Theoretical and practical results of the optimisation of Hamburg’s WWTPs with dynamic simulation

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Abstract To assess the influence of the connection of a further 250,000 PE in addition to the 1.85 m PE already served by the combined WWTPs Köhlbrandhöft/Dradenau, a dynamic simulation study was started in 1996. A previous study developing the extension of the WWTP proposed several solutions with costs between €25 million and €100 million. Those concepts were examined by a dynamic simulation study for comparison and further optimisation.

The simulation results indicated that with an increased volume for the storage of sludge liquor it would be likely to fulfil the effluent requirements in spite of the increased load. The construction of the additional storage tank was finished at the end of 1999 together with the connection of the additional load to the WWTP. The cost of this concept was less than €1 million, which is significantly less than if the plants had been extended in a traditional manner.

The first two years of operation showed that the chosen solution is able to fulfil the requirements. The effluent values can be kept within the required limits. A very good correspondence between the measured and the simulated values could be observed.

Keywords Cost-effective treatment processes; dynamic simulation; large WWTPs; optimisation

Introduction
Until the end of the year 1999 approximately 1.85 m PE of wastewater were treated in the combined wastewater treatment plants (CWWTPs) Köhlbrandhöft/Dradenau. From the beginning of the year 2000 the Stellinger Moor catchment area (approximately 250,000 PE) had to be connected to the CWWTPs. To cope with this additional 10% load a concept had to be found which would enable the plant to fulfil the effluent requirements. Especially an increase of the nitrogen concentrations in the effluent was expected.

This paper will describe the procedures carried out to achieve these objectives with emphasis on the dynamic simulations.

Description of Hamburg’s WWTPs
Since the beginning of the 1960s, the wastewater treatment plants have been extended in several phases by carrying out a large number of construction and operational measures. These measures have led to the current concept of the WWTP.

The CWWTPs consist of the WWTPs at Köhlbrandhöft-North and -South and the WWTP at Dradenau. Owing to the limited space available at the Köhlbrandhöft WWTP area, which is located in the Port of Hamburg, the most recent extension was constructed about 2.3 km away from Köhlbrandhöft at the Dradenau site.

The CWWTPs have been designed for biological nitrogen removal and for phosphate precipitation. The Köhlbrandhöft-North WWTP provides the mechanical stage for a part of the influent wastewater. The rest of the wastewater is subjected to mechanical and primary biological treatment (carbon and partial nitrogen elimination) at the Köhlbrandhöft-South plant. After this, both wastewater streams flow to the Dradenau WWTP, which provides nitrification, denitrification and P-elimination. Figure 1 shows the flow scheme of the
CWWTPs. A detailed description of the entire CWWTPs can be found in Ladiges et al. (2000).

The sludge liquor from sludge dewatering (after anaerobic digestion) can be kept in a single 4,000 m³ storage tank (before carrying out the optimisation measures described in this paper) and is added to the influent of the Dradenau plant at suitable times and quantities. Because the sludge liquor contains very high ammonium concentrations, this allows the nitrogen load on the WWTP Dradenau to be levelled and adjusted to the current nitrogen elimination capacity, which varies with the influent characteristics.

As far as the nitrogen parameters are concerned the required standards in the months of May to October are $N_{\text{inorg}} = 18$ mg/l and $\text{NH}_4\text{-N} = 2$ mg/l in 2-hour composite samples. For the rest of the year (November to April) the required standard for $\text{NH}_4\text{-N}$ is 8 mg/l; there is no explicit $N_{\text{inorg}}$ standard, but this parameter has to be minimised. Averaged over the year the plant eliminates more than 70% of the influent nitrogen with reference to the $N_{\text{inorg}}$ effluent value.

**Development of concepts based on daily averages**

A concept had to be developed to be able to maintain the effluent standards mentioned in the previous section when 2.1 m PE are connected to the CWWTPs. Together with the engineering consultancy iat, Stuttgart, a wide range of possible variants was assessed. The final report was prepared in 1995, describing 19 different concepts. These included alternatives for one or two stage activated sludge systems, additional aeration tank volume at Dradenau or Köhlbrandhöft, post denitrification, separate sludge liquor treatment and several further optimisation measures.

Calculation approaches based on daily average values were used in that study to assess the concepts, which proved to vary considerably in technical, operational and financial aspects.

Two very dissimilar variants of the solutions developed appeared to be particularly suitable:

- A concept based on a “standard dimensioning” comprised the construction of 120,000 m³ aeration tank volume at Dradenau which would be a doubling of the size of the biological stage. The total cost for this concept was estimated to be approximately €100 million.
An alternative approach involved the yet unutilised treatment capacity of the WWTP such as an optimisation of the final clarifiers, additional recirculation, separate biological sludge liquor treatment and a bypass optimisation at Köhlbrandhöft-South. The costs of these measures were estimated at approximately €25 million.

Details about the study and the different concepts can be found in Ladiges et al. (2000). As these conventional design approaches could only be used to provide an estimate of the treatment capacity created by the proposed measures, these were subjected to a further investigation using dynamic simulation. The following chapter will describe the steps taken and the results of the dynamic simulation.

