A comparison of continuous flow and sequencing batch reactor plants concerning integrated operation of sewer systems and wastewater treatment plants

J. Simon*, **J. Wiese**** **and H. Steinmetz*****

*Institute of Urban Water Management, University of Kaiserslautern, Paul-Ehrlich-Str. 14, 67663 Kaiserslautern, Germany (E-mail: *simonj@rhrk.uni-kl.de*)

**Anlagen- und Sondermaschinen Automation (ASA) GmbH, Robert-Bosch-Str. 7, 32547 Bad Oeynhausen, Germany (E-mail: *wiese@asagmbh.de*)

***Institute for Innovative *Waste*water Technologies, University of Kaiserslautern, Paul-Ehrlich-Str. 14, 67663 Kaiserslautern, Germany (E-mail: *hsteinme@rhrk.uni-kl.de*)

Abstract Integrated operation strategies for combined sewer and WWTP are becoming more and more popular because of numerous benefits. One can find many examples in literature, but many of these studies deal with partly fictitious systems and/or were accomplished within the planning. Hence most of these studies do not have to deal with the restrictions given by already built constructions. The authors, who worked on several integrated projects, will discuss the requirements of SBR and CFR plants concerning an implementation of integrated operation.
Keywords Continuous flow reactor (CFR); integrated operation; real-time control (RTC); sequencing batch reactor (SBR)

Water Science & Technology **Vol 54 No 11–12 pp 241–248** © IWA Publishing 2006

Introduction

During recent years, the boundary conditions in the field of urban water management have continuously changed: e.g. higher environmental protection regulations, new emission-based directives. Consequently, today's urban water problems are very complex. Further, the financial situation of many municipalities is very difficult and/or the public budgets are low. So, it becomes important to find solutions and/or technologies, which are ecologically and economic reasonable ('ideas instead of concrete'). In this context, integrated RTC concepts and operation strategies, which are trying to operate drainage systems and wastewater treatment plants (WWTP) depending on the current capacities of both systems, are becoming more and more interesting. This especially applies because state of the art instrumentation, control and automation (ICA) equipment has become a powerful, reliable and economical tool. Consequently, in recent years, integrated operation strategies have become important research fields. One can find numerous examples in literature (e.g., Rauch and Harremoes, 1999; Hernebring *et al.*, 1999; Seggelke and Rosenwinkel, 2002; Hoppe *et al.*, 2004). Many of these studies deal with partly fictitious systems and were accomplished using simulation only or are part of planning phases of projects. Hence most of these studies do not have to deal with the restrictions given by already-built constructions. As in Central and Western Europe, Scandinavia and some other countries, the degree of connection to treatment plants is $>90\%$ and nutrient removal efficiency averages $>70\%$ for plants $>5{,}000$ p.e., there are no longer hints on urgent needs for extensive new WWTP constructions or reconstruction measures in many countries. Furthermore, almost all of these studies refer to CFR plants, because this type is still mostly used in the world. Nevertheless, in the meantime

doi: 10.2166/wst.2006.814

integrated approaches have also been developed for discontinuous SBR plants, which are built more and more often. In recent years, the authors of this paper worked on several integrated projects for continuous flow as well as SBR plants in simulation as well as in full-scale (Steinmetz *et al.*, 2002). Some experiences of the authors clearly deviate from other statements, which can be found in literature:

Continuous flow reactor plants. One can find many (simulation) studies which conclude that it seems to be easily possible to increase the flow rate to CFR plants during phases of combined sewage flow. In contrast to these statements, the authors have the experience that the implementation of integrated operation strategies for CFR plants is not as easy as many studies let presume. In the case of existing CFR plants a lot of bottlenecks (e.g., limited hydraulic capacities of connecting pipes, limited capacity of secondary clarifiers caused by unpredictable scum and foam problems) can occur, which can complicate or prevent the transfer of integrated RTC concepts into practice (Simon *et al.*, 2004).

Sequencing batch reactor plants. Even when there is no doubt about the suitability of the SBR technology in general, there are still many objections against the use of this technology for plants with high hydraulic loads. In the literature one can find prejudices that the SBR technology is not able to treat combined sewage as well as CFR plants or that a SBR is not able to treat more than two times the dry weather peak flow rate because of the process engineering properties of this technology (e.g. ATV, 1997). In contrast to these statements, the authors have shown that integrated RTC strategies are possible for SBR plants, when modern automation and control equipment is used (Wiese *et al.*, 2005).

In the following sections, results of these projects, technical bottlenecks etc. will be discussed.

System comparison between SBR and CFR

In this section, the advantages, disadvantages and bottlenecks of SBR and CFR plants concerning an implementation of integrated operation strategies and/or integrated planning are discussed. Therefore the two plant types are analyzed for the different categories: biological treatment, hydraulic aspects, ICA and/or operational aspects. Thereby, the comparison is carried out for typical types of SBR (i.e. discontinuous SBR plant with an optional influent buffer tank and ≥ 2 reactors) and CFR (i.e. single stage WWTPs with pre-denitrification or simultaneous nitrification/denitrification) plants. Thus, the following statements can, but must not be valid for all the numerous variants of SBR (e.g. SBBR, CASS, CAST) and CFR plants, which have been developed during recent decades.

