WP9

DESIGN AND CONTROL OF DUAL MBR CONFIGURATIONS FOR PLANT REFURBISHMENT

D53

EVALUATION REPORT OF THE OPTIMAL CONTROL STRATEGIES FOR THE CAS-MBR DUAL 1 CONCEPT

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1. Executive summary

Goals of this Deliverable

The *Evaluation Report of the Optimal Control Strategies for the CAS-MBR Dual 1 Concept* encompasses an evaluation of a novel model-based feedforward control that the Aquafin team has developed, implemented and tested on a full scale at the Schilde MBR wastewater treatment plant (WWTP), Belgium. The theoretical basis of the controller is described in the Deliverable D52.

Because of the current severe pollutant overloading, the objective of the controller is to make the best possible use of the capacity available in existing tanks for nitrogen removal. The feedforward action is based primarily upon two water quality signals, namely the ammonium and the suspended solids concentrations, measured on-line in the WWTP influent. The model which the algorithm is based on, is a simplified version of the International Water Association Activated Sludge Model 2D (ASM 2D). Iron chloride is used as a temporary expedient to relieve the overloaded CAS unit by improving the efficiency of the primary sedimentation (enhanced primary clarification, or EPC).

Assessment methodology (§ 2)

The assessment is based on full scale data and on the interpretation of these data with a calibrated ASM 2D model. The yardstick for the evaluation is the previous flow repartition control algorithm.

Robustness of the signals (§ 3.1)

The signals from the water quality devices installed in the WWTP influent proved to be very reliable if appropriate maintenance is carried out by the plant operators. Among other things, a regular visual inspection of the pre-filtration unit of the ammonium meter and of possible clogging problems around the suspended solids immersed sensor, seems indispensable for a trustworthy measurement. In the initial evaluation phase, the new controller was often off because of the clogging of the pre-filtration unit of the ammonium device. In one case, the EPC control was activated as a result of the clogging of the suspended solids device.

Goodness of the algorithm's predictions (§ 3.2)

In the evaluation period, the control algorithm underestimated the nitrogen removal performance. The simulations prove that this is to be attributed primarily to the safety factors applied to the algorithm's parameters. Conservative parametric values were used for both the estimation of the influent load and the nitrifiers' kinetics. As we have no indications of significant shifting of model parameters over time, the conservative parametric values will be relaxed in the future.

The effluent results have improved (§ 4.1)

The nitrification activity could be maintained in the CAS lane for two consecutive winters. As it was expected by the theoretical study, at water temperatures below 12°C this has not led to statistically significant improvements in the total nitrogen removal performance (i.e., the extra total nitrogen load coming in was merely converted into nitrate). Mainly because of the limited aeration capacity but also because of the precautionary assumptions initially set for the feedforward control, during a long period of the year the aeration basins in the CAS lane remained virtually fully aerated.

The nitrogen removal efficiencies could however improve of 5 points on a yearly basis, and of over 10% during dry weather flow. The controller could triggered a safe, yet (much) higher denitrification time in the intermittent aeration basin of the CAS lane during dry weather flow operation in the warmer season.

In a representative year, the nitrogen removal efficiency of the WWTP might be further increased by (a maximum of) 8%, by dosing an external carbon source in the bioreactor of the CAS lane during the non aerated phase of operation. The testing of the dosing was planned, but actually not tested during the evaluation period because of managerial problems. Calculations show that this dosing can contributed highly to lower the risk of non-compliance with (1) the daily maximum norm of 20 mg/L during hot, dry days and with (2) the yearly average nitrogen norms of 15 mg N/L and 50% nitrogen removal. Under optimal operating conditions, in a representative year the yearly average total nitrogen removal efficiency of the WWTP should approach 60%.

Evaluation of the enhanced primary clarification (EPC) (§ 4.2)

The compliance problems associated with wet weather flows are mitigated, yet the risk of non compliance is still high. Full scale tests have shown that the enhanced primary clarification is effective as a temporary expedient to relieve the overloaded CAS unit. In the period under study, the EPC control was activated an average of 5 times a month, mainly as a result of first flush events. The dosage of iron chloride allowed a substantial improvement of the suspended solids performance. With a dosage of 50 µl/L it is realistic to attain the 65%-removal of the particulate matter, which was assumed in the theoretical part of the study (cf. Deliverable D52, project Amedeus). It is estimated that in a representative year this mode of operation gives rise to a sludge production increase of 7%. No corrosion problems have been detected.

In conclusion, the newly-developed controller seems promising and its use at WWTP Schilde will be extended beyond the evaluation period. Because of the current severe pollutant overloading, a extension of the biological treatment seems nonetheless necessary (cf. Deliverable D52, project Amedeus).

Further recommendations (§ 5)

The EPC mode of operation can be further optimised by ensuring a more balanced flow to the primary clarifiers, as well as an increased monitoring of the primary sludge concentration and a tighter control of the primary sludge blanket level. At that moment, further testing should be carried out on the viability of sending part of secondary sludge to the primary clarifier (wasting), to improve the primary flocculation at low influent SS concentrations. Because of the limited margin of operation, tighter control on the MLSS concentration in the CAS lane is also recommended. The provision of a MLSS meter in the CAS bioreactor should be considered. As precautionary action, addition of polymers to aid settling (e.g. PAX) should be carried out any time the sludge's sludge volume index in the CAS is over 130 ml/L. The suitability of installing additional pumping capacity for the recycling of the sludge from the (old) secondary clarifiers to the head of the biological reactors should be further investigated.

A number of improvements can also be brought into the control algorithm. Foreseen short term improvements encompass the adaptation of the equation for the estimation of the organic load, the introduction of temperature dependencies directly into the equations, and the direct estimation of the nitrifiers' population in the control algorithm. Other possible improvements in the medium term are the development of a feedforward control also for the intermittent aeration of the MBR bioreactor, and the expansion of the equations to include the full ASM 2D model.

Transferability of approach to other WWTPs

While the control algorithm developed for the Schilde WWTP is definitely site-specific, the concept can be transferred to every plant built or designed according to the Dual 1 scheme.

To make the control algorithm universally applicable, the objective of the controller is to be expanded to account for additional elements such as e.g. cost functions/cost optimisation. Cost modelling is now being developed within the context of a Marie Curie grant (MBR train programme, project 5).

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2. Materials and methods

2.1. WWTP Schilde, Belgium

WWTP Schilde serves a conglomeration of 28,000 p.e. and presents a Dual 1 MBR configuration (Figure 1):

1. The conventional activated sludge (CAS) lane: was built in 1989 with a nominal capacity of 18,000 population equivalents (PE) and a hydraulic capacity of 150 l/s (i.e. approximately 5 times the nominal dry weather flow, or 3 times the Q_{14}). The facility was built to comply with carbonaceous and particulate norms. After renovation (in 2003), the hydraulic capacity increased to 400 l/s (i.e. 4.8 times the Q_{14}). The primary treatment consists of 2 step screens, a sand trap and 3 rectangular primary clarifiers (660 m^3). Secondary treatment is achieved by a conventional activated sludge system (2 x 594 m^3). Phosphorus is removed by simultaneous chemical precipitation. Sludge-effluent separation is achieved by three round settlement tanks (total surface area of 993 m^2).
2. The membrane bioreactor (MBR) lane: was built in 2003, with the aim of (a) meeting more stringent water quality norms (including the requirement for nutrient removal), (b) increasing the biological capacity to 28,000 PE and (c) the hydraulic capacity to 6 times Q_{14} (or approx. 10 times the nominal dry weather flow). The MBR lane is composed of a drum-sieve to protect the downstream system, a pre-denitrification tank (500 m^3), an aeration basin (500 m^3) and a filtration unit (V = 240 m^3). The filtration unit is composed of 4 Zenon MBR filtration trains having a total surface area of 10,000 m^2 and being able to treat, in total, an average flow of 230 m^3/h, and maximum peak flow of 355 m^3/h.

