by MBR offline EKF **351**.

[0382] After step **476**, the method returns to step **468** to provide real time operation data of MBR **30** for the next time point to MBR online EKF **352**.

[0383] In some embodiments, at least one of the estimated parameters of offline dynamic model **361** of MBR **30** and model based inferred variables of online dynamic model **362** of said MBR **30** are estimated with confidence intervals.

[0384] Further, in some embodiments, the adapted model parameters of online dynamic model **362** of MBR **30** are tuned using different weights for online measurements and prior knowledge of measurement accuracy. Additionally, in some embodiments, limits are applied to one or more of the estimated parameters and adapted model parameters, and constraints are applied to one or more of the model based inferred variables.

[0385] It is contemplated that the method of operating MBR **30** includes variations of the methods depicted in FIGS. **16***a*-*b*. Some embodiments of such methods may be arrived at by substituting steps or underlying details of one of **16***a* or **16***b*, and using the steps or underlying details in the other of **16***a* or **16***b*.

[0386] It is contemplated that in some embodiments, at least one of monitoring MBR **30** or controlling MBR **30** is performed using a computer.

[0387] While online monitoring is very useful in itself to maintain a good understanding of the process operation in the presence of significant variations in AD **20** and MBR **30**. The online monitoring solution discussed above for AD **20** and MBR **30** can be used in conjunction with a supervisory control solution to improve the stability, robustness and operational efficiency of the AD **20** and MBR **30** processes. Accordingly, it is contemplated that one or more embodiments of control system **200** of AD **20** may include one or more of the following controls shown in FIG. **21**-**27**.

[0388] Good pH control in AD reactor **24** helps to ensure its stability. Poor pH control can easily lead to a cascading instability where pH drop leads to methanogenesis inhibition, leading to further pH drop and eventual biomass deactivation and washout. The pH in AD reactor **24** is impacted by continuous unknown changes in the feed as well as variations in biomass activity in the digester.

[0389] FIG. **17***a* depicts AD reactor pH supervisory controller **700** for AD reactor **24** with a nonlinear PI control and an alkalinity control in cascade structure. AD reactor pH supervisory controller **700** is comprised of an AD reactor nonlinear Proportional-Integral (PI) pH controller **705**, AD reactor Proportional (P) alkalinity controller **710**, AD reactor **24**, and AD online EKF **252**. AD reactor nonlinear PI pH controller **705** is provided with the difference between a user selected pH setpoint for AD reactor **24** and the measured pH value for AD reactor **24**. AD reactor nonlinear PI pH controller **705** then outputs the AD reactor alkalinity setpoint. AD reactor P alkalinity controller **710** is provided with the difference between the AD reactor alkalinity setpoint from AD reactor nonlinear PI pH controller **705** and the estimated alkalinity of AD reactor **24**. The estimated alkalinity of AD reactor **24** is ascertained via estimation by the AD online EKF **252** of AD **20**. In some embodiments, AD online EKF **252** may also enable feedforward control action to maintain the alkalinity of AD reactor **24**. AD reactor P alkalinity controller **710** adjusts the alkalinity dosing flow rate to AD reactor **24** based on the AD alkalinity setpoint and estimated alkalinity of AD reactor **24** from AD online EKF **252**. It is understood that alternatively an operator may also manually manipulate the AD reactor alkalinity setpoint by an operator on the operator control panel **1070**.

[0390] FIG. **17***b* depicts another embodiment of AD reactor pH supervisory controller **700** that controls the pH of AD reactor **24** with a nonlinear PI control and an alkalinity control in cascade structure. This embodiment can be used when PA reactor pH supervisory controller **701** is not present. In this embodiment, AD reactor pH supervisory controller **700** is comprised of an AD reactor nonlinear PI pH controller **705**, PA reactor P alkalinity controller **711**, PA reactor **22**, AD reactor **24**, and the AD online EKF **252** of AD **20**. In operation, AD reactor nonlinear PI pH controller **705** is provided with the difference between a user selected pH setpoint for AD reactor **24** and the measured pH value for AD reactor **24**. AD reactor nonlinear PI pH controller **705** then outputs the PA reactor alkalinity setpoint. PA reactor P alkalinity controller **711** is provided with the difference between the PA reactor alkalinity setpoint from AD reactor nonlinear PI pH controller **705** and the estimated alkalinity of PA reactor **22**. The estimated alkalinity of PA reactor **22** is ascertained via estimation by the AD online EKF **252** of AD **20**. PA reactor P alkalinity controller **711** adjusts the alkalinity dosing flow rate to PA reactor **22** based on the PA reactor alkalinity setpoint and the estimated PA reactor alkalinity. This control structure has less components but is still able to respond fast to disturbances coming into the AD **20**. The AD online EKF **252** of AD **20** makes this cascade control possible by providing real-time estimate of the alkalinity of PA reactor **22**. It is understood that alternatively, an operator may also manually manipulate the PA reactor alkalinity setpoint by an operator on the operator control panel **1070**. In some embodiments, AD online EKF **252** may enable feedforward control action to maintain the alkalinity of PA reactor **22** based on inferred variations in the raw influent.

[0391] FIG. **18** depicts PA reactor pH supervisory controller **701** for PA reactor **22** with a nonlinear PI control and an alkalinity control in cascade structure. The PA reactor pH supervisory controller **701** is comprised of PA reactor nonlinear Proportional-Integral (PI) pH controller **706**, PA reactor Proportional (P) alkalinity controller **711**, PA reactor **22**, and the AD online EKF **252**. PA reactor nonlinear PI pH controller **706** is provided with the difference between a user selected pH setpoint for PA reactor **22** and the measured pH value for PA reactor **22**. PA reactor nonlinear PI pH controller **706** then outputs the PA reactor alkalinity setpoint. PA reactor P alkalinity controller **711** is provided with the difference between the PA reactor alkalinity setpoint from PA reactor nonlinear PI pH controller **706** and the estimated alkalinity of PA reactor **22**. The estimated alkalinity of PA reactor **22** is ascertained via estimation by the AD online EKF **252** of AD **20**. In some embodiments, AD online EKF **252** may enable feed forward control action to maintain the alkalinity of PA reactor **22**. PA reactor P alkalinity controller **711** adjusts the alkalinity dosing flow rate to PA reactor **22** based on the AD alkalinity setpoint and estimated alkalinity flow rate to PA reactor **22**. It is understood that alternatively an operator may also manually manipulate the PA reactor alkalinity setpoint on the operator control panel **1070**.

[0392] The pH controllers described above in FIGS. **17-18** for AD reactor **24** and PA reactor **22** improves pH control by using a nonlinear transformation on the controlled output pH, and by using a cascaded control structure. The nonlinear transformation that is applied to the controlled variable pH, allows for better handling of the nonlinear relation between pH and the molar quantities of the species inside AD reactor **24** and PA reactor **22**, such as the interaction between bicarbonate and VFA alkalinity. The cascade control loop allows for separation of fast and slow dynamics on the alkalinity balance inside the reactors and therefore is able to take earlier control actions in the face of disturbances.

[0393] As mentioned earlier, a concern in digester operation is the presence of a toxic/inhibitory ingredient in the wastewater feed that leads to reduction in methanogenesis activity, which if significant and un-mitigated can lead to biomass deactivation and washout. The online EKF discussed above provides the ability to detect such an inhibition online and early.

[0394] FIG. **19***a-b* depict an PA:AD overall recycle flow ratio supervisory controller **720** for the coordination of PA reactor **22** and AD reactor **24** for acidogenesis and methanation. PA:AD overall recycle flow ratio supervisory controller **720** is comprised of PA:AD recycle ratio controller **725** and PA reactor and AD reactor recycle flow rate controller **730**. PA:AD recycle ratio controller **725** is provided the measured pH of PA reactor **22**, the maximum pH setpoint of PA reactor **22**, the minimum pH setpoint of PA reactor **22**, the estimated VFA/SCOD of PA reactor **22**, target VFA/SCOD of PA reactor **22**, maximum VFA/SCOD setpoint of PA reactor **22**, and minimum VFA/SCOD setpoint of PA reactor **22**. The contents of PA:AD recycle ratio controller **725** is described in FIG. **20**. PA:AD recycle ratio controller **725** then outputs the PA:AD Rratio (Recycle ratio) to PA reactor and AD reactor recycle flow rate controller **730**, which sets the flow rates of PA recycle pump **28** and AD recycle pump **29** of AD **20** based on the PA:AD Rratio, AD feed flow rate, target AD flow rate, maximum/minimum recycle flow rates. It is contemplated that in some embodiments, PA reactor and AD reactor recycle flow rate controller **730** can be one controller, as is shown in FIG. **19***a*. Further, it is contemplated that in other embodiments, PA reactor and AD reactor recycle flow rate controller **730** can be comprised of an individual PA reactor recycle flow rate controller **730***a* and an AD reactor recycle flow rate controller **730***b* which set the flow rates of PA recycle pump **28** and AD recycle pump **29** of AD **20** such as is shown in FIG. **19***b*.