Biological treatment process

In a CFR plant, the different steps of the treatment process take place in several different reactors. The reactors are connected by numerous pipes, drains etc. In contrast to this, in a SBR all treatment processes take place in one single reactor step after step. The time between the beginning of the fill and the end of the treatment process is called a cycle. CFR and SBR plants are based on the principles of the activated sludge treatment process, so the biological processes in CFR and SBR plants do not differ fundamentally. Furthermore, the dynamic changes in wastewater composition (Krebs *et al.*, 1999) during the combined sewage flow are also independent from the type of wastewater treatment. Nevertheless, there are a couple of differences between CFR and SBR plants:

In contrast to a CFR plant, an SBR can hold treated wastewater for testing before being discharged to the receiving water. This especially applies when online sensors and analyzers are used for RTC (e.g. NH_4-N, NO_3-N and PO_4-P analyzers).

A lot of SBR plants are operated with a dump fill strategy, i.e., high and low concentrations of readily biodegradable substrates alternate during each cycle. As a result, a SBR plant with a dump fill strategy reacts less sensitively to shock loads, which might be caused by first flush effects at the beginning of a combined sewer overflow event or the emptying of stormwater tanks after the end of rainfall event. Further, many SBR plants are equipped with an influent buffer tank, which can also equalize high pollution loads.

Due to the dump fill strategy, an excess growth of filamentous bacteria is suppressed (Wilderer *et al.*, 2001). Consequently, the sludge settling characteristics of a SBR are usually good and often better than in case of CFR plants.

In a CFR the volumes of the different tanks are usually constant (Exception: optional anoxic/aerobic tanks). Especially the volumes for the biological process and the sludge settling are separated. In an SBR plant it is possible to adapt the duration of each different treatment step to the current operating conditions and/or load situations. In case of scum problems, it is possible to increase the duration of the settling phase (= enlargement of secondary clarifier). In overload situations it is possible to enlarge the react phase and to reduce the sedimentation and draw phases.

Hydraulics

CFR. Due to the continuous principle it is possible to react fast and flexibly to changing influent flow rates (of course only within the hydraulic boundaries of the plant); no influent buffer tanks are necessary. On the other hand, the continuous principle leads to negative effects during phases of hydraulic load: During periods of high hydraulic load, a significant sludge shift from the activated sludge tank (AST) to the secondary clarifiers can be observed. This can lead to a disturbance of the sludge balance and a reduction of the biodegradability (Krebs *et al.*, 1999). Furthermore, fine particles in the secondary settling tank (SST) can be washed out when the hydraulic design of the SST is insufficient, scum/foam problems occur or the sludge flocculation is incomplete (Ekama *et al.*, 1997). Further, the shock load caused by a push-out effect of dissolved compounds from the sewer system (and eventually from the primary settling tank) can deteriorate the nitrification process. As a consequence of the numerous interactions between the different tanks, pipes etc. it can be difficult to determine the hydraulic reserves of CFR plants (i.e. full-scale experiments must be carried out where appropriate) as the following example illustrates.

Example. Figure 1 shows the results of a field test where a SST has been loaded with twice the flow rate (155 l/s) of the design value (77.5 l/s). The plant is a municipal CFR plant (12,000 p.e.) with 2 ASTs and 2 SSTs. The increased hydraulic loading was realized by the shutdown of one SST. The flow towards the plant was not increased. During the shown event, which was the longest measured during 8 weeks (approx. 49 h of maximum influent flow rate), no measurable increased TSS concentration in the effluent (monitored by an online turbidity probe) could be observed. During the measuring campaign of 8 weeks in total 17 combined sewage flow events with increased loading of one SST were measured (7 times <1 h max. influent flow rate, 5 times >4 h max. influent flow rate). During all events no significant effluent TSS (continuously <20 mg/l) could be observed. This increase could be realized due to hydraulic reserves mainly caused by the design for unfavourable operating conditions (design SVI: 100 ml/g, operation: 80 ml/g). However, hydraulic calculations have shown that due

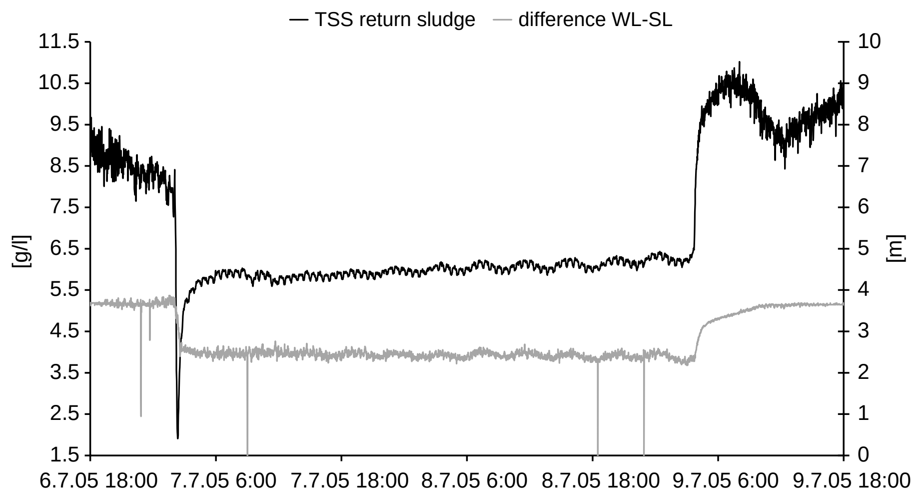

Figure 1 Difference between water level (WL) and sludge level (SL) and/or TSS concentration in the return sludge during