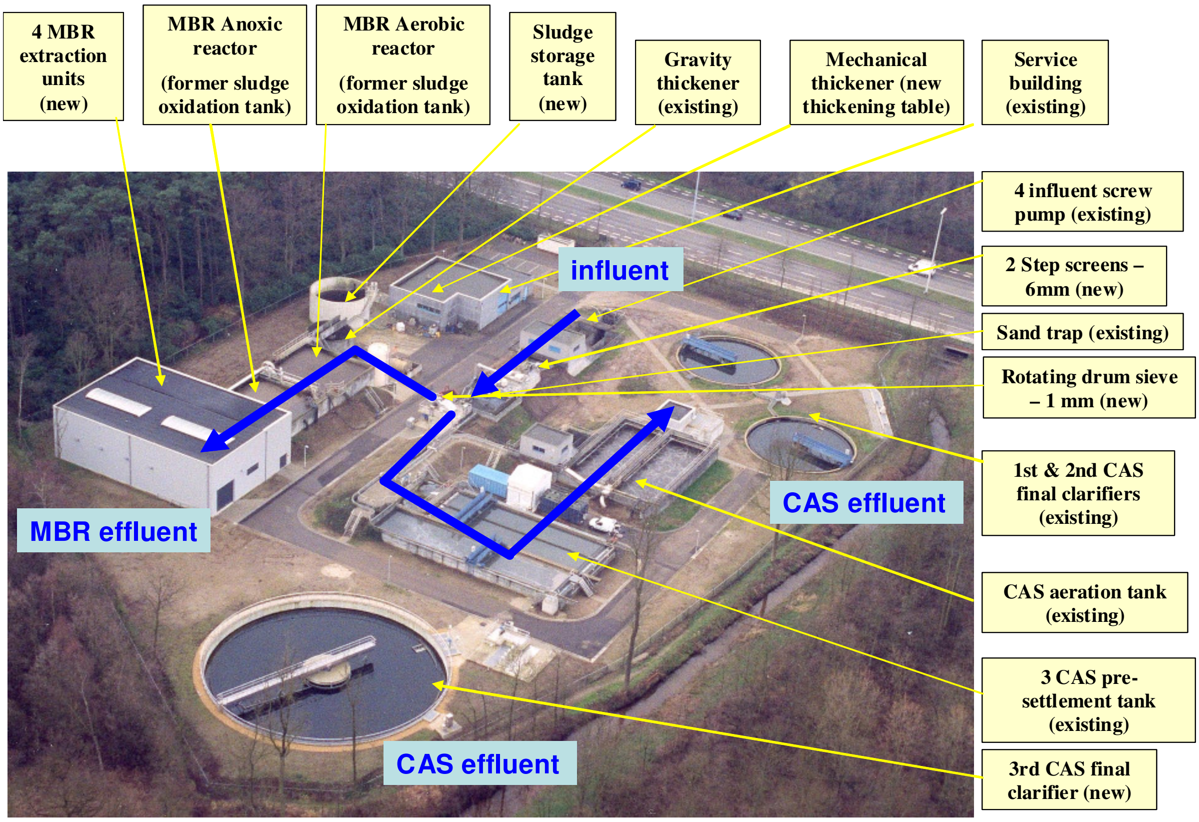


Figure 1: Aerial view of the WWTP Schilde

The secondary excess sludge from the two lanes is thickened mechanically in a newly-built thickening table, while the primary sludge of the CAS lane is thickened in the existing gravity thickener. Primary and secondary thickened sludge are then mixed in a buffer tank and transported to a nearby centralised waste sludge treatment facility where it is digested and dried before final disposal or reuse. All the supernatant from the sludge handling devices is conveyed to the MBR lane.

For the very nature of the Dual 1 design, the two lanes are subjected to very different operational conditions (Table 1).

Table 1: Operating determinants for the dual wastewater treatment scheme of Schilde

Parameter	CAS	MBR
Biomass conc. bioreactor (g MLSS/L)	2.5 – 4	10 – 12
Solids Retention Time (days)	4 – 9	14 - 21
Hydraulic Retention Time (hours)	3 – 75	3.5 – 5
Operating temperature (°C)	8 – 22	9-23
Operating pH	6.9 – 7.4	7 – 7.7

The scheme is severely overloaded, even after renovation. Table 2 reports on influent vs. design loads and on the effluent quality achieved in 2007 compared to the effluent compliance norms.

Table 2: Influent vs design loading, WWTP effluent quality vs norms (year 2007)

	Loading (kg)/day			Design capaticy	Effluent (2007) / norm (mg/l)			Efficiency (2007) / norm (%)
	Avg	St.Dev.	Max.	(kg/day)	Avg.	95%ile	Max.	Avg.
BOD_5	1,290	831	4,149	*513*	3.3/-	20.7*/25	24.5*/50	93*/90
COD	4,176	2,874	14,033	*1,723*	35.4/-	57.8*/125	105*/250	83*/75
SS	2,422	2,832	14,237	*1,073*	7.4/-	14.9/35	23/88	94/84
Tot-N	437	163	891	*207*	12.5/15	21.6/-	27.1/24	55/50
Tot-P	78	44	232	*38*	0.5/1	1.0/-	2.0/-	89/80

*excluding one measuring point (accidental release of the external carbon source used for denitrification)

Despite the severe overloading, in 2007 the WWTP complied with all the effluent norms except for the daily maximum for total nitrogen. While this non-compliance corresponds to a single unfortunate event (namely: heavy first flush event in combination with the failure, during the weekend of the MBR pre-treatment unit), the system is vulnerable to compliance problems associated with wet weather flows. It is worth mentioning that the WWTP was not designed to comply with such norm, nor with removal efficiency norms, since these norms have been established after the WWTP renovation and are valid since 1 January 2006.

2.2. Compliance problems associated with wet weather flows

Hydraulic peaks due to wet weather flow can be associated to pollutant peaks that can exceed two to three times the average load. During first flush events, suspended solids concentrations stay over the dry weather levels for up to 6 hours. The suspended solids profile of a typical rain event is shown in Figure 2. A first and a last flush are clearly detectable.

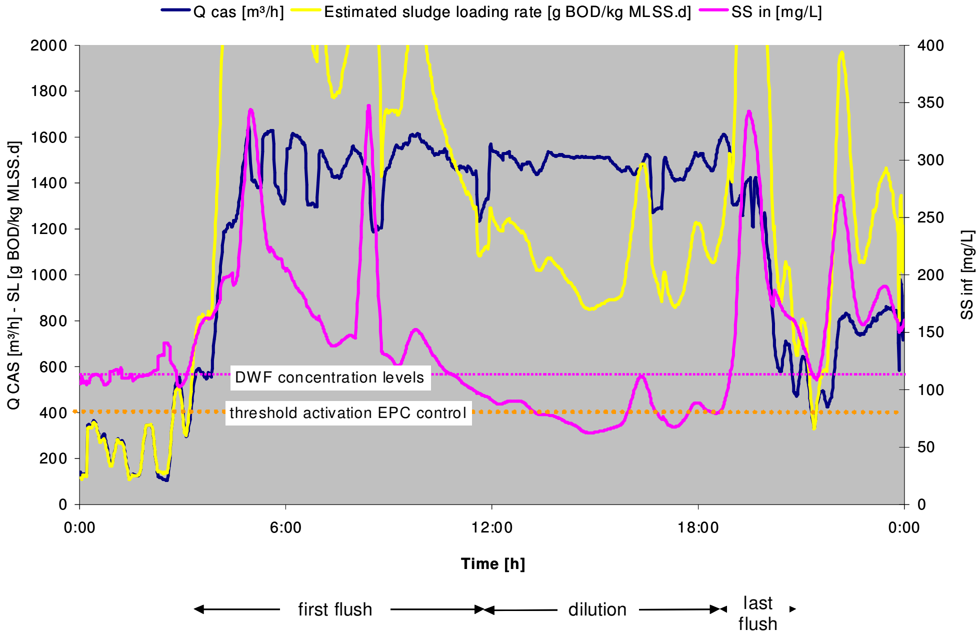


Figure 2: Flow distribution and suspended solid profile of a typical rain event (5 January 2008)

Considering that, for the very nature of the Dual 1 concept, the excess wet weather flow is handled in the CAS lane -and that in Flanders a maximum of 10 dry weather flows are pumped and treated biologically (Bixio *et al.*, 2004), during first flush events the mass organic load load can be as high as 3 kg BOD/ kg MLSS. This value is far above the critical design limit for nitrification. In contrast, during low flow days, the sludge load to the CAS can be as low as 0.02 kg BOD/ kg MLSS. The first flush event can convey to the CAS lane a suspended solids load as high as 2,000 kg in only 5 hours; this is two to four times the daily load under dry weather conditions to the full WWTP, over twenty times that to the CAS lane.

This leads to a number of suboptimal situations such as:

- Increased sensitivity of wet weather days to the compliance with the yearly-average efficiency norms. The yearly averages are calculated based on the total pollutant load entering (and exiting) the system and the pollutant load is much higher during wet weather days.
- Increased importance of the CAS effluent to the daily maxima norms, as most of the wet weather flow is treated in the CAS lane.
- During first flush events, the high sludge load along with the reduced hydraulic detention time in secondary treatment process, leads to significant ammonia peaks in the CAS effluent.
- There is also a risk of solids washout from secondary clarifiers. Because of the limited sludge retention time, a too conservative decrease of the MLSS concentration during dry weather days would make the nitrifiers to be outcompeted in the CAS lane.

It is therefore of primary importance to optimise the process control and utilize on-line data to make prompt process decisions for wet weather events.