[0395] FIG. **20** depicts the PA:AD Recycle Ratio controller **725**. PA:AD Recycle Ratio controller **725** is comprised of multiple conventional controllers (e.g., PI or PID controller) working simultaneously, and passing their outputs through signal selection operations, i.e., min/max selection functions, and then through the constraints of PA:AD flow ratio range limits, which and then forms the controller outputs. The arrangement of the min/max selection operations makes the final output signal capable of satisfying all the desired limits of the input signals to the controller.

[0396] As mentioned earlier, another concern in digester operation is biomass deactivation and washout. The AD online EKF **252** discussed above provides the ability to detect the biomass concentration within AD reactor **24** and add additional biomass if necessary.

[0397] FIG. **21** depicts a control scheme for regulating the biomass concentration in AD reactor **24** of AD **20**. If additional biomass is required in AD reactor **24**, the additional biomass is provided by biomass tank **44**, which is controlled by AD reactor biomass concentration controller **735**. A block diagram of AD reactor biomass concentration controller **735** is detailed in FIG. **22**. As can be seen, AD reactor biomass concentration controller **735** is provided with the estimated biomass concentration in AD reactor **24** by AD online EKF **252** of AD **20**, and the operator defined setpoint for biomass in AD reactor **24** on the operator control panel **1070**. The AD online EKF **252** of AD **20** ascertains the concentration of biomass in AD reactor **24** by detecting and tracking biomass inhibiting events. AD reactor biomass concentration controller **735** then determines whether an adjustment is required of the concentration of biomass in AD reactor **24** by examining whether the estimated biomass concentration in AD reactor **24** is less than the operator defined setpoint. If the operator defined setpoint for biomass concentration in AD reactor **24** is greater than the estimated biomass concentration in AD reactor **24**, AD reactor biomass concentration controller **735** instructs biomass tank **44** to add biomass to AD reactor **24** such that the biomass concentration in AD reactor **24** substantially corresponds with the operator defined setpoint for biomass concentration in AD reactor **24**.

[0398] FIG. **23** is a flow chart detailing the operations taking place within AD reactor biomass concentration controller **735**. In step **1080** the estimated concentration of biomass in AD reactor **24** is obtained from the AD online EKF **252** of AD **20** and the setpoint for the concentration of biomass in AD reactor **24** is obtained from the operator control panel **1070**. Following step **1080**, in step **1085** the estimated concentration of biomass in AD reactor **24** is compared with the setpoint for the concentration of biomass in AD reactor **24**. Following step **1085**, in step **1090**, if the estimated concentration of biomass in AD reactor **24** is less than the setpoint the concentration of biomass in AD reactor

24, AD reactor biomass concentration controller **735** instructs biomass tank **44** to add biomass to AD reactor **24**. Following step **1090**, AD reactor biomass concentration controller **735** returns to step **1080** and repeats the operations in steps **1080-1090**.

[0399] Further, another consideration is adjusting the fluid level in PA reactor **22** to absorb transient perturbations to the plant, rather than keeping the fluid level in PA reactor **22** at a constant setpoint. FIG. **24** depicts a control scheme for the fluid level within PA reactor **22** in which PA fluid level sensor **736** senses the level of fluid with PA reactor **22**, PA fluid level sensor **736** passes the level to PA fluid level controller **737**, which make any necessary adjustment to the flow rate of PA recycle pump **28** to return the fluid level within PA reactor **22** to an acceptable level by increasing or decreasing the amount of water recycled from AD reactor **24** to PA reactor mixing stage **21**, which is immediately upstream of PA reactor **22**, or directly to PA reactor **22** if PA reactor mixing stage **21** is not present.

[0400] A block diagram of PA fluid level controller **737** is detailed in FIG. **25**. As can be seen, PA fluid level controller **737** is provided with the maximum PA fluid level setpoint, minimum PA fluid level setpoint, ideal PA fluid level setpoint, and PA fluid level measurement. The setpoints are provided by the operator on the operator control panel **1070**. The PA fluid level measurement is provided by PA fluid level sensor **736**. PA fluid level controller **737** then determines whether an adjustment of PA recycle pump **28** is required. PA fluid level sensor **736** then reports any changes in fluid level of PA reactor **22** to PA fluid level controller **737**.

[0401] FIG. **26** is a flow chart detailing the operations taking place within PA fluid level controller **737**. In step **2000**, PA fluid level controller **737** obtains the maximum PA fluid level setpoint, minimum PA fluid level setpoint, ideal PA fluid level setpoint, and PA fluid level measurement. In step **2005**, the PA fluid level measurement is compared to the maximum PA fluid level setpoint. If the PA fluid level measurement is less than the maximum PA fluid level setpoint, the program advances to step **2010**. However, if the PA fluid level measurement is greater than the maximum PA fluid level setpoint, PA fluid level controller **737** reduces the flow rate of the PA recycle pump **28** until the PA fluid level sensor **736** informs the PA fluid level controller **737** that the PA fluid level substantially corresponds to the ideal PA fluid level setpoint and then proceeds back to step **2000**.

[0402] In step **2010**, the PA fluid level measurement is compared to the minimum PA fluid level setpoint. If the PA fluid level measurement is not less than the minimum PA fluid level setpoint, the program returns to step **2000**. However, if the PA fluid level measurement is less than the minimum PA fluid level setpoint, PA fluid level controller **737** increases the flow rate of the PA recycle pump **28** until the PA fluid level sensor **736** informs the PA fluid level controller **737** that the PA fluid level substantially corresponds to the ideal PA fluid level setpoint and then proceeds back to step **2000**.

[0403] FIG. **27** shows a scheme for regulating the nutrient concentration within some embodiments of PA reactor **22** of AD **20**. It is contemplated in some embodiments of AD **20**, the amount and type of nutritional additives, provided to PA reactor **22** will be determined by the estimated composition of the bacteria contained within PA reactor **22**. It is contemplated that in some embodiments, a PA reactor nutritional additive concentration controller **51** and PA reactor nutritional additive tank **52** will be provided for each nutrient of interest for PA reactor **22**. Further, it is contemplated that in some embodiments, all of the additive nutrients for PA reactor **22** are combined in a single PA reactor nutritional additive tank **52**, accordingly, in those embodiments, only one PA reactor nutritional additive concentration controller **51** and PA reactor nutritional additive tank **52** will be present for AD **20**.

[0404] In one embodiment, PA reactor nutritional additive concentration controller **51** is a PI controller. The nutritional additives may include, but are not limited to, nitrogen and phosphorus. The composition of bacteria in PA reactor **22** will be estimated by AD online EKF **252**. A PA reactor bacteria composition lookup table **53** is used to ascertain the nutritional additive concentration requirement for the composition of bacteria within PA reactor **22** and output the concentration requirement for the specific nutritional additive of interest. The concentration of the nutritional additive of interest within PA reactor **22** is ascertained via direct measurement via PA reactor additive concentration sensor **54** contained within PA reactor **22**, or AD online EKF **252**. The concentration of the nutritional additive of interest present within PA reactor **22** is subtracted from the concentration of the nutritional additive requirement to determine if a deficiency exists for the nutrient of interest and the difference is provided to PA reactor nutritional additive concentration controller **51**, which adjusts the flow rate of the nutritional additive of interest flowing from PA reactor nutritional additive tank **52** into PA reactor **22**.

[0405] Accordingly, if a nutrient deficiency exists, nutritional additives are provided to PA reactor **22** until the nutrient deficiency is rectified. Accordingly, the flow rates of the various nutritional additives of interest provided to PA reactor **22** from the various PA reactor nutritional additive tanks **52** are individually adjusted based on the amount of each species of bacteria present within each of PA reactor **22** and nutrient concentration present within PA reactor **22**, so as not to overfeed or starve the bacteria.

[0406] In another embodiment in which all of the additive nutrients for PA reactor **22** are combined in a single PA reactor nutritional additive tank **52**, the composition of bacteria in PA reactor **22** will be estimated by AD online EKF **252**. A PA reactor bacteria composition lookup table **53** is used to ascertain the nutritional additive concentration requirement for the composition of bacteria within PA reactor **22** and output the concentration requirement for the nutritional additives of interest. The concentration of the nutritional additives of interest within PA reactor **22** is ascertained via direct measurement via PA reactor additive concentration sensor **54** contained within PA reactor **22**, or AD online EKF **252**. The concentration of the nutritional additives of interest present within PA reactor **22** is subtracted from the concentration of the nutritional additive requirement to determine if a deficiency exists for the nutrients of interest and the difference is provided to PA reactor nutritional additive concentration controller **51**, which adjusts the flow rate of the nutritional additives of interest flowing from PA reactor nutritional additive tank **52** into PA reactor **22**.