Simulation of the Hamburg WWTPs

Objectives of the simulation study

The aim of the simulation study was a more detailed investigation of the concepts which had been developed within the first study described above (iat, 1995).

The additional load of about 250,000 PE on the CWWTPs will essentially only affect the nitrogen effluent values. The critical point is the compliance with maximum values in 2-hour composite samples, as only these are legally relevant. The decisive factor for the evaluation of the optimisation measures therefore was their particular capacity to reduce the peak values.

As the NH$_4$-N effluent value for the most part can be adjusted by means of aeration control, the main emphasis was on the NO$_3$-N effluent value and on the parameter N$_{\text{inorg}}$ (the sum of NH$_4$-N, NO$_2$-N and NO$_3$-N). It was particularly important to reduce the occurrence of high effluent N values at weekends, when the BOD$_5$/N ratio is the most unfavourable.

Realisation of the simulation study

All the simulation procedures were carried out with the SIMBA programme package, versions 3.0+/3.2+ by ifak Magdeburg (ifak, 1997). This programme package is based on the IAWQ model No. 1 (Henze et al., 1987), to which models of the primary and secondary clarifiers have been added.

In the beginning of 1997 the Hamburger Stadtentwässerung (HSE) awarded a contract for the simulation studies to Otterpohl Wasserkonzepte, Lübeck, in cooperation with iat, Stuttgart. For the purpose of the study a project team was set up consisting of representatives from the Otterpohl Consultancy, representatives of HSE (planning, operations and laboratory department) and on occasion from iat. Such project teams have proved very effective in other simulation projects and are an important factor in the success of any such project (Bernatzky et al., 1997).

Modelling and calibration

For the modelling of the CWWTPs and calibration of the model two 14-day intensive sampling phases were carried out in 1996 and 1997. During both phases daily hydrographs of the concentrations and flow rates were measured at various points of the plant. The biological and kinetic parameters were also established. More than 2,000 samples were analysed in each of the two measurement phases, carried out by the Wupperverband (first phase) and the HSE laboratory (second phase).

A model of the whole CWWTPs was set up including both plants at Köhlbrandhöft and the Dradenau WWTP. The modelling of the aeration tanks at Dradenau posed particularly difficult problems. Since the gyroscopic surface aerators in the tanks produce complicated flow conditions which change with aeration control actions, a model had to be found which produces proper results without being too complicated and thus requiring too much.
calculation time. These difficulties, which had never been encountered by simulation specialists before, were solved as described by Ladiges et al. (1999).

Simulation of the variants for nitrogen removal

The following variants for optimising the nitrogen removal were simulated:

- Increase of the MLSS concentration at the Dradenau plant involving reconstruction of the final sedimentation tanks. (The effects of an increased MLSS concentration were simulated, not the settling processes in the final sedimentation tanks.)
- Increase of the storage tank volume for managing the sludge liquor from the sludge treatment (doubling or more of the current tank volume which corresponds approximately to the daily sludge liquor flow).
- Treatment of the sludge liquor from the sludge treatment in a separate treatment plant. (Here the effects of the sludge liquor treatment and not the sludge liquor treatment plant itself were simulated.)
- Addition of internal recirculation in the aeration tanks at Dradenau.
- Denitrification in the connecting siphon between Köhlbrandhöft and Dradenau by means of specific dosage of excess sludge from Dradenau into the siphon.
- Optimisation of the BOD$_5$ elimination at the Köhlbrandhöft-South plant. The aim of this procedure was to reduce the BOD removal in Köhlbrandhöft-South at times when insufficient BOD is available at the Dradenau plant in order to increase the overall denitrification capacity.

The first stage involved the simulation of all variants on the basis of the results from the two 14-day intensive measurement phases and comparing their efficacy. The most effective optimisation measures resulting from the 14-day simulation phases were subjected to a further investigation on the basis of annual hydrographs. The preparation of the annual hydrographs proved to be very time-consuming (Ladiges et al., 1999).

By presenting and discussing the results with the project team at reasonable intervals, all relevant aspects of each variant could be taken into consideration and checked for practical application. This led to many new solutions during the project, so many more possible variants than originally expected could be examined.

Simulation results

In Figure 2 the results achieved in the first phase of the simulations using the 14-day hydrograph data are shown for the increased storage tank volume.

![Figure 2](https://iwaponline.com/wst/article-pdf/47/12/27/422283/27.pdf)

**Figure 2** Doubling of the storage tank volume for sludge liquor. Effluent values. Simulation of the 14-day period
The figure shows the effluent hydrographs before (dashed line) and after (continuous line) the implementation of the measure. The upper lines show the NO$_3$-N and the lower lines the NH$_4$-N concentrations. It can be seen that on individual days increased effluent values occur e.g. due to storm weather or at weekends.

From the 14-day simulations, three variants proved to be particularly effective. These were:
1. Increase in the storage tank volume for sludge liquor
2. Separate treatment of the sludge liquor
3. Additional internal recirculation in the aeration tanks at Dradenau
   in combination with an increase in the MLSS concentration at Dradenau.