2.3. Newly developed flow repartition control algorithm

The central idea of the newly developed control is that a maximum allowable flow will be conveyed to the CAS lane, maintaining the high-flow MBR operation mode for when this maximum capacity of the CAS is exceeded. In those cases where the MBR is not able to handle enough load, i.e. when the MBR is at its maximum capacity and maximum allowable load conveyed to the CAS lane is exceeded, then the pollutant load to the biology of the CAS lane is reduced by an appropriate dosage of coagulants into the primary clarifier -enhanced primary clarification (EPC) mode of operation (cf. Section 2.3.1). The flow repartition algorithm is outlined in Table 3.

Table 3: Alternative feed-forward/feedback control strategy

Mode of operation	WWTP Inflow (m^3/h)	MBR Inflow (m^3/h)	CAS inflow (m^3/h)
1	0- 2*$Q_{CAS[min]}$	0.5*Q_{WWTP}	0.5*Q_{WWTP}
2	<($Q_{CAS[min]}$ +230)	Q_{WWTP} - $Q_{CAS[min]}$	$Q_{CAS[min]}$
3	<($Q_{CAS[max]}$+230)	230	Q_{WWTP}-230
4	>($Q_{CAS[max]}$+230)	High/low flow MBR operation (i.e. 355/230)	Q_{WWTP}-Q_{MBR} EPC, when needed

Where:

$Q_{CAS[min]} = f(KjN_{infl}$, biomass composition, Temperature, TN_{eff}, NO_3-$N_{eff})$ and

$Q_{CAS[max]} = f(KjN_{infl}$, SS_{infl}, Q_{MBR}, biomass comp., Temperature, NH_4-N_{eff}, TN_{eff}, $RE[TN]_{WWTP})$

KjN_{INF} and SS_{INF} are the estimated Kjeldahl nitrogen and suspended solids load in the WWTP influent, while NH_4-N_{EFF}, TN_{EFF} and $RE[TN]_{WWTP}$ are the predicted ammonium concentration in the WWTP effluent, total nitrogen concentration in the WWTP effluent, and N removal efficiency in the WWTP at that given load and given operating conditions. The algorithm is therefore based on hydraulic and biological load considerations, the objective functions $Q_{CAS[min]}$ and $Q_{CAS[max]}$ depending on the organic nitrogen loading.

The objective functions are expressed as follows:

$(Q_{CAS} * RE[TN]_{CAS} + Q_{MBR} * RE\ [TN]_{MBR})/Q_{WWTP} > \alpha * 50\%$;

$(Q_{CAS} * c[TN]_{CAS} + Q_{MBR} * c[TN]_{MBR})/Q_{WWTP} < \beta * 15$ mg N/L;

$c[NH_4\text{-}N]_{CAS} < 6$ mg N/L

Sludge load $_{CAS}$ < X kg BOD / kg MLSS, X depending on the process temperature

with α and β being the assigned safety factors to comply with the nitrogen norms.

In the calculation of the objective function, the WWTP flow repartition, as well as the operating determinants such as the aeration set-points and chemical dosing determined by the feedback control, are compared with an estimate of the capacity required and available in the two systems. This is done by comparing the estimated incoming Kjeldahl nitrogen load with the calculated performance of the activated sludge biomass in the two systems.

The incoming Kjeldahl nitrogen load is estimated based on three on-line signals, namely: the influent flow rate, and the ammonia and suspended solids concentrations in the WWTP influent. Analysis of the historical series reveals that in the WWTP influent, suspended solids are good correlated with the organic nitrogen fraction ($R^2 = 85\%$, cf. Deliverable D52, Project Amedeus).

In the objective function, the nitrifiers' population is approximated based on stationary NH_4-N mass balances. Key kinetic values such as the net growth rate of nitrifiers (i.e. $\mu_{max\ [AUT]} - b_{[AUT]}$) in both the CAS and MBR systems were determined by batch tests.

Based on the above-mentioned predictions, the algorithm adapts also the intermittent aeration phases of the CAS lane. The non-aerated phase can vary between a minimum of 0% and a maximum of 70%

of the intermittent aeration cycle. During the non-aerated cycle automatic dosage of external carbon source is possible, but the dosing amount is to be adapted manually by the operators. This feature is particularly important during the summer / low-flow events, as nitrate peaks are possible.

2.3.1. Enhanced primary clarification (EPC) mode of operation

The Enhanced Primary Clarification (EPC) mode of operation consists in dosing a coagulant (iron chloride) in the canal preceding the primary clarifier whenever both the flow and the estimated BOD load in the CAS influent exceed a given threshold. The dosing of coagulants is activated only if a minimum period of time is passed between two EPC modes of operations, and it is stopped automatically if the pH in the primary clarifier drops below a given threshold. During EPC, the dosing of iron chloride in the CAS bioreactor is discontinued.

Batch tests carried out in the screening phase indicated that the dosage of coagulants in the PSTs may greatly enhance the PST performance (cf Deliverable D52, Project Amedeus). Under optimal experimental conditions, a coagulant dosage as low as 50 µl/L would be sufficient to reduce the SS load to the biological treatment down to 50 kg SS/h or lower. The associated drop in pH was deemed to be acceptable, decreasing from neutrality down to 6.5-6.7 (data not shown).

2.3.2. Yardstick for the evaluation

The yardstick for the evaluation is the previous flow repartition control algorithm, which is described in Table 4. More information is reported in the Deliverable D52 (Project Amedeus).

Table 4: Algorithm used in the previous flow repartition control

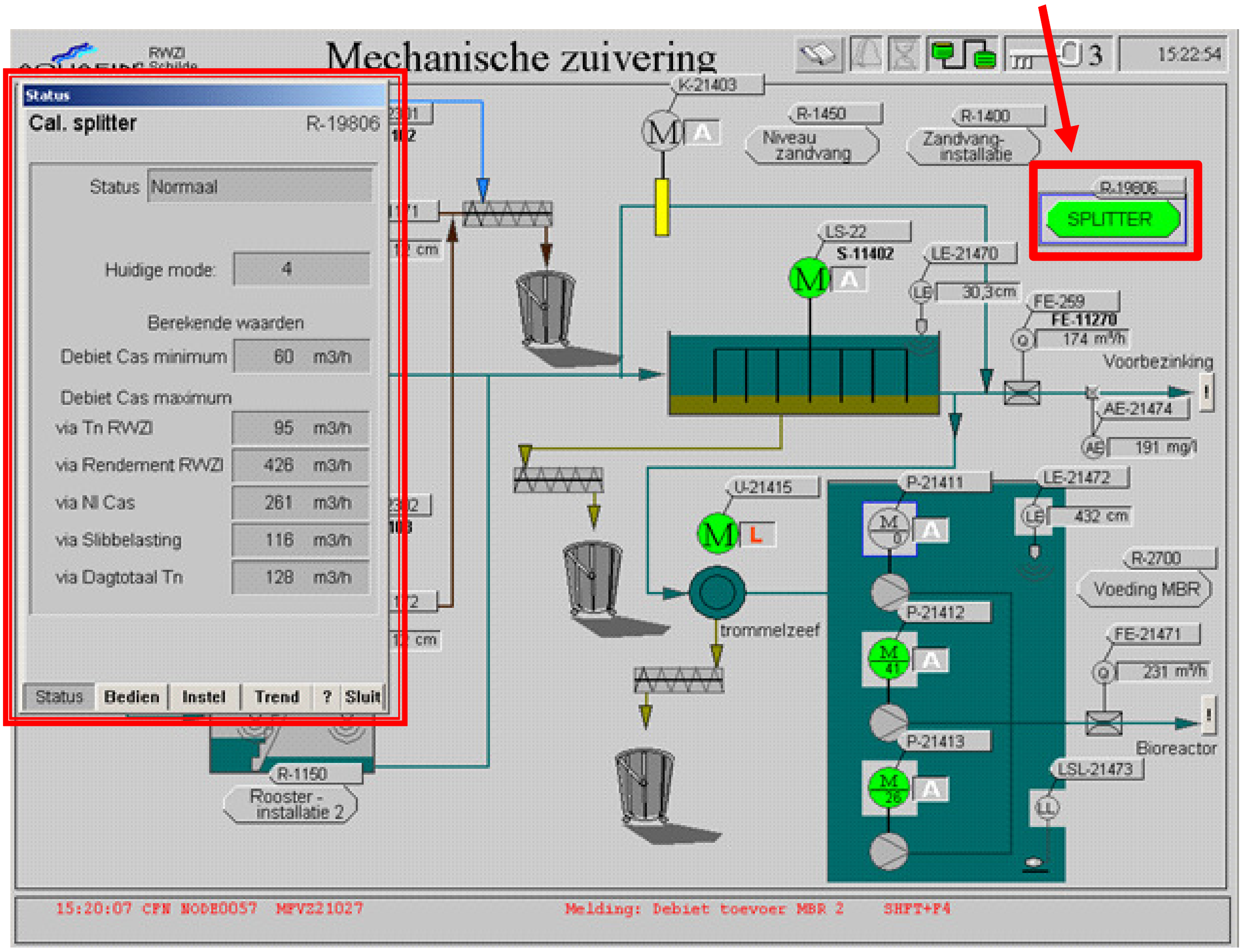
WWTP Inflow (m^3/h)	**MBR Inflow (m^3/h)**	**CAS inflow (m^3/h)**
0-450	* < 16h00: 4 h @ 355 + 8h @ 230 + 4 h @ 355 (or full Q_{INF}) * > 16h00: -IF influent volume to CAS of that day < 800 m^3 ➔ 0 until the volume of 800 m^3 in the CAS for that day is reached -IF influent volume to CAS of that day > 800 m^3 ➔ 230	WWTP inflow – MBR inflow
450-1,800	230	