[0407] Accordingly, if a nutrient deficiency exists, nutritional additives are provided to PA reactor **22** until the nutrient deficiency is rectified. Accordingly, the flow rate of the nutritional additives of interest provided to PA reactor **22** is adjusted based on the amount of each species of bacteria present within each of PA reactor **22** and nutrient concentration present within PA reactor **22**, so as not to overfeed or starve the bacteria.

[0408] FIG. **28** shows a scheme for regulating the nutrient concentration within some embodiments of AD reactor **24** of AD **20**. It is contemplated in some embodiments of AD **20**, the amount and type of nutritional additives, provided to AD reactor **24** will be determined by the estimated composition of the bacteria contained within AD reactor **24**. It is contemplated that in some embodiments, a AD reactor nutritional additive concentration controller **61** and AD reactor nutritional additive tank **62** will be provided for each nutrient of interest for AD reactor **24**. Further, it is contemplated that in some embodiments, all of the additive nutrients for AD reactor **24** are combined in a single AD reactor nutritional additive tank **62**, accordingly, in those embodiments, only one AD reactor nutritional additive concentration controller **61** and AD reactor nutritional additive tank **62** will be present for AD **20**.

[0409] In one embodiment, AD reactor nutritional additive concentration controller **61** is a PI controller. The nutritional additives may include, but are not limited to, nitrogen and phosphorus. The composition of bacteria in AD reactor **24** will be estimated by AD online EKF **252**. An AD reactor bacteria composition lookup table **63** is used to ascertain the nutritional additive concentration requirement for the composition of bacteria within AD reactor **24** and output the concentration requirement for the specific nutritional additive of interest. The concentration of the nutritional additive of interest within AD reactor **24** is ascertained via direct measurement via AD reactor additive concentration sensor **64** contained within AD reactor **24**, or AD online EKF **252**. The concentration of the nutritional additive of interest present within AD reactor **24** is subtracted from the concentration of the nutritional additive requirement to determine if a deficiency exists for the nutrient of interest and the difference is provided to AD reactor nutritional additive concentration controller **61**, which adjusts the flow rate of the nutritional additive of interest flowing from AD reactor nutritional additive tank **62** into AD reactor **24**.

[0410] Accordingly, if a nutrient deficiency exists, nutritional additives are provided to AD reactor **24** until the nutrient deficiency is rectified. Accordingly, the flow rates of the various nutritional additives of interest provided to AD reactor **24** from the various AD reactor nutritional additive tanks **62** are individually adjusted based on the amount of each species of bacteria present within each of AD reactor **24** and nutrient concentration present within AD reactor **24**, so as not to overfeed or starve the bacteria.

[0411] In another embodiment in which all of the additive nutrients for AD reactor **24** are combined in a single AD reactor nutritional additive tank **62**, the composition of bacteria in AD reactor **24** will be estimated by AD online EKF **252**. An AD reactor bacteria composition lookup table **63** is used to ascertain the nutritional additive concentration requirement for the composition of bacteria within AD reactor **24** and output the concentration requirement for the nutritional additives of interest. The concentration of the nutritional additives of interest within AD reactor **24** is ascertained via direct measurement via AD reactor additive concentration sensor **64** contained within AD reactor **24**, or AD online EKF **252**. The concentration of the nutritional additives of interest present within AD reactor **24** is subtracted from the concentration of the nutritional additive requirement to determine if a deficiency exists for the nutrients of interest and the difference is provided to AD reactor nutritional additive concentration controller **61**, which adjusts the flow rate of the nutritional additives of interest flowing from AD reactor nutritional additive tank **62** into AD reactor **24**.

[0412] Accordingly, if a nutrient deficiency exists, nutritional additives are provided to AD reactor **24** until the nutrient deficiency is rectified. Accordingly, the flow rate of the nutritional additives of interest provided to AD reactor **24** is adjusted based on the amount of each species of bacteria present within each of AD reactor **24** and nutrient concentration present within AD reactor **24**, so as not to overfeed or starve the bacteria.

[0413] As was previously stated, while online monitoring is very useful in itself to maintain a good understanding of the process operation in the presence of significant variations in AD **20** and MBR **30**. The online monitoring solution discussed above for AD **20** and MBR **30** can be used in conjunction with a supervisory control solution to improve the stability, robustness and operational efficiency of the AD **20** and MBR **30** processes. Accordingly, it is contemplated that one or more embodiments of MBR control system **300** of MBR **30** may include one or more of the controls described below.

[0414] To realize control objectives, several basic control loops are used in the process: the Dissolved Oxygen (DO) in aerobic tank is controlled by the air blower flow rate (aeration) as shown in FIG. **29**, pH levels in aerobic and anoxic tanks are controlled by the chemical flow rates (alkali, e.g. KOH) as shown in FIGS. **30-31**, MLSS concentration in the membrane tank is controlled by the purge flow rate as shown in FIG. **32***a*, the aerobic tank fluid level is controlled by the permeate pump flow as shown in FIG. **33**, and the total recycle flow is controlled to anoxic tank generally (in some cases the total recycle flow is controlled to aerobic tank and anoxic tank two reactors respectively). These lower level control loops are implemented with single loop PI control structure.

[0415] Some of the setpoints of the PI loops listed above are set by a MBR supervisory control system **301** of MBR control system **300** in cascade control configuration and min/max selection logic are used to determine the setpoints for some of the lower level control loops, to realize the ultimate MBR control objectives. Further, the operator control panel **1070** allows for manual adjustment of the setpoints.

[0416] The structure of MBR control system **300** is primarily based on feedback mechanism. For prompt response to known or measurable disturbances, feedforward control action is also added to the control structure to make sure the process can respond to disturbances swiftly. A fast response is ideal for an MBR system since the bio-chemical (bacteria growth) is a sensitive process. For the wastewater processing system, the most significant disturbances come from the raw feed variations. Feed characterization or measurement can be used for feedforward control action to overcome the feed variations.

[0417] Further, in the MBR control system **300**, both anoxic tank recycle line **34** and additional bCOD (e.g. methanol) are used to control the NO_3 concentration in the permeate stream—the additional COD is used to augment COD feed for nitrification in the anoxic tank if the feed is lacking COD.

[0418] FIG. **29** depicts a control scheme for the dissolved oxygen (DO) within aerobic tank **32**. The control scheme is comprised of aerobic tank DO concentration controller **745**, aerobic tank aeration **38** (air blower), and aerobic tank **32**. In some embodiments, aerobic tank DO concentration controller **745** is a PI controller. In operation, aerobic tank DO concentration controller **745** is provided with the difference between the setpoint for DO in aerobic tank **32** and the measured DO in aerobic tank **32**. The DO measurement is provided by an aerobic tank DO sensor **65** situated in aerobic tank **32**. aerobic tank DO concentration controller **745** then makes adjustments to the aerobic tank aeration **38** (air blower flow rate), which changes the amount of air provided to aerobic tank **32**, such that the measured DO in aerobic tank **32** substantially corresponds with the setpoint for DO in aerobic tank **32**. The setpoint for DO in aerobic tank **32** is determined by aerobic tank DO supervisory controller **1040**. It is understood that alternatively an operator may also manually manipulate the aerobic tank DO setpoint on the operator control panel **1070**.

[0419] FIG. **30** depicts a control scheme for the pH level within aerobic tank **32**. The control scheme is comprised of aerobic tank pH controller **750**, alkali tank **49**, and aerobic tank **32**. In some embodiments, aerobic tank pH controller **750** is a PI controller. In operation, aerobic tank pH controller **750** is provided with the difference between the setpoint of pH in aerobic tank **32** and the measured pH in aerobic tank **32**. The pH measurement is provided by an aerobic tank pH level sensor **66** in aerobic tank **32**. Aerobic tank pH controller **750** then makes adjustments to the chemical flow rate from alkali tank **49** (e.g. KOH or another suitable alkali), which changes the pH in aerobic tank **32**, such that the measured pH in aerobic tank **32** substantially corresponds with the setpoint for pH level in aerobic tank **32**. The setpoint for pH in aerobic tank **32** is determined by an operator on the operator control panel **1070**. It is understood that alternatively, the setpoint for pH in aerobic tank **32** may be established by a controller of MBR supervisory control system **301**.