These variants were subjected to closer investigation on the basis of the annual hydrographs and simulated with hydrographs before and after the connection of the additional 250,000 PE. Figures of the annual hydrograph results are shown in Ladiges et al. (1999). Details of a comparison of the variants are described in Ladiges et al. (2000).

The simulation results show that the increase of the storage tank volume for sludge liquor is likely to be suitable to provide continued compliance with the required effluent standards in the future. As this variant is the most favourable both regarding investment costs and operational aspects involved, it was decided to carry out this measure.

Results of the first two years of operation in 2000 and 2001

At the end of the year 1999 the construction of the additional storage tank was finished at the same time as the additional load was connected to the WWTP. Since that time the WWTP comprises 8,000 m$^3$ storage volume instead of 4,000 m$^3$, which corresponds to the sludge liquor production of about 2 days.

For the first two years of operation (2000 and 2001) the legal requirement for the parameter N$_{inorg}$ was increased from the usual 18 mg/l to 23 mg/l in the period from May to October, since higher effluent peaks could be expected in the first time of operating the WWTP with the new wastewater and the doubled storage volume.

The operating strategy for the storage tanks is based on the influent situation of the WWTP. On weekends the influent concentration of BOD decreases; caused by a slowdown of the production processes of the industry in the catchment area. In these periods (and also during stormwater inflows) the sludge liquor has to be stored to prevent NO$_3$-N – peaks in the effluent. The most critical situations are “long weekends” when holidays are connected to weekends. In these periods of 3 and sometimes 4 days a sufficient percentage of the sludge liquor production has to be stored.

The goal of the operation of the two storage tanks was to keep the effluent values within the required limits. Although 23 mg/l was the set limit, the target maximum value was 18 mg/l according to the requirement for 2002. The results between January 2000 and November 2001 (time of submitting this paper) are shown in Figure 3.

Since the commissioning of the second storage tank the effluent values can be kept within the set limits. The concentrations of N$_{inorg}$ were lower than 18 mg/l in the whole summer period (for the winter period there are no denitrification requirements, but the parameter N$_{inorg}$ has to be minimised). Also the ammonia effluent concentrations met the set limits, which are 2 mg/l in summer and 8 mg/l in winter.

The results from the first two years of operation are rather promising. Despite the changed influent conditions the effluent values could not just be kept within the set limits for the years 2000 and 2001 but even the stricter requirements for the period beginning in 2002 were met. The aim to keep to the stricter requirements was pursued for two reasons:
- The two-year period between 2000 and 2001 should show that the plant is able to fulfil the new requirements in future.
The permanent operation of the plant with lower effluent values for inorganic N did save effluent charges, which in Germany are calculated based on the declared maximum value for a certain period.

Looking at the two-year experience with the optimised WWTP the effluent values show that the chosen solution of doubling the sludge liquor storage volume is sufficient to meet the requirements. The measured effluent values are corresponding to the simulated values, which have been calculated on a long-term basis for the six summer months (no figures in this paper).

The following conclusions can be drawn from these results:

- The simulation did save a considerable amount of construction cost. While the total costs for the dynamic simulation including laboratory analyses were approximately €150,000 (caused by the rather complex WWTP and the 4,000 samples necessary for the calibration) the chosen solution was calculated to cost less than €1 million. Compared to the preliminary solutions with costs of €100 million and €50 million this aspect alone has proven the value of the application of dynamic simulation.

- During the project of modelling and simulating the WWTP a much deeper understanding of the plant behaviour and the treatment processes could be obtained.

- In the negotiations about the operating permit the simulation results helped to convince Hamburg’s environmental authority of the feasibility of the chosen non-standard solution.

- With the operating results of the years 2000 and 2001 the dynamic simulation’s calculation results could be verified. The model behaviour shows a sufficient correspondence to the real WWTP. Since the dynamic simulation was shown to be a suitable tool for the described optimisation, the computer model can be used for further optimisation projects. After finishing the simulation study in 1998 HSE has carried out several simulation projects for further optimisation of Hamburg’s CWWTPs.

To further increase the treatment capacity of the WWTP the Store and Treat (SAT) process was installed in one of the sludge liquor storage tanks in the autumn of 2001. This is a new concept which combines the advantages of both quantity management and biological treatment of ammonium-rich waste waters. The SAT process was presented at this conference by Laurich and Günner (2003). The dynamic simulation model has been used to develop an operational strategy for the WWTP with the SAT process.

**Conclusions**

For a large and complex WWTP like Hamburg’s it is advantageous to depart from the standard dimensioning approach when seeking to develop optimisation concepts and
undertake detailed investigations of a large number of possibilities. The dynamic simulation of these variants proved particularly suitable to allow the assessment and comparison of a multitude of possibilities at relatively low expense and in a short time. According to the experience of the first two year’s operation the results of the simulation model could be verified.

The dynamic simulation has been established at the Hamburger Stadtentwässerung as a valuable tool for planning and operational purposes. It is in use for further optimisation of the WWTP.

References