2.4. Control algorithm implementation

2.4.1. Activation/deactivation of the feedforward control

The main functionalities of the newly developed flow repartition control can be accessed from the *Mechanical treatment* board of the plant's supervision system, clicking on the button *SPLITTER* R-19806 (indicated with an arrow in Figure 3). The service window "*Cal. Splitter"* will then open and offer the possibility to activate/deactivate the controller (button '*instel*'). When the splitter control is active (non-active), the background colour of the button R-19806 is displayed in green (grey).

The "*Cal. Splitter"* window displays the status of the flow repartition control, including its current mode of operation (Mode 4 in Figure 3), and the predicted minimum and maximum flow that may be conveyed to the CAS lane depending on the given set-points and measured influent load (in Figure 3: Q_{cas}[min] = 60 m³/h, Q_{cas}[max] = min [95, 426, 261,116,128] = 95 m³/h, the maximum flow being in that moment limited by the WWTP effluent total nitrogen concentration set-point).



Cal. splitter R-19806

Status: Normaal

Huidige mode: 4

Berekende waarden

Debiet Cas minimum: 60 m3/h

Debiet Cas maximum

via Tn RWZI: 95 m3/h

via Rendement RWZI: 426 m3/h

via NI Cas: 261 m3/h

via Slibbelasting: 116 m3/h

via Dagtotaal Tn: 128 m3/h

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15:20:07 CPN NODE0057  MPV221027          Melding: Debiet toevoer MBR 2     SHFT+F4
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Figure 3: Supervision window of the mechanical units, now with splitter control activator

2.4.2. Modification of the Feedforward control parameters

Details of the calculations as well as the algorithm parameters can be accessed from the *Biological treatment* board of the plant's supervision system (one for the CAS and one for the MBR lanes) by clicking on dedicated, newly established buttons. The *Biological treatment* board of the CAS unit contains now 6 dedicated buttons (R-19800 to R-19805, marked in red in Figure 4).

The newly developed feedforward control of the intermittent aeration can be activated/deactivated via the service window of the aeration control (R-2300 "beluchting", in green -i.e. active- in Figure 4). Three mode of operation are now possible, namely: the already existing BK1 and BK2 mode of operation –both based on feedback control–, and the newly developed BK3 –based on feedforward control–, where the intermittent aeration is calculated based on the predictions of the newly developed flow repartition control algorithm. The activation of the automatic denitrification control has been made independent from that of the flow repartition control, with the objective of providing more flexibility to the process control (i.e. the splitter control may be activated independently from the activation of the feedforward control on the intermittent aeration).

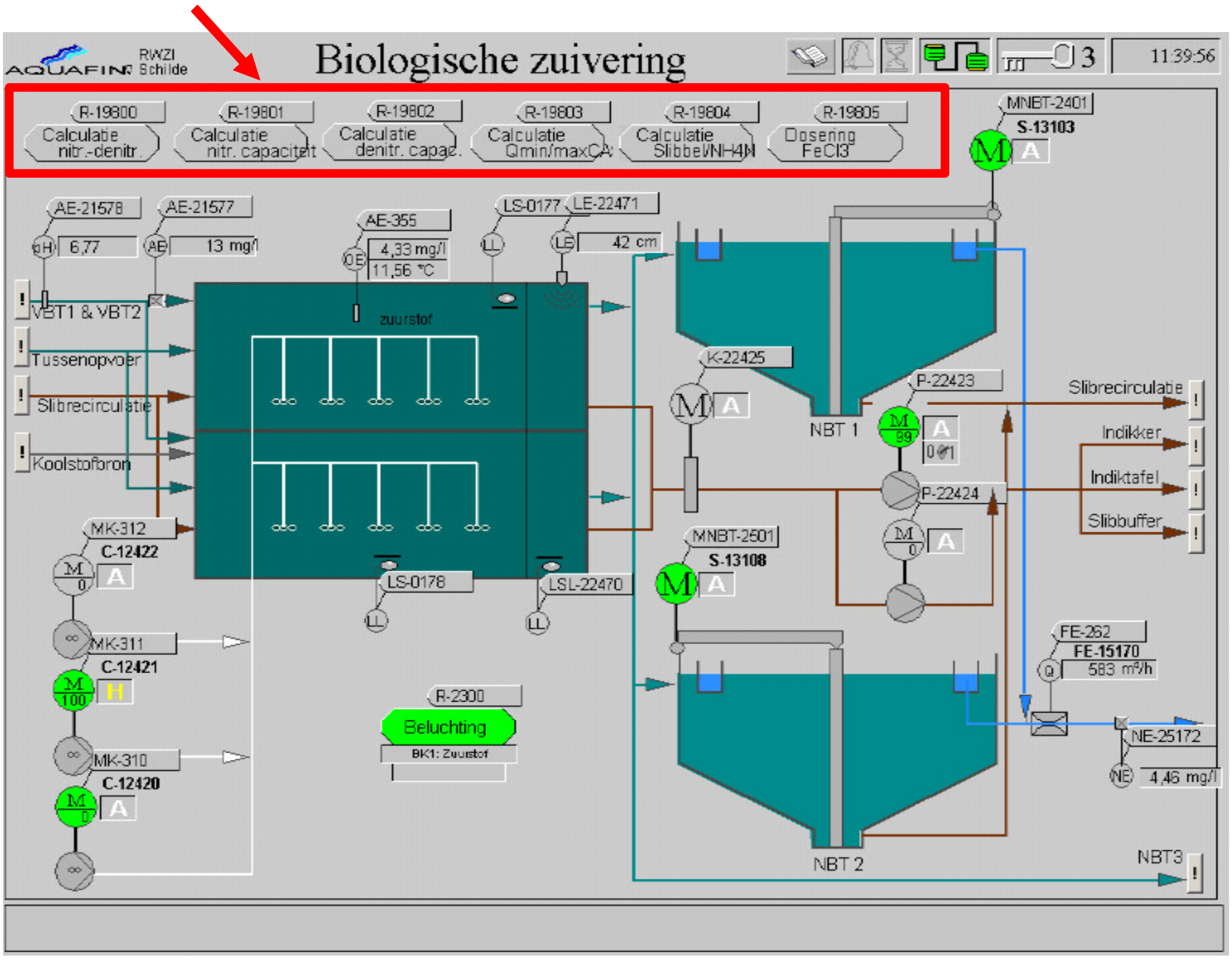


Figure 4: Supervision window of the biological unit of the CAS lane, now with access to the parameters of the feedforward control

2.5. Equipment

On-line turbidimeters in the WWTP influent and in the PST effluent

A *Dr lange SOLITAX* device is now installed in the influent canal of the CAS lane, just after the flow repartition with the MBR lane. The signal is logged on the supervision system with tag HT_21474, and it operates within the range 0-700 mg suspended solids/L. The signal is used by the controller algorithm to estimate the influent organic load (cf. Deliverable D52, Project Amedeus).

For the sake of evaluating the dynamics of the PST performance with and without the dosing of coagulants, during the evaluation period of the flow repartition control the Aquafin team has also placed a *Hach Lange SOLITAX* device at the end of the primary settling tank (PST). Data are stored in the local PLC of the AMEDEUS Dual 2 pilot plant and can be retrieved remotely from the Aquafin headquarters.

On-line pH meter in the PST

An on-line pH sensor has been placed in the PST 1 to alert of potential corrosivity problems related to the dosage of iron chloride during the enhanced primary clarification mode of operation. The signal, which is connected to the PLC of the plant (tag HT_21578), is used for automatically shutting off the coagulant dosing pump, should the pH value drop below a given alert value (currently set at 6.5).

On-line ammonium analyser in the primary clarifier effluent

A *Hach Lange AMTAX compact* device has been installed in the PST 1 effluent. The sample is filtered before entering the process photometer, reagents sets are for the measuring range 2-120 mg NH_4-N/L. The sample preparation, analysis and calibration are fully automatic. The signal is continuously logged on the PLC of the WWTP (tag HT_21577), the control algorithm makes use of 15-minute averages.