[0420] FIG. **31** depicts a control scheme for the pH level within anoxic tank **31**. The control scheme is comprised of anoxic tank pH controller **755**, alkali tank **45**, and anoxic tank **31**. In operation, anoxic tank pH controller **755** is provided with the difference between the setpoint of pH in anoxic tank **31** and the measured pH in anoxic tank **31**. The pH measurement is provided by anoxic tank pH sensor **67** in anoxic tank **31**. Anoxic tank pH controller **755** then makes adjustments to the chemical flow rate from alkali tank **45** (e.g. KOH or another suitable alkali), which changes the pH in anoxic tank **31**, such that the measured pH in anoxic tank **31** substantially corresponds with the setpoint for pH level in anoxic tank **31**. The setpoint for pH in anoxic tank **31** is determined by an operator on the operator control panel **1070**. It is understood that alternatively, the setpoint for pH in anoxic tank **31** may be established by a controller of MBR supervisory control system **301**.

[0421] FIGS. **32***a*-*b* depicts a control scheme for the MLSS or MLVSS concentration within membrane tank **33**. The control scheme is comprised of membrane tank MLSS concentration PI controller **760**, membrane tank sludge discharge **43** of membrane tank **33**, and MBR online EKF **352**. FIG. **32***a* depicts an embodiment of membrane tank MLSS concentration PI controller **760** which controls the concentration of MLSS within membrane tank **33**. In operation, membrane tank MLSS concentration PI controller **760** is provided with the difference between the setpoint for the MLSS concentration within membrane tank **33** and the estimated MLSS concentration within membrane tank **33**. The estimated MLSS concentration within membrane tank **33** is provided by MBR online EKF **352**. Membrane tank MLSS concentration PI controller **760** then makes adjustments to the purge flow rate of membrane tank **33** via the membrane tank sludge discharge **43**, such that the estimated MLSS concentration within membrane tank **33** substantially corresponds with the setpoint for the MLSS concentration within membrane tank **33**. The setpoint for the MLSS concentration within membrane tank **33** is determined by an operator on the operator control panel **1070**. It is understood that alternatively, the MLSS concentration within membrane tank **33** may be established by a controller of MBR supervisory control system **301**.

[0422] In the embodiment shown in FIG. **32***b*, it is contemplated that membrane tank MLSS concentration PI controller **760** is used to control the MLVSS in membrane tank **33**. In such embodiments, membrane tank MLSS concentration PI controller **760** is provided with the difference between the setpoint for the MLVSS concentration within membrane tank **33** and the estimated MLVSS concentration within membrane tank **33**. The estimated MLVSS concentration within membrane tank **33** is provided by MBR online EKF **352**. Membrane tank MLSS concentration PI controller **760** then makes adjustments to the purge flow rate of membrane tank **33** via the membrane tank sludge discharge **43**, such that the estimated MLVSS concentration within membrane tank **33** substantially corresponds with the setpoint for the MLVSS concentration within membrane tank **33**. The setpoint for the MLVSS concentration within membrane tank **33** is determined by an operator on the operator control panel **1070**. It is understood that alternatively, the MLVSS concentration within membrane tank **33** may be established by a controller of MBR supervisory control system **301**. It is contemplated that in other embodiments, a membrane tank MLVSS concentration PI controller carries out the actions performed above in FIG. **32***b* by membrane tank MLSS concentration PI controller **760**. If a membrane tank MLVSS concentration PI controller is present, it will be considered part of the MBR low-level control system **302**.

[0423] FIG. **33** depicts a control scheme for the fluid level within aerobic tank **32**. The control scheme is comprised of aerobic tank fluid level PI controller **765**, permeate pump **35**, and aerobic tank fluid level sensor **37**. In operation, aerobic tank fluid level PI controller **765** is provided with the difference between the setpoint for the fluid level of aerobic tank **32** and the measured fluid level of aerobic tank **32**. The measurement of the fluid level in aerobic tank **32** is provided by aerobic tank fluid level sensor **37**. Aerobic tank fluid level PI controller **765** then makes adjustments to the flow rate of the membrane tank permeate pump **35**, which changes the fluid level in aerobic tank **32**, such that the measured fluid level of aerobic tank **32** substantially corresponds with the setpoint for the fluid level of aerobic tank **32**. The setpoint for fluid level of aerobic tank **32** is established by an operator on the operator control panel **1070**. It is understood that alternatively, the fluid level of aerobic tank **32** may be established by a controller of MBR supervisory control system **301**.

[0424] FIG. **34** depicts a control scheme for the flow rate of anoxic tank recycle line **34**. The control scheme is comprised of anoxic tank recycle line flow rate PI controller **770**, permeate pump **35**, MBR recycle line flow diverter **68**, and anoxic tank recycle line flow sensor **46**. In operation, anoxic tank recycle line flow rate PI controller **770** is provided with the difference between the setpoint for anoxic tank recycle line flow rate and the measured anoxic tank recycle line flow rate. The anoxic tank recycle line flow rate is provided by anoxic tank recycle line flow sensor **46** in anoxic tank recycle line **34**. Anoxic tank recycle line flow rate PI controller **770** then makes an adjustment to permeate pump **35** and MBR recycle line flow diverter **68**, which changes the recycle line flow rate, such that the measured anoxic tank recycle line flow rate substantially corresponds to the setpoint for anoxic tank recycle line flow rate. The MBR recycle line flow diverter **68** changes the ratio of fluid flowing between anoxic tank recycle line **34** and aerobic tank recycle line **36**. In some embodiments, the anoxic tank recycle line flow rate setpoint is established by anoxic tank recycle flow supervisory control **1045**. It is understood that alternatively, the anoxic tank recycle line flow rate setpoint may be determined by an operator on the operator control panel **1070**.

[0425] FIG. **35** depicts a control scheme for the flow rate of aerobic tank recycle line **36**. The control scheme is comprised of aerobic tank recycle line flow rate PI controller **771**, permeate pump **35**, MBR recycle line flow diverter **68**, and aerobic tank recycle line flow sensor **47**. In operation, aerobic tank recycle line flow rate PI controller **771** is provided with the difference between the setpoint for aerobic tank recycle line flow rate and the measured aerobic tank recycle line flow rate. The aerobic tank recycle line flow rate is provided by aerobic tank recycle line flow sensor **47** in aerobic tank recycle line **36**. Aerobic tank recycle line flow rate PI controller **771** then makes an adjustment to permeate pump **35** and MBR recycle line flow diverter **68**, which changes the aerobic tank recycle line flow rate, such that the measured aerobic tank recycle line flow rate substantially corresponds to the setpoint for aerobic tank recycle line flow rate. The MBR recycle line flow diverter **68** changes the ratio of fluid flowing between anoxic tank recycle line **34** and aerobic tank recycle line **36**. In some embodiments, the aerobic tank recycle line flow rate setpoint is determined by the MBR recycle line flow diverter **68**. It is understood that alternatively, the aerobic tank recycle line flow rate setpoint may be determined by an operator on the operator control panel **1070**.

[0426] FIG. **36** depicts a control scheme for controlling the total recycle flow rate in embodiments of MBR **30** having both anoxic tank recycle line **34** and aerobic tank recycle line **36**. The control scheme is comprised of total MBR recycle flow rate PI controller **775**, permeate pump **35**, anoxic tank recycle line flow sensor **46**, and aerobic tank recycle line flow sensor **47**. In operation, total MBR recycle flow rate PI controller **775** is provided with the difference between the setpoint for total recycle flow rate and the sum of the measured anoxic tank recycle line flow rate and measured aerobic tank recycle line flow rate. The anoxic tank recycle line flow rate is provided by anoxic tank recycle line flow sensor **46** in anoxic tank recycle line **34**. The aerobic tank recycle line flow rate is provided by aerobic tank recycle line flow sensor **47** in aerobic tank recycle line **36**. Total MBR recycle flow rate PI controller **775** then makes an adjustment to permeate pump **35**, which changes the flow rate of fluid through anoxic tank recycle line **34** and aerobic tank recycle line **36**, such that the sum of the recycle flow rates through aerobic tank recycle line **36** and anoxic tank recycle line **34** substantially corresponds to the setpoint for total recycle flow rate. The total recycle flow rate is established by an operator on the operator control panel **1070**. It is understood that alternatively, the total recycle flow rate may be determined by a controller of MBR supervisory control system **301**.