Automatic sampling devices

The treatment plant is equipped with 3 automatic devices, taking 24-h composite flow-proportional samples in the WWTP influent, and in the effluent of the WWTP and of the MBR lane.

During the evaluation period of the flow repartition control algorithm, five additional samplers have been installed that take time proportional samples, namely:

- in the influent canal after the sand trap (1),
- in the effluent of each of the three PSTs (3) and
- in the effluent of the CAS lane (1).

The sampler in the CAS effluent is meant for verification and comparison of the effluent results, when the Environmental Agency seals the WWTP effluent for process performance verification.

The other four samplers are in stand-by, and can be automatically activated whenever the iron chloride is dosed to enhance primary clarification (i.e. to evaluate the enhanced primary clarification mode of operation performance).

2.6. Modification of the flow distribution to the primary clarifiers

During the investigated period, the way the PSTs were operated changed four times, the key points of each change are pointed out in Table 5. The main reason was that the study pointed an uneven performance of the settlers.

Table 5: Phases of the evaluation period of the EPC mode of operation

Period	Since – to (2007)	What	EPC Controlled by
1	10/01- 25/04	combination of a 10 m³/h of secondary sludge with Fe^{3+}, mixers in PST 1 and 2	Water level in the WWTP influent pit
2a	26/04 -07/05	Adaptation of the influent channel for better divide to PST 1 and 2. Stop of the secondary sludge return, no mixers	Suspended solids load (i.e. inflow rate and suspended solids concentration, both online)
2b	07/05-13/09	”	Suspended solids load and (minimum) flow
3	13/09 on	Adaptation of the influent channel for better split between PST 1&2 and PST 3	”

In the first evaluation phase, where we studied the impact of merging part of the secondary sludge into the first two primary settlers with the coagulants to improve flocculation, it was clearly observed that there was a significant short circuiting to primary clarifiers 1 (i.e. that closer to the biological unit).

After closer evaluation, a plate was put in place in the preceding canal to improve the separation of the influent among the two settlers. Yet, the following measuring campaign indicated that the separation between the two primary settlers improved it while remaining uneven. A higher loading to the first primary settler is still experienced today. NB This is also the settler chosen for the evaluation of the primary settler performance.

In the second evaluation phase, we decided to improve also the flow repartition between the two settlers and the third one, which was formerly used as rain water tank. The third settler accounts for 47% of the primary settling volume. The changes, which include a perforation of the concrete weir and the setting of a metal plate, have been implemented in the third phase (starting from October 2007). A flow sensor has been installed in the canal leading to the third settler with the aim of evaluating the flow reparation after the upgrading works. The results show that the bypass capability of the new construction is around 20% at high flows, and approx. 40-50% at low flow.

3. Evaluation of the settings of the control strategy

3.1. Robustness of the water quality signals in the WWTP influent

3.1.1. Ammonia

The pre-treatment unit (pre-filtration) required a great deal of interventions and improvements, including the substitution of the membrane unit provided by the manufacturer, while the device as such has proven to require limited follow-up.

Today, the system is fit for use, with the plant operators who are requested to

- perform a visual inspection three days a week (Monday, Wednesday and Friday) and anytime a first flush / septic water reaches the plant,
- Carry out preventive cleaning of the filter once a week, possibly on Friday.

The reagents need to be replaced approximately 8 times a year.

3.1.2. Suspended Solids

The signal of the suspended solid sensor was relatively stable from the very beginning, specially because no pre-treatment (pre-filtration) is here required. The setting is however prone to accumulation of debris on the sensor device. Debris such as fibres and hair are regularly present in relatively big amounts in the sand trap effluent.

It is therefore very important that the operators carry out a visual inspection on a daily basis. A case has been identified where the EPC control was activated as a result of the clogging of the sensor.

3.2. Goodness of the algorithm's predictions

Figure 5 illustrates the observations versus the predictions of the last three months of the evaluation period (i.e. 7 September and 30 November 2007) for the nitrogen concentrations in the effluent of the CAS lane. The predictions for the MBR lane have little practical meaning in this context in that (i) the controller makes active use of the online nitrate measurement in the permeate, (ii) the ammonium concentration is for most of the time below the detection limit, and (iii) the MBR lane removes all the particulate organic nitrogen. The algorithm prediction refers to 15-minute averages composing the 24h composite sample, while the observations refer to 24h-composite samples.

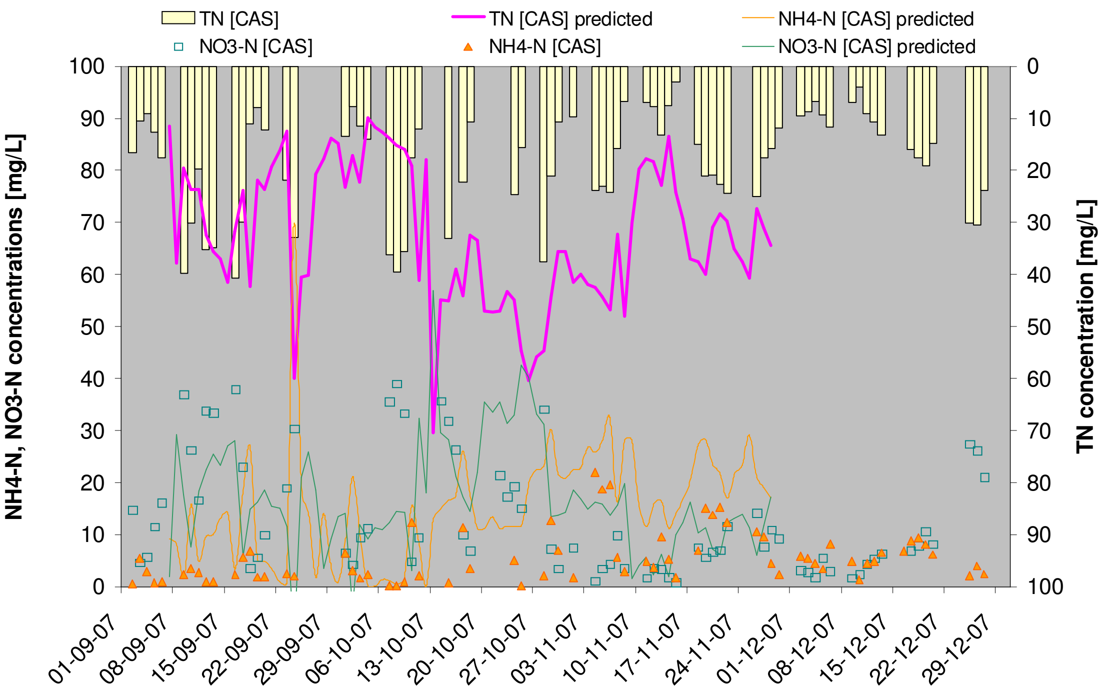


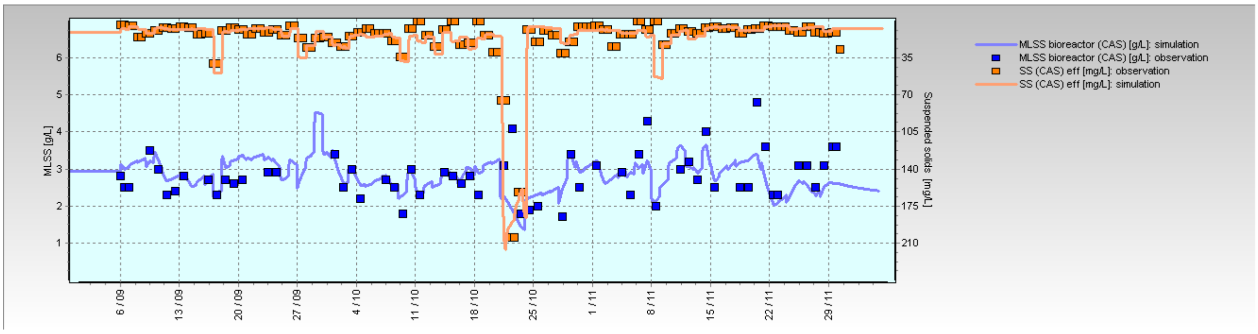
Figure 5: Observed vs. predicted nitrogen levels in the CAS effluent: 7 September – 30 November 2007

Figure 5 clearly points out that the control algorithm underestimated the nitrogen removal performance, exception made for the period between 7 and 9 October[1]. If one considers that the predictions underestimated the formation of nitrate, one can conclude that the estimation of the denitrification capacity was also frequently underestimated, to a lesser extent though.

This is mainly due to the conservative choices made about both the kinetic parameters and the estimation of the influent load. The impact of the precautionary parameters on the algorithm predictions can better be understood by looking at the simulation results with realistic parametric values.

Figure 6 shows the predicted process dynamics, and compares it with the simulation results using the calibrated ASM 2D model (cf. Deliverable D52, Project Amedeus, for details about the calibration exercise).

(a) SS mass balance



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[1] Non-representative period, characterised by chemical cleaning of the membranes

(b) Nitrogen removal: realistic assumptions

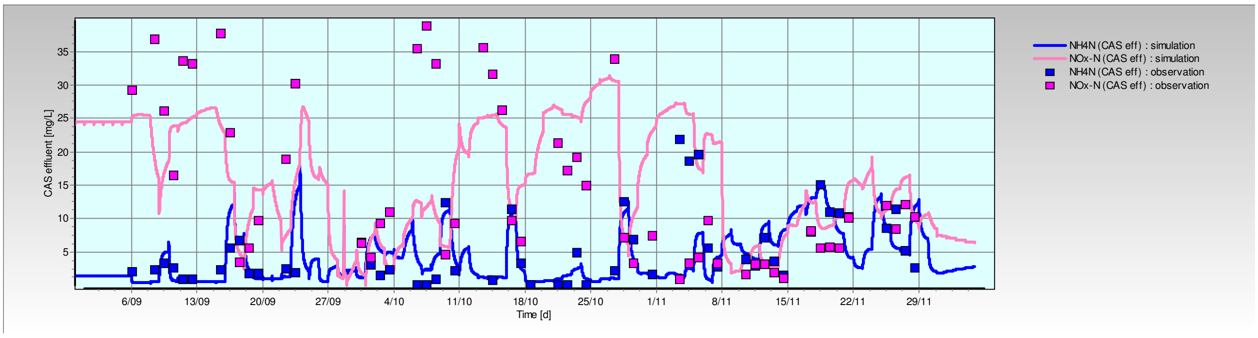


Figure 6: Full ASM 2D predictions: precautionary versus realistic assumptions

Figure 6 shows that the moment only partial nitrification occurs the controller consistently underestimated the system's nitrification capacity. The level of conservatism increased since mid October, when the water temperature decreased (data not shown) and more conservative parametric values were inserted as a precautionary action to prevent nitrifiers' washout.

4. Have the effluent results improved ?

4.1. Dry weather flow

Basic statistics of the measured effluent results are documented below. The results of the evaluation series – which was extended until the end of February 2008 to consider the performance of the newly developed, fully integrated control strategy during the winter season - are compared to the performance of the previous (benchmark) mode of operation during the year 2006. Note that the total nitrogen content in the WWTP influent in the year 2006 was on average 13% lower than in the time series used for the evaluation of the new control strategy.

The average ammonia and nitrate load in the WWTP effluent during dry weather flow is set out in Figure 7. The results are shown for four classes of process water temperatures (<12°C, 12-15°C, 15-18°C and >18°C) The error lines represent the standard deviation.

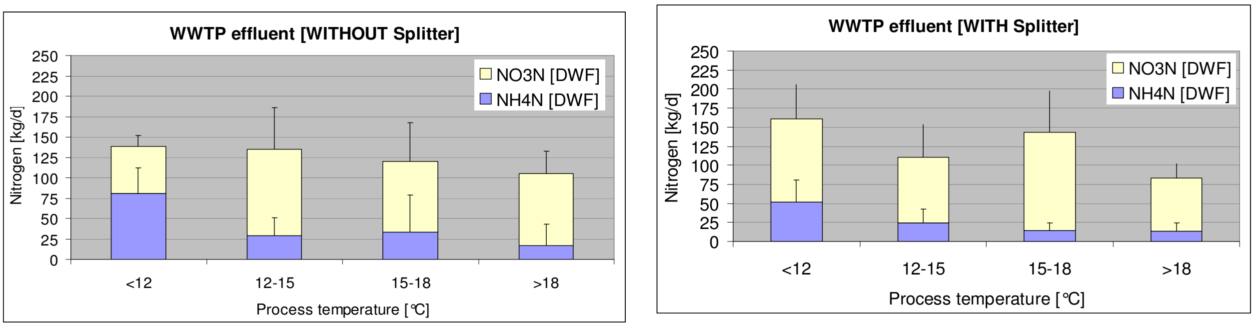


Figure 7: N load in the WWTP effluent during dry weather: (left) previous and (right) new control strategy

Figure 7 points out a number of interesting pieces of information, including the following:

- despite the 13%-increase in the nitrogen load in the WWTP influent, during winter the ammonium content in the WWTP effluent decreased by an average of 36%. This is one of the empirical results that corroborate the outcome of the theoretical study after which **the nitrification activity can be kept into the CAS lane with a much higher degree of certainty all year round** (cf. Deliverable D52, Project Amedeus).

As it was expected by the theoretical study, at water temperatures below 12°C no improved total nitrogen efficiency is obtained (i.e., the extra total nitrogen load coming in, gets just converted into nitrate). Because of both the limited aeration capacity and the conservative assumptions set for the feedforward control (cf. Section 3), during winter the aeration basins in the CAS lane remain virtually fully aerated

In contrast, on a yearly basis **the nitrogen removal efficiency has increased** (over 10 points under dry weather flow conditions, and 5 points considering all the data set). While the overall total nitrogen load in the WWTP effluent remained virtually unchanged, the influent load has increased by more than 10%. The improvement is mainly due to the fact that the controller triggered a higher denitrification time in the intermittent aeration basin of the CAS lane during the warm, drier season.

This was only possible because of the feedforward action (cf. Deliverable D52, Project Amedeus). The denitrification percentage in the CAS lane in the third evaluation period is set out in Figure 8. The inflow to the CAS lane (expressed in Q_{14}, 1 Q_{14} = 1.71 * Q $_{\text{dry weather flows}}$) and the water temperature measured in the bioreactor of the CAS lane are also reported.

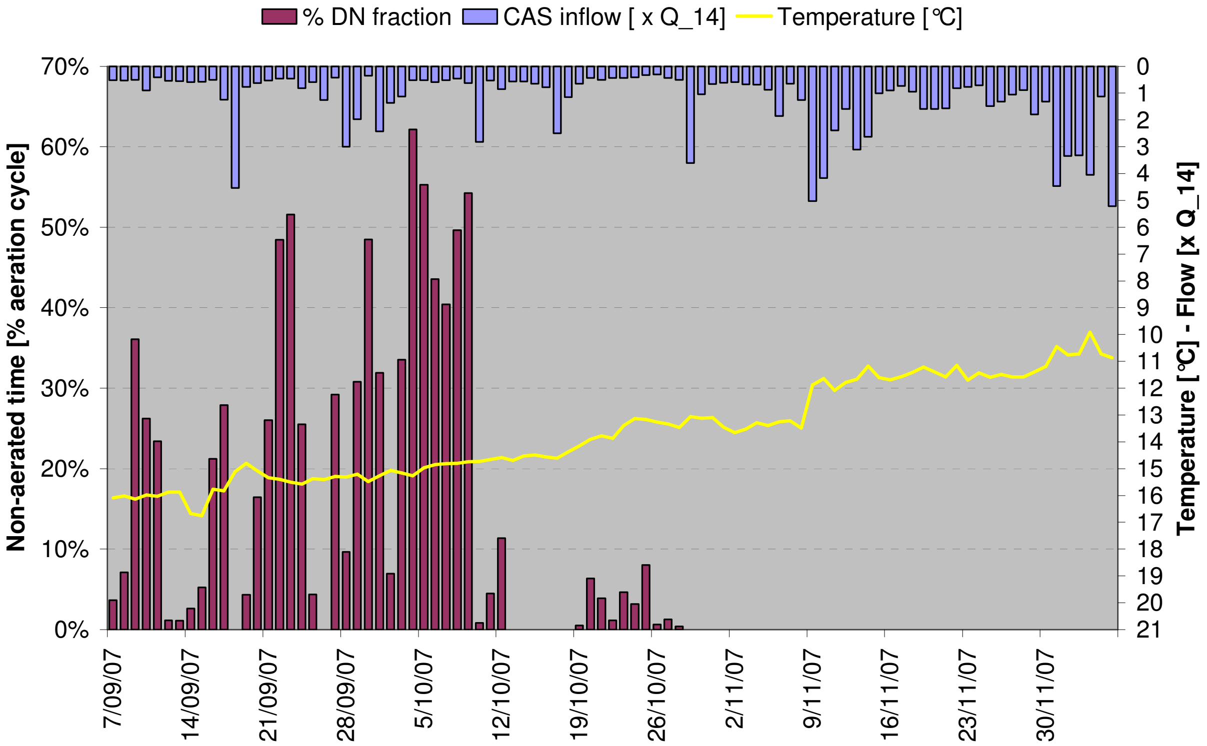


Figure 8: Denitrification percentage of the intermittent of the CAS lane during the third evaluation period (7 September – 6 December 2007)

Figure 8 indicates that during dry weather flow conditions, at water temperatures above 15°C a non-aerated time between 30 and 50% could be (safely) set. Due to the increase in parasitic water, at water temperatures below 14°C the non-aerated time dropped constantly to 0% (i.e. fully aerated basins).