[0427] FIG. **37** shows a scheme for regulating the nutrient concentration within some embodiments of anoxic tank **31** of MBR **30**. It is contemplated in some embodiments of MBR **30**, the amount and type of nutritional additives, provided to anoxic tank **31** will be determined by the estimated composition of the bacteria contained within anoxic tank **31**. It is contemplated that in some embodiments, a anoxic tank nutritional additive concentration controller **777** and anoxic tank nutritional additive tank **778** will be provided for each nutrient of interest for anoxic tank **31**. Further, it is contemplated that in some embodiments, all of the additive nutrients for anoxic tank **31** are combined in a single anoxic tank nutritional additive tank **778**, accordingly, in those embodiments, only one anoxic tank nutritional additive concentration controller **777** and anoxic tank nutritional additive tank **778** will be present for MBR **30**.

[0428] In one embodiment, anoxic tank nutritional additive concentration controller **777** is a PI controller. The nutritional additives may include, but are not limited to, nitrogen and phosphorus. The composition of bacteria in anoxic tank **31** will be estimated by MBR online EKF **352**. An anoxic tank bacteria composition lookup table **776** is used to ascertain the nutritional additive concentration requirement for the composition of bacteria within anoxic tank **31** and output the concentration requirement for the specific nutritional additive of interest. The concentration of the nutritional additive of interest within anoxic tank **31** is ascertained via direct measurement via anoxic tank additive concentration sensor **779** contained within anoxic tank **31**, or MBR online EKF **352**. The concentration of the nutritional additive of interest present within anoxic tank **31** is subtracted from the concentration of the nutritional additive requirement to determine if a deficiency exists for the nutrient of interest and the difference is provided to anoxic tank nutritional additive concentration controller **777**, which adjusts the flow rate of the nutritional additive of interest flowing from anoxic tank nutritional additive tank **778** into anoxic tank **31**.

[0429] Accordingly, if a nutrient deficiency exists, nutritional additives are provided to anoxic tank **31** until the nutrient deficiency is rectified. Accordingly, the flow rates of the various nutritional additives of interest provided to anoxic tank **31** from the various anoxic tank nutritional additive tanks **778** are individually adjusted based on the amount of each species of bacteria present within each of anoxic tank **31** and nutrient concentration present within anoxic tank **31**, so as not to overfeed or starve the bacteria.

[0430] In another embodiment in which all of the additive nutrients for anoxic tank **31** are combined in a single anoxic tank nutritional additive tank **778**, the composition of bacteria in anoxic tank **31** will be estimated by MBR online EKF **352**. An anoxic tank bacteria composition lookup table **776** is used to ascertain the nutritional additive concentration requirement for the composition of bacteria within anoxic tank **31** and output the concentration requirement for the nutritional additives of interest. The concentration of the nutritional additives of interest within anoxic tank **31** is ascertained via direct measurement via anoxic tank additive concentration sensor **779** contained within anoxic tank **31**, or MBR online EKF **352**. The concentration of the nutritional additives of interest present within anoxic tank **31** is subtracted from the concentration of the nutritional additive requirement to determine if a deficiency exists for the nutrients of interest and the difference is provided to anoxic tank nutritional additive concentration controller **777**, which adjusts the flow rate of the nutritional additives of interest flowing from anoxic tank nutritional additive tank **778** into anoxic tank **31**.

[0431] Accordingly, if a nutrient deficiency exists, nutritional additives are provided to anoxic tank **31** until the nutrient deficiency is rectified. Accordingly, the flow rate of the nutritional additives of interest provided to anoxic tank **31** is adjusted based on the amount of each species of bacteria present within each of anoxic tank **31** and nutrient concentration present within anoxic tank **31**, so as not to overfeed or starve the bacteria.

[0432] FIG. **38** depicts the aerobic tank DO supervisory controller **1040**, which establishes the aerobic tank DO setpoint.

[0433] In operation, aerobic tank DO supervisory controller **1040** receives the following inputs: permeate NH3-N upper limit setpoint, permeate NH3-N measurement, permeate bCOD upper limit setpoint, and permeate bCOD measurement or estimate, aerobic tank DO maximum setpoint, aerobic tank DO minimum setpoint. The permeate NH3-N upper limit setpoint permeate bCOD upper limit setpoint, aerobic tank DO maximum setpoint, and aerobic tank DO minimum setpoint are established by the operator on the operator control panel **1070**. The permeate bCOD measurement is obtained from a laboratory analysis or estimate is received from MBR online EKF **352**. The permeate NH3-N measurement is obtained from an NH3-N sensor in the permeate stream of membrane tank **33**. Aerobic tank DO supervisory controller **1040** outputs the aerobic tank DO setpoint, which is connected to the setpoint for Dissolved Oxygen in Aerobic Tank as an input for FIG. **29**. The operations that take place within aerobic tank DO supervisory controller **1040** are detailed in FIG. **41**.

[0434] FIG. **39** depicts anoxic tank recycle flow rate supervisory controller **1045**. Anoxic tank recycle flow rate supervisory controller **1045** receives the following inputs: permeate bCOD upper limit setpoint, permeate bCOD measurement or estimate, anoxic tank DO upper limit setpoint, anoxic tank DO measurement, permeate NO3-N upper limit setpoint, permeate NO3-N measurement, minimum anoxic tank recycle flow rate setpoint, and maximum anoxic tank recycle flow rate setpoint. The permeate bCOD upper limit setpoint, anoxic tank DO upper limit setpoint, permeate NO3-N upper limit setpoint, minimum anoxic tank recycle flow rate setpoint, and maximum anoxic tank recycle flow rate setpoint are determined by an operator on the operator control panel **1070**. The permeate bCOD measurement is obtained from a laboratory analysis (slow manual feedback) or an estimate received in real time from MBR online EKF **352**. The anoxic tank DO measurement is obtained from a DO sensor in anoxic tank **31**. The permeate NO3-N measurement is obtained from an NH3-N sensor in the permeate stream of membrane tank **33**. Anoxic tank recycle flow rate supervisory controller **1045** outputs the anoxic tank recycle flow rate setpoint, which is connected to the Setpoint for Anoxic tank recycle line flow rate as the input of FIG. **34**. The operations that take place within anoxic tank recycle flow rate supervisory controller **1045** are detailed in FIG. **42**.

[0435] FIG. **40** depicts anoxic tank biodegradable COD (bCOD) addition flow rate supervisory control scheme **1035**, which is comprised of anoxic tank bCOD setpoint supervisory controller **1050**, anoxic tank bCOD addition flow rate supervisory feedback controller **1055**, anoxic tank bCOD addition flow rate supervisory feedforward controller **1065**, and anoxic tank bCOD addition flow rate summation block **1060**.

[0436] Anoxic tank bCOD setpoint supervisory controller **1050** receives the following inputs: default anoxic tank bCOD setpoint, permeate NO3-N upper limit setpoint and permeate NO3-N measurement. The permeate NO3-N upper limit setpoint and default anoxic tank bCOD setpoint are determined by an operator on the operator control panel **1070**. The permeate NO3-N measurement is obtained from a sensor in the permeate stream of membrane tank **33**. Anoxic tank bCOD setpoint supervisory controller **1050** outputs the anoxic tank bCOD setpoint. The operations that take place within anoxic tank bCOD setpoint supervisory controller **1050** are detailed in FIG. **43**.

[0437] Anoxic tank bCOD addition flow rate supervisory feedback controller **1055** receives the following inputs: anoxic tank bCOD setpoint, anoxic tank bCOD measurement or estimate, anoxic tank bCOD addition flow rate maximum setpoint, and anoxic tank bCOD addition flow rate minimum setpoint. The anoxic tank bCOD setpoint is determined upstream by Anoxic tank bCOD setpoint supervisory controller **1050** or by an operator on the operator control panel **1070**. The anoxic tank bCOD addition flow rate maximum setpoint and anoxic tank bCOD addition flow rate minimum setpoint are determined by an operator on the operator control panel **1070**. The anoxic tank bCOD measurement is obtained from a laboratory analysis (slow manual feedback control) or estimate is received in real time from MBR online EKF **352**. Anoxic tank bCOD addition flow rate supervisory feedback controller **1055** outputs the anoxic tank bCOD addition flow rate (feedback control) setpoint. The operations that take place within anoxic tank bCOD addition flow rate supervisory feedback control **1055** are detailed in FIG. **44**.

[0438] Anoxic tank bCOD addition flow rate supervisory feedforward controller **1065** receives the following inputs: feed bCOD measurement or estimate at anoxic tank inlet, feed NH3-N measurement at anoxic tank inlet, feed NO3-N measurement at anoxic tank inlet, feed flow rate measurement at anoxic tank inlet, bCOD addition flow rate concentration setpoint, reference COD/N ratio setpoint, and feedforward scale factor setpoint. The bCOD addition flow rate concentration setpoint, reference bCOD/N ratio setpoint, and feedforward scale factor setpoint are determined by an operator on the operator control panel **1070**. The feed NH3-N measurement, feed NO3-N measurement, and feed flow measurement are obtained from sensors at the inlet stream of anoxic tank **31**. Anoxic tank bCOD addition flow rate supervisory feedforward controller **1065** outputs the anoxic tank bCOD addition flow rate (feedforward control) setpoint. The operations that take place within anoxic tank bCOD addition flow rate supervisory feedback control **1055** are detailed in FIG. **45**.