With this regard, it is worth noting that during the entire investigated period the pump which was foreseen in the newly developed control strategy for dosing external carbon in the non-aerated phase of the intermittent aeration cycle of the CAS bioreactors was off. Simulations show that at water temperatures above 15°C, during dry weather flow the activation of this pump can lead to a decrease of the nitrate concentration in the CAS lane of up to 50%. This means that in a representative year the nitrogen removal efficiency of the WWTP can further increase by another of 8% (under optimal operating conditions), the yearly average total nitrogen removal efficiency approaching 60%.

NOTE. *The testing of the impact of the dosage of external carbon in the CAS lane will be starting the moment the process water temperature will reach 15°C (that is to say: May/June 2008). The simulation results indicate that under the mode of operation 1, an extra up to 18 mg/L can be removed by dosing an external carbon source. The mode of operation 1 gets activated only for few weeks a year during the dry, hottest period of the summer season, i.e. between mid June and mid August (data not shown).*

4.2. *Wet weather flow*

Although there are not enough data yet to discuss statistically representative results, the same trends of the dry weather flow are also experienced for rain weather flow. As expected, the extent of the improvement progressively decreases at increasing inflow.

Regarding first flush events, we wanted to verify on full scale whether the enhanced primary clarification is effective as a temporary expedient to relieve the overloaded CAS unit. In the period under study, the EPC control was activated an average of 5 times a month, mainly as a result of first flush events.

4.2.1 Removal efficiency

The EPC control increases considerably the performance of the primary settlers. The removal performance of the primary settler tank (VBT) 1 under normal and EPC conditions is set out in Figure 9.

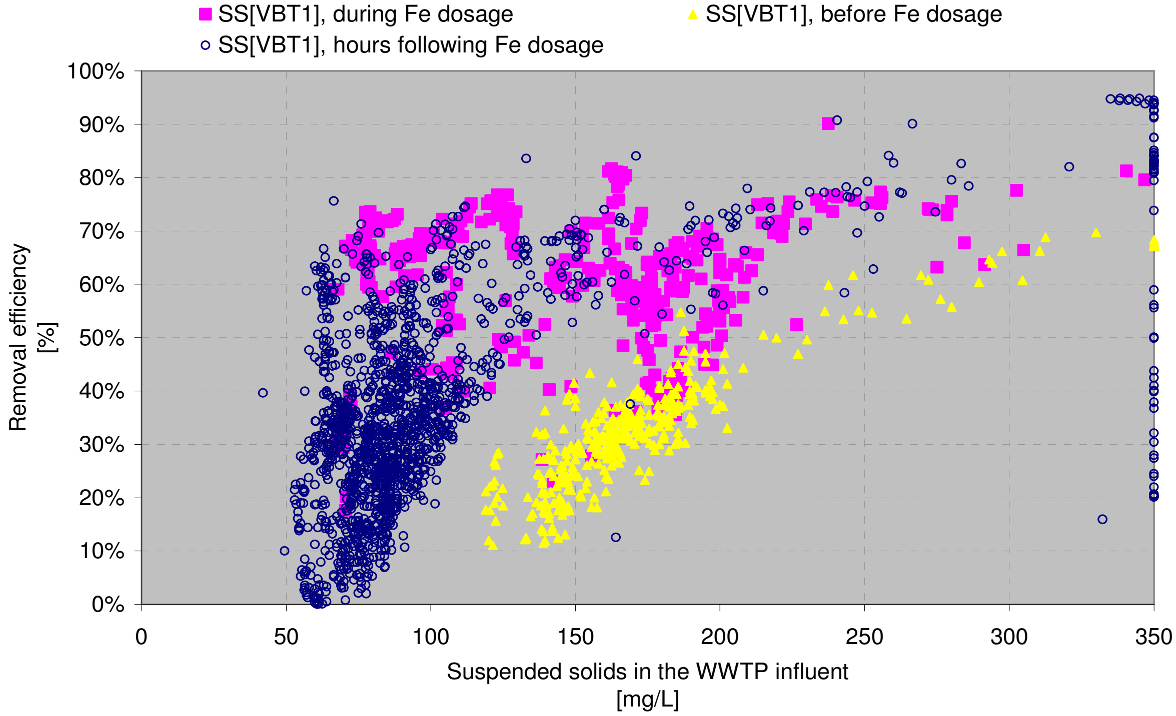


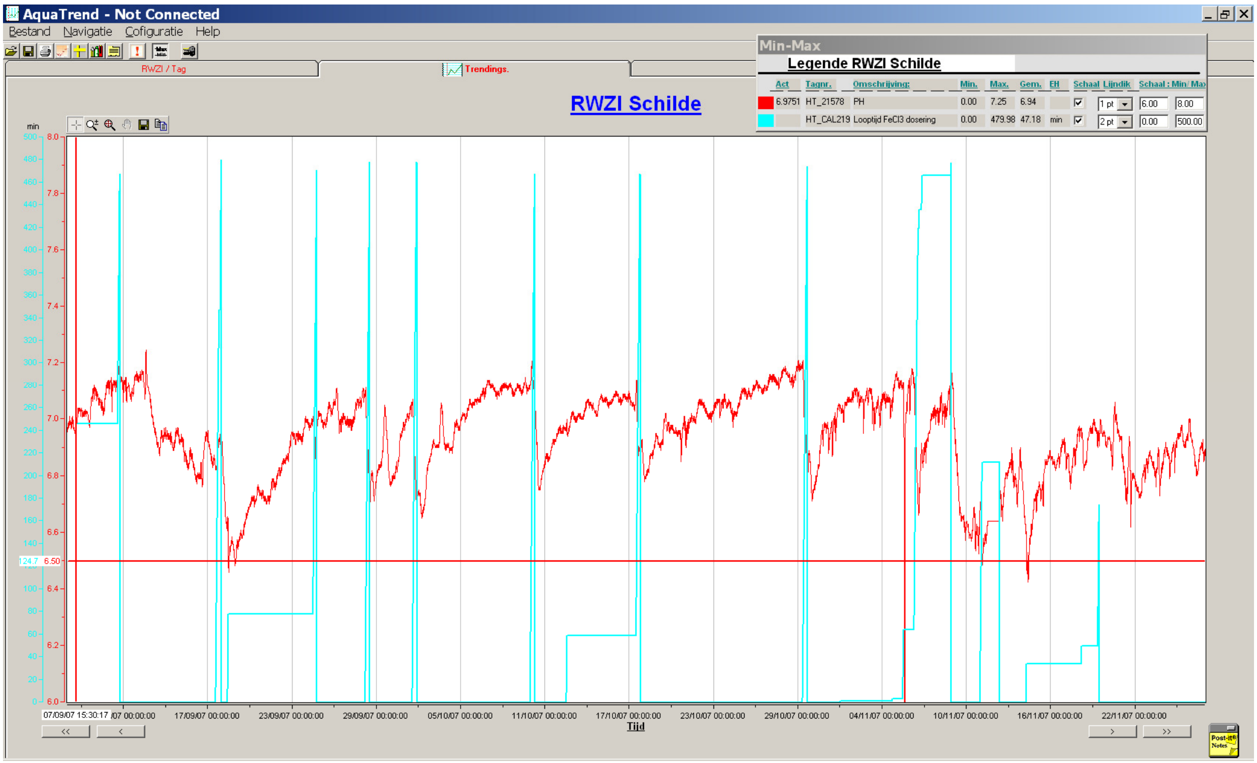
Figure 9: Removal performance of primary clarifier 1 with and without coagulant dosage

Figure 9 shows that:

- The primary reason for the poor removal in primary settlers is the low suspended solids content in the sewage. It is worth mentioning that the surface loading seems to have only a secondary effect (data not shown).
- Dosage of iron chloride allows a substantial improvement of the primary settlers' performance. It is realistic to attain the removal of 65% of the particulate matter, which was assumed in the model-based scenario analysis (cf. Deliverable D52, Project Amedeus).
- An increased removal rate is experienced even after several hours subsequent to the stopping of the dosing.

4.2.1. Corrosivity potential

Observations confirm that the coagulant dosing has a clear effect on pH, but that under the established settings this should not endanger neither the operation of the primary settlers nor that of the downstream reactors. In Figure 10 one can observe the pH at the end of the primary clarifier (red line) and the timer of the coagulant dosing in the influent canal (blue line) for the period September 7 – November 27 2007.



Legende RWZI Schilde

	Act	Tagnr.	Omschrijving:	Min.	Max.	Gem.	EH	Schaal	Lijndik	Schaal : Min/ Max	
🟥	6.9751	HT_21578	PH	0.00	7.25	6.94		☑	1 pt	6.00	8.00
🟦		HT_CAL219	Looptijd FeCl3 dosering	0.00	479.98	47.18	min	☑	2 pt	0.00	500.00

Figure 10: pH variations in the primary clarifier effluent vs coagulant dosing in the influent canal

Figure 10 shows that

- under normal operating conditions, the pH in the primary clarifier effluent is around or slightly lower than neutrality.
- After 480 minutes of dosing (i.e. the currently set maximum time of dosing), the pH drops by about 0.3-0.4 units, only in two occasions the pH level triggered the preventive shutoff of the dosing pump.
- The pH value was back to normal before the currently-set waiting time of 48 hours.
- There is a lag time between the dosing in the influent canal and the drop of the pH at the effluent of the primary clarifier. As expected, this lag time is of about 30-60 minutes, depending on the influent flow conveyed to the CAS lane.

4.2.2. Additional sludge production

The downside of chemically enhanced primary coagulation is the increase in sludge production as compared to primary settling only. The sludge produced during chemical coagulation consists basically of the suspended solids removed and the coagulated/precipitated matter, and it can be described as below:

$$SP = SS_{in} - SS_{out} + K_{prec} * D_{FE}$$

Where

SP = sludge production (g SS/m^3)

SS_{in}, SS_{out} = suspended solids concentration in influent and effluent respectively (g SS/m^3)

K_{prec} = sludge production coefficient (g SS/g Fe), according to literature around 4 for Fe

D_{FE} = dosage of iron coagulant (g Fe/m^3)

Assuming an average suspended solids concentration in the WWTP influent of 150 g/m^3 and a removal of either 65% or 25% (cf. Figure 9) depending on whether coagulants are dosed or not dosed, the extra primary sludge production would amount to 140 g SS/m^3. The estimated extra primary sludge production for a representative year (i.e. activation of the coagulant dosage for 5 events a month having an average duration of 6 hours each) amounts to 50 tons SS/year. The resulting reduction of secondary waste sludge is estimated at approx. 10 ton SS/year. The net increased sludge production is therefore estimated at 40 ton SS/year. This represents **7% of the total WWTP sludge production** in 2007.

5. Recommendations

5.1. *Further optimisation of the control algorithm*

5.1.1. Improved estimation of the organic load to the CAS bioreactor

The rich data set generated during the evaluation period makes it possible to improve the equations estimating the removal of organics in the primary clarifier.

In the equation [SS *out* = (1-$RE_{SS,VBT}$) * SS $_{in}$], the suspended solids removal efficiency parameter $RE_{SS,VBT}$ should now be defined as follows:

- EPC mode of operation:

  $RE_{SS,VBT}$ = 0.6

  (i.e. as a constant, which may be adapted by the operators, and that may vary between 0 and 1).

  Note. A time lag from the activation/deactivation of the EPC mode of operation should be provided (default time lag activation / deactivation of this value: 40 / 120 minutes).

- Otherwise:

  $RE_{SS,\ VBT}$ = [=0.3034*LN(SS $_{in}$)-1.1613], with

  $RE_{SS,\ VBT}$ = 0, if SS $_{in}$ is below 50 mg/L and

  $RE_{SS,\ VBT}$ = 0.5, if SS $_{in}$ is over 250 mg/L

  Note. SS $_{in}$ is expressed in mg/L and RE may vary between 0 and 1.

There is no additional piece of information to think that the conversion factor from suspended solids to organic matter should be changed (cf. Deliverable D52, Project Amedeus). As a matter of a fact, the controller uses for now a conservative value, leading to a lower COD/N ratio in the primary effluent (i.e. overestimation of the nitrate concentration in the CAS effluent).

5.1.2 Introduction of temperature dependencies

Because of difficulties of implementation in the programming language, until now temperature-dependencies were taken into account by changing the related temperature-dependent parameters manually. This is a task that should ultimately be automated. The process water temperature signals of the CAS and MBR lanes are already logged to the PLC, it remains therefore only the programming issue to be solved. Default values of the temperature dependencies of the ASM 2D can be taken.

5.1.3 Control of the intermittent aeration in the MBR bioreactor

The denitrification phase in the intermittent aeration cycle is now defined by the pure feedback control loop triggered by the nitrate signal in the filtration unit. This can be corrected by a feedforward action triggered by the influent NH_4-N and flow repartition signals. A minimum feedforward action could be to let the PLC control whether the nitrification time is long enough to get complete nitrification (e.g. objective function NH4N $_{eff,MBR}$ < 0.5 mg/L).

5.2. Further optimisation of the process operation

5.2.1. Primary Settling

1 *Assure balanced flow.* Especially during storm water events, the first settler shows still a lower performance than the second one, sometimes primary sludge is even washed out from this less performing clarifier.

2 *Control of the sludge blanket levels.* The operators should measure the sludge blanket(s) daily. The frequency of the activation of the waste pumps should be adjusted accordingly. The automation department should take care that the primary sludge waste pump be activated more frequently during the EPC mode of operation (e.g., introduction of two settings, namely: one for conventional primary settling and one for the EPC operation.

3 *Monitor primary sludge concentration*. The operators should measure the primary sludge concentration more often, at least once a week, and then adjust the frequency of the waste pumps accordingly.

4 *Consider to recycle part of secondary sludge (wasting) at low influent SS concentrations.* In order to reduce the excess primary sludge produced during the EPC operation, tests should be carried out to lower the chemical dosage. Part of the metal cation can be replaced with (excess) secondary sludge. Excess secondary sludge would only add little extra sludge production caused by coagulation. The tests should be carried out possibly once the above mentioned points are optimised (i.e. once the inflow is balanced and the sludge blanket maintained low at all times), in order to reduce the risk of sludge washout from the primary clarifier(s).

5.2.2. Secondary Settling (CAS unit)

1 *Maintain low sludge blanket levels.* The model-based analysis of the historical data indicates that the MLSS setting in the aeration tank is strongly dependent on the sludge volume index (SVI). At a SVI of 90, 120 and 150 ml/l, the indicative set-point for the MLSS concentration in the aeration basins is 2.5, 2.0 and 1.8 g/L, respectively (nominal $3Q_{14}$ values). This corresponds to a critical MLSS concentration during maximum flow of respectively 2.5, 2.0 and 1.8 g/L (objective function: to maintain the sludge blanket at 1 meter from the overflow). The enhanced primary clarification mode of operation has improved the situation, yet because of the limited margin of operation, the daily control by the operators is still required.

2 *Consider chemical addition to aid settling*. With the current settings, it is recommended that, as precautionary action, chemicals are added any time the SVI of the sludge in the CAS bioreactor passes the threshold of 130 ml/L. For the type of chemical and the quantity to be dosed, the operator will have to send a sludge sample to the Aquafin central lab and take contact with the O&PO project manager.

3 *Consider the installation of additional pumping capacity*. A model-based analysis shows that at maximum inflows and relatively high SVI, an increased recycling rate from the old clarifiers may substantially decrease the risk of sludge washout (or put in other terms: a higher MLSS concentration in the bioreactor can be maintained). For details about the current settings of the secondary clarifier recycling flow strategy , the reader can refer to the Amedeus Deliverable D52.

6. Conclusions

The newly-developed controller seems to be of practical use and its application at WWTP Schilde is being extended beyond the evaluation period of the AMEDEUS project. The installed online influent water quality devices are deemed to be robust enough for practical use, yet regular maintenance by the plant operators will be crucial for the controller success. Frequent visual inspection of the devices is strongly recommended.

In the evaluation period, the control algorithm underestimated the nitrogen removal performance. The report proves that this is to be attributed primarily to the safety factors applied to the algorithm's parameters. As there are no indications of significant shifting of model parameters over time, the conservative parametric values will be relaxed in the future.

The dosage of iron chloride has proven to be a good temporary expedient to relieve the overloaded CAS unit by improving the efficiency of the primary sedimentation. With a dosage of 50 µl/L it is realistic to attain the 65%-removal of the particulate matter, which was assumed in the theoretical part of the study. The downside of the enhanced primary clarification is that the sludge handling and disposal costs will increase. An extra sludge production of 7%±3% is to be expected on a yearly basis. In theory, this might be decreased by recycling part of the secondary sludge to the primary clarifier. Test should be carried out to verify this on full scale.

The compliance problems associated with wet weather flows are mitigated, yet the risk of non compliance during heavy first flush events is still high. An enlargement of the basins is therefore still recommended.

While the work performed for the Schilde WWTP is definitely site-specific, many of the points discussed here can be applied for basically every plant built or designed according to the Dual 1 scheme.

Acknowledgements

This study would have not been possible without the dedication and competence of Solaiman Amensour, who maintained and optimised the research setup.

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