[0439] Anoxic tank bCOD addition flow rate summation block **1060** receives the anoxic tank bCOD addition flow rate (feedback control) setpoint from anoxic tank bCOD addition flow rate supervisory feedback controller **1055** and anoxic tank bCOD addition flow rate (feedforward control) setpoint from anoxic tank bCOD addition flow rate supervisory feedforward controller **1065**. Anoxic tank bCOD addition flow rate summation block **1060** outputs the anoxic tank bCOD addition flow rate setpoint, which determines the flow rate of bCOD entering anoxic tank **31** from bCOD tank.

[0440] Aerobic tank DO supervisory controller **1040** is detailed in FIG. **41**. In subtraction block **805**, the permeate NH3-N measurement is subtracted from permeate NH3-N upper limit and the difference is passed to NH3-N gain scheduling control **810**. Depending upon whether the difference between the permeate NH3-N upper limit and permeate NH3-N measurement exceeds a predetermined value established by a person having ordinary skill in the art, either a low gain or a high gain is applied to the output of subtraction block **805** and passed to maximum block **815**.

[0441] In subtraction block **820**, the permeate bCOD measurement or estimate is subtracted from the permeate bCOD upper limit and the difference is passed to bCOD gain scheduling control **825**. Depending upon whether the difference between the permeate bCOD measurement or estimate and permeate bCOD upper limit exceeds a predetermined value established by a person having ordinary skill in the art, either a low gain or a high gain is applied to the output of subtraction block **820** and passed to maximum block **815**. Maximum block **815** passes the greater of the outputs of bCOD gain scheduling control **825** or NH3-N gain scheduling control **810** to minimum block **830**.

[0442] In subtraction block **835**, the aerobic tank DO setpoint is subtracted from the aerobic tank DO maximum setpoint. Gain block **840** applies a gain to the output of subtraction block **835** and provides an output to minimum block **830**. Minimum block **830** ensures that the aerobic tank DO setpoint does not exceed a maximum limit by passing the lesser of the output of gain block **840** or maximum block **815** to maximum block **845**.

[0443] In subtraction block **850**, the aerobic tank DO setpoint is subtracted from the aerobic tank DO minimum setpoint. Gain block **855** applies a gain to the output of subtraction block **850** and provides an output to maximum block **845**. The greater of the output from gain block **855** and minimum block **830** is passed by maximum block **845**, which ensures that the aerobic tank DO setpoint does not fall below a minimum limit. Integration control is provided to the output of maximum block **845** by discrete-time integrator block **860**, which outputs the aerobic tank DO setpoint.

[0444] Anoxic tank recycle flow rate supervisory controller **1045** is detailed in FIG. **42**. In subtraction block **865**, the permeate bCOD measurement or estimate is subtracted from the permeate bCOD upper limit setpoint. Gain block **870** applies a gain to the output of subtraction block **865** (control action for bCOD) and provides an output to maximum block **875**. In subtraction block **880**, the anoxic tank DO measurement is subtracted from the anoxic tank DO upper limit setpoint. Gain block **885** applies a gain to the output of subtraction block **880** (control action for anoxic tank DO concentration) and provides an output to minimum block **890**. In subtraction block **895**, the permeate NO3-N measurement is subtracted from the permeate NO3-N upper limit setpoint. Gain block **900** applies a gain to the output of subtraction block **895** (control action for NO3-N level) and provides an output to minimum block **890**.

[0445] The lesser of the outputs from gain block **885** and gain block **900** are passed by minimum block **890** to maximum block **875** and switch **905**. Minimum block **890** ensures that the minimum DO and NO3-N needs are satisfied and balanced in anoxic tank **31**. The greater of the output from gain block **870** and minimum block **890** is passed by maximum block **875** to switch **905**. Switch **905** passes the output of maximum block **875** to minimum block **920** if recycle is provided to both anoxic tank **31** and aerobic tank **32**, otherwise switch **905** passes the output of minimum block **890** to minimum block **920**.

[0446] In subtraction block **910**, the anoxic tank recycle flow rate setpoint is subtracted from the maximum anoxic tank recycle flow rate setpoint and the difference is passed to gain block **915**. Gain block **915** applies a gain to the output of subtraction block **910** and provides an output to minimum block **920**, which ensures that the anoxic tank recycle flow rate setpoint does not exceed a maximum limit by passing the lesser of the outputs from switch **905** or gain block **915**.

[0447] In subtraction block **930**, the anoxic tank recycle flow rate setpoint is subtracted from the minimum anoxic tank recycle flow rate setpoint and the difference is passed to gain block **935**. Gain block **935** applies a gain to the output of subtraction block **930** and provides an output to maximum block **925**, which ensures that the anoxic tank recycle flow rate setpoint does not fall below a minimum limit by passing the greater of the outputs from minimum block **920** or gain block **935**. Integration control is provided to the output of maximum block **925** by discrete-time integrator block **940**, which outputs the anoxic tank recycle flow rate setpoint.

[0448] Anoxic tank bCOD setpoint supervisory controller **1050** is detailed in FIG. **43**. Anti-windup PI control **945** receives an anti-windup correction signal from subtraction block **950**, permeate NO3-N upper limit setpoint, permeate NO3-N measurement, and default anoxic tank bCOD setpoint. Anti-windup PI control **945** provides an output to anoxic tank bCOD range limiter **955**, which outputs the anoxic tank bCOD setpoint. In subtraction block **950**, the anoxic tank bCOD setpoint is subtracted from the output of anti-windup PI control **945**, and subtraction block **950** provides an anti-windup correction signal to anti-windup PI control **945**. The output of anoxic tank bCOD setpoint supervisory controller **1050** is cascaded to the input of the anoxic tank bCOD addition flow rate supervisory feedback controller **1055**.

[0449] Anoxic tank bCOD addition flow rate supervisory feedback controller **1055** is detailed in FIG. **44**. In subtraction block **965**, the anoxic tank bCOD measurement or estimate is subtracted from the anoxic tank bCOD setpoint. Gain block **970** applies a gain to the output of subtraction block **965** and provides an output to minimum block **975**. In subtraction block **980**, the anoxic tank bCOD addition flow rate setpoint (feedback control) is subtracted from the anoxic tank bCOD addition flow rate maximum setpoint. Gain block **985** applies a gain to the output of subtraction block **980** and provides an output to minimum block **975**.

[0450] In subtraction block **990**, the anoxic tank bCOD addition flow rate setpoint (feedback control) is subtracted from the anoxic tank bCOD addition flow rate minimum setpoint. Gain block **995** applies a gain to the output of subtraction block **990** and provides an output to maximum block **1000**.

[0451] Minimum block **975** ensures that the anoxic tank bCOD addition flow rate setpoint (feedback control) does not exceed a maximum limit by passing the lesser of the output from gain block **970** or gain block **985** to maximum block **1000**. The greater of the output from minimum block **975** and gain block **995** is passed by maximum block **1000**, which ensures that the anoxic tank bCOD addition flow rate setpoint (feedback control) does not fall below a minimum limit. Integration control is provided to the output of maximum block **1000** by discrete-time integrator block **1005**, which outputs the anoxic tank bCOD addition flow rate setpoint (feedback control).

[0452] Anoxic tank bCOD addition flow rate supervisory feedforward controller **1065** is detailed in FIG. **45**. In addition block **1010**, the anoxic tank inlet NO3-N concentration and anoxic tank inlet NH3-N concentration are added together. The output of addition block **1010** is provided to operation block **1015** and operation block **1020**. Operation block **1020** divides the anoxic tank inlet bCOD concentration by the output of addition block **1010**. The output of operation block **1020** is provided to block **1025**, which subtracts the output of operation block **1020** from the reference bCOD/Nitrogen ratio setpoint. The output of block **1025** is provided to operation block **1015**.

[0453] In operation block **1015**, the output of addition block **1010**, the output of block **1025**, and the anoxic tank inlet flow rate are multiplied together, and that product is divided by the anoxic tank addition bCOD concentration setpoint. The output of operation block **1015** is provided to block **1030**. In block **1030**, the output of operation block **1015** is multiplied by the feedforward scale factor, which is to tune the aggressiveness of the feedforward control. The result of block **1030** is the anoxic tank bCOD addition flow rate setpoint (feedforward control). The anoxic tank bCOD addition flow rate setpoint is established by adding the anoxic tank bCOD addition flow rate setpoint (feedback control) to the anoxic tank bCOD addition flow rate setpoint (feedforward control).

[0454] As can be seen, disclosed in FIGS. **29-45** is an improved method of providing optimal control of MBR **30**. The method allows a operator to define optimal setpoints for multiple available control inputs through operator control panel **1070** show in FIG. **46**, which includes setpoints for multiple process variables for AD control system **200** setpoints and MBR control system **300** setpoints. Operator panel includes setpoints such as, dissolved oxygen (DO) concentration setpoints, recycling flow from the membrane tank **33** to anoxic tank **31**, recycling flow from the membrane tank **33** to aerobic tank **32** and bypassing the anoxic tank, adding additional chemical oxygen demand (COD) concentrations to the anoxic tank, and mixed liquor suspended solids (MLSS) concentration setpoint. Further, the method can automate setpoint adjustment based on monitoring permeate demands, feed flow rate, feed composition, as well as other factors. The optimal setpoints can then be defined by the MBR model discussed above, or obtained by system perturbations. The optimal setpoints are obtained with or without chemical addition for MBR membrane fouling inhibition. Accordingly, AD control system **200** and MBR control system **300** are both comprised of operator control panel **1070**. It is understood that in some embodiments, a single operator control panel **1070** can provide setpoints for both AD control system **200** and MBR control system **300**. Further, in other embodiments, AD control system **200** includes an operator control panel **1070**, and MBR control system **300** includes a operator control panel **1070**.

[0455] In practice, the proposed method regulates the setpoints of the operational variables controlled in MBR control system **300**, such as permeate control, RAS control, DO control, and additional COD control, and identifies their optimal values.

[0456] The MBR control system **300** acts to regulate permeate quality of MBR **30** (concentration of bCOD, NH_3—N, NO_3—N in the output), and to maintain the concentration below a maximum specification limit. The MBR control system **300** also minimize aeration (energy use) and chemical use (pH regulation). These controls are maintained by calculating optimal set points for multiple control inputs.

[0457] As shown in FIGS. **38-45**, the MBR supervisory control system **301** utilizes both maximum values, minimum values, and current feedback to calculate optimal set points. Specifically, the maximum value for permeate bCOD, the current value for permeate bCOD, the maximum value for permeate NH3-N, the current value for permeate NH3-N, the maximum value for permeate NO3-N, the current value for permeate NO3-N, the maximum value for anoxic tank DO, and the current value for anoxic tank DO are used in MBR supervisory control system **301** to calculate the optimal operation to satisfy the setpoints for permeate bCOD, NH3-N, and NO3-N. Specifically, MBR supervisory control system **301** utilizes these limits and the max/min signal selection logic to enable the MBR supervisory control system **301** to calculate the optimal setpoints for the lower control loops, therefore optimal operation condition for the process, which in turn, regulates permeate quality and maintain it below the maximum specification limit, and minimizes aeration and chemical use.

[0458] As can be seen, MBR control system **300** is comprised of a MBR supervisory control system **301** and a MBR low-level control system **302**. MBR supervisory control system **301** is comprised of operator control panel **1070**, aerobic tank DO supervisory controller **1040**, anoxic tank recycle flow supervisory controller **1045**, and anoxic tank bCOD addition flow supervisory control scheme **1035**.

[0459] Anoxic tank bCOD addition flow supervisory control scheme **1035** is comprised of anoxic tank bCOD setpoint supervisory controller **1050**, Anoxic tank bCOD addition flow rate supervisory feedback controller **1055**, and Anoxic tank bCOD addition flow rate supervisory feedforward controller **1065**.

[0460] Further, MBR low-level control system **302** is comprised of aerobic tank fluid level PI controller **765**, aerobic tank pH controller **750**, anoxic tank pH controller **755**, anoxic tank recycle line flow rate PI controller **770**, aerobic tank recycle line flow rate PI controller **771**, total MBR recycle flow rate PI controller **775**, aerobic Tank DO concentration controller **745**, membrane tank MLSS concentration controller **760**, and anoxic tank nutritional additive concentration controller **777**.

[0461] Additionally, AD control system **200** is comprised of an AD supervisory control system **201** and an AD low-level control system **202**. AD supervisory control system **201** is comprised of operator control panel **1070**, AD reactor pH supervisory controller **700**, PA reactor pH supervisory controller **701**, and PA:AD overall recycle flow ratio supervisory controller **720**.

[0462] AD reactor pH supervisory controller **700** is comprised of AD reactor nonlinear PI pH controller **705** and AD reactor P alkalinity controller **710**. PA reactor pH supervisory controller **701** is comprised of PA reactor nonlinear PI pH controller **706** and PA reactor P alkalinity controller **711**. PA:AD overall recycle flow ratio supervisory controller **720** is comprised of PA:AD recycle ratio controller **725**, and PA reactor and AD reactor recycle flow rate controller **730**.

[0463] Further, AD low-level control system **202** is comprised of AD reactor biomass concentration controller **735**, PA reactor fluid level controller **737**, PA reactor nutritional additive concentration controller **51**, and AD reactor nutritional additive concentration controller **61**.

[0464] While preferred embodiments of the present invention have been described, it should be understood that the present invention is not so limited and modifications may be made without departing from the present invention. The scope of the present invention is defined by the appended claims, and all devices, processes, and methods that come within the meaning of the claims, either literally or by equivalence, are intended to be embraced therein.

[0465] While this invention has been described in conjunction with the specific embodiments described above, it is evident that many alternatives, combinations, modifications and variations are apparent to those skilled in the art. Accordingly, the preferred embodiments of this invention, as set forth above are intended to be illustrative only, and not in a limiting sense. Various changes can be made without departing from the spirit and scope of this invention. Therefore, the technical scope of the present invention encompasses not only those embodiments described above, but also all that fall within the scope of the appended claims.

[0466] This written description uses examples to disclose the invention, including the best mode, and also to enable any person skilled in the art to practice the invention, including making and using any devices or systems and performing any incorporated processes. The patentable scope of the invention is defined by the claims, and may include other examples that occur to those skilled in the art. These other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal language of the claims.

What is claimed is:

1. A method of monitoring and controlling the operating conditions of a membrane bioreactor (MBR), comprising:

providing a MBR;

monitoring said MBR, wherein said monitoring comprises:

providing a MBR offline extended Kalman filter (EKF) having an offline dynamic model of said MBR, providing a MBR online EKF having an online dynamic model of said MBR; wherein said offline and said online dynamic models of said MBR are comprised of states, process material balances, energy balances, bio-chemical reaction kinetics, estimated parameters, and adapted model parameters; wherein said adapted model parameters are a subset of said estimated parameters;

providing historical operation data for said MBR, wherein said historical operation data is comprised of historical measured input data, historical measured output data, and historical laboratory analysis data;

identifying said estimated parameters of said offline dynamic model of said MBR using said MBR offline EKF and said historical operation data for said MBR;

importing said estimated parameters from said offline dynamic model of said MBR into said online dynamic model of said MBR;

providing real time operation data for said MBR to said MBR online EKF, wherein said real time operation data is comprised of real time measured input data and real time measured output data of said MBR;

updating said adapted model parameters of said online dynamic model of said MBR and estimating one or more model based inferred variables of said MBR using said MBR online EKF, said online dynamic model of said MBR, said real time measured input data of said MBR, and said real time measured output data of said MBR; and

providing one or more of said adapted model parameters of said online dynamic model of said MBR and said model based inferred variables of said MBR to an operator of said MBR;

wherein limits are applied to one or more of said estimated parameters and said adapted model parameters; wherein constraints are applied to one or more of said model based inferred variables;

controlling said MBR, wherein said controlling comprises:

providing an MBR control system;

wherein said MBR is comprised of an aerobic tank, a membrane tank, and optionally an anoxic tank;

wherein said MBR control system uses one or more of said real time measured input data of said MBR, said real time measured output data of said MBR, said estimated parameters of said online dynamic model of said MBR, or said model based inferred variables of said MBR to control at least one of a pH of said anoxic tank, a pH of said aerobic tank, fluid level of said aerobic tank, dissolved oxygen (DO) concentration of said aerobic tank, mixed liquor suspended solids (MLSS) concentration of said membrane tank, biodegradable COD (bCOD) addition flow rate setpoint of said anoxic tank, at least one nutritional additive concentration of said anoxic tank, or at least one recycle flow setpoint of said MBR;

wherein said MBR control system is comprised of an MBR supervisory control system and an MBR low-level control system.

2. The method of claim **1**, wherein said MBR is comprised of an aerobic tank, a membrane tank, and optionally an anoxic tank; wherein said aerobic tank is located upstream of said membrane tank; wherein said anoxic tank is located either immediately upstream or downstream of said aerobic tank when said anoxic tank is present.

3. The method of claim **2**, wherein said aerobic tank and said anoxic tank are modeled separately in both of said online and offline dynamic models of said MBR when both of said aerobic and said anoxic tanks are present.

4. The method of claim **2**, wherein said MBR is further comprised of a mixer and at least one recycle line.

5. The method of claim **4**, wherein said at least one recycle line of said MBR is an anoxic tank recycle line or an aerobic tank recycle line.

6. The method of claim **1**, wherein materials for said material balances in said online and offline dynamic models of said MBR are comprised of at least one of particulate inert, slowly degradable substrate, heterotrophic biomass, autotrophic biomass, decayed biomass, soluble inert, soluble readily degradable substrate, dissolved oxygen, dissolved nitrate-N(Nitrogen), dissolved ammonia-N, particulate biodegradable-N, or bicarbonate alkalinity.

7. The method of claim **1**, wherein said bio-chemical reaction kinetics in said online and offline dynamic models of said MBR are comprised of at least one of aerobic heterotroph, anoxic heterotroph, aerobic autotroph, decay of heterotroph, decay of autotroph, ammonification of soluble organic N, hydrolysis of organics, or hydrolysis of organic N.

8. The method of claim **1**, wherein said historical operation data of said MBR and said real time operation data of said MBR are comprised of at least one of raw influent pH, raw influent temperature, raw influent flow rate, raw influent total organic carbon (TOC), raw influent total inorganic carbon (TIC), added alkali flow rate, added alkali concentration, effluent flow out rate, raw influent soluble chemical oxygen demand (SCOD), raw influent total chemical oxygen demand (TCOD), raw influent readily biodegradable chemical oxygen demand (COD), raw influent slowly biodegradable COD, raw influent volatile suspended solids (VSS), raw influent total suspended solids (TSS), raw influent nitrate nitrogen, raw influent ammonia-nitrogen, raw influent soluble biodegradable organic nitrogen, raw influent particulate degradable organic nitrogen, raw influent inorganic inert particulate, membrane permeate flow rate, wasting sludge flow rate, anoxic tank addition biodegradable COD flow, anoxic rank reactor pH, anoxic tank Dissolved Oxygen, anoxic tank temperature, anoxic tank liquid level, anoxic tank mixed liquor volatile suspended solids (MLVSS), anoxic tank MLSS, aerobic rank blower air flow rate, aerobic tank reactor pH, aerobic tank alkalinity, aerobic tank MLVSS, aerobic tank MLSS, aerobic tank Dissolved Oxygen, aerobic tank temperature, aerobic tank liquid level, membrane tank MLSS, membrane tank MLVSS, membrane permeate SCOD, membrane permeate TCOD, membrane permeate TOC, membrane permeate TIC, membrane permeate nitrate nitrogen, membrane permeate ammonia-nitrogen, wasting sludge MLSS, or wasting sludge MLVSS.

9. The method of claim **1**, wherein said estimated parameters and said adapted model parameters of said offline dynamic model of said MBR and said online dynamic model of said MBR are comprised of at least one of hetrotrophic maximum specific growth rate, anoxic/aerobic hetrotroph growth rate, anoxic/aerobic hydrolysis rate fraction, particulate hydrolysis max specific rate constant, autotrophic maximum specific growth rate, decay constant for heterotrophs, decay constant for autotrophs, yield of hetrotrophic biomass, yield of autotrophic biomass, carbon content in soluble substrate, carbon content of particulate substrate, carbon content of soluble inert, carbon content of particulate non-degradable organic, mass transfer coefficient for O_2 removal in aerobic tank, or mass transfer coefficient for CO_2 removal in anoxic tank.

10. The method of claim **1**, wherein at least one of said estimated parameters of said offline dynamic model of said MBR and said model based inferred variables of said online dynamic model of said MBR are estimated with confidence intervals.

11. The method of claim **1**, wherein said model based inferred variables of said online dynamic model of said MBR are comprised of at least one of the following unmeasured inputs or outputs of said MBR: raw influent alkalinity, raw influent nitrate nitrogen, raw influent ammonia-nitrogen, raw influent SCOD, raw influent TCOD, raw influent readily biodegradable COD, raw influent slowly biodegradable COD, raw influent VSS, raw influent TSS, raw influent inorganic inert particulate, anoxic rank SCOD, anoxic tank MLVSS, anoxic tank nitrate nitrogen, anoxic tank ammonia-nitrogen, anoxic tank biodegradable COD, aerobic tank SOCD, aerobic tank MLVSS, aerobic tank nitrate nitrogen, aerobic tank ammonia-nitrogen, aerobic tank biodegradable COD, membrane tank MLVSS, membrane permeate SCOD, membrane permeate biodegradable COD, membrane permeate TCOD, membrane permeate nitrate nitrogen, membrane permeate ammonia-nitrogen, wasting sludge MLVSS, COD removal rate, or nitrogen removal rate.

12. The method of claim **1**, further comprising tuning said adapted model parameters of said online dynamic model of said MBR using different weights for said real time operation data and a prior knowledge of measurement accuracy of said real time operation data.

13. The method of claim **1**, further comprising adjusting said adapted model parameters of said online dynamic model of said MBR by one or both of:

calculating model predicted outputs of said MBR using said MBR online EKF, said online dynamic model of said MBR, said real time measured input data of said MBR, and said real time measured output data of said MBR, comparing said measured output data of said MBR and said model predicted outputs of said MBR, and updating said adapted model parameters of said online dynamic model of said MBR such that said real time measured output data of said MBR substantially correspond with said model predicted outputs of said MBR; or

periodically re-identifying said estimated parameters of said offline dynamic model of said MBR using said MBR offline EKF and said historical operation data for said MBR, and importing said estimated parameters from said offline dynamic model of said MBR into said online dynamic model of said MBR.

14. The method of claim **1**, wherein at least one of said monitoring said MBR or said controlling said MBR is performed using a computer.

15. The method of claim **1**, wherein controlling at least one nutritional additive concentration of said anoxic tank prevents biomass overfeeding and starvation, wherein controlling said pH of said anoxic tank minimizes alkali dosing, wherein controlling said pH of said aerobic tank minimizes alkali dosing, wherein controlling the fluid level of said aerobic tank minimizes the affect of fluid perturbations of said aerobic tank, wherein controlling the dissolved oxygen (DO) concentration of said aerobic tank ensures that a proper concentration of DO is present in said aerobic tank, wherein controlling the MLSS concentration of said membrane tank maximizes membrane permeability, wherein controlling the bCOD addition flow rate setpoint of said anoxic tank minimizes bCOD usage, wherein controlling at least one recycle flow setpoint of said MBR helps to maintain flow through said MBR.

16. The method of claim **1**, wherein said MBR supervisory control system is comprised of at least one of an aerobic tank DO supervisory controller, an anoxic tank recycle flow supervisory controller, or an anoxic tank bCOD addition flow rate supervisory control scheme.

17. The method of claim **16**, wherein said anoxic tank bCOD addition flow supervisory control scheme of said MBR is comprised of an anoxic tank bCOD setpoint supervisory controller, an anoxic tank bCOD addition flow rate supervisory feedback controller, and an anoxic tank bCOD addition flow rate supervisory feedforward controller.

18. The method of claim **1**, wherein said MBR low-level control system is comprised of at least one of an aerobic tank fluid level PI controller, an aerobic tank pH controller, an anoxic tank pH controller, an anoxic tank recycle line flow rate controller, an aerobic tank DO concentration controller, an anoxic tank nutritional additive concentration controller, an aerobic tank recycle line flow rate Proportion-Integration (PI) controller, a total MBR recycle flow rate PI controller, or a membrane tank MLSS concentration controller.

19. The method of claim **18**, wherein said membrane tank MLSS concentration controller uses one or more of said model based inferred variables of said MBR.

20. The method of claim **19**, wherein said model based inferred variables of said MBR include MLVSS concentration and/or MLSS concentration.

21. The method of claim **16**, wherein said aerobic tank DO supervisory controller, said anoxic tank recycle flow supervisory controller, and said anoxic tank bCOD addition flow rate supervisory control scheme satisfy membrane permeate requirements on COD, nitrate, and ammonia, while minimizing aeration, recycle flow, and bCOD addition.

22. The method of claim **16**, wherein at least one of said aerobic tank DO supervisory controller, said anoxic tank recycle flow supervisory controller, or said anoxic tank bCOD addition flow rate supervisory control scheme uses at least one of said estimated parameters of said online dynamic model of said MBR or said model based inferred variables of said MBR.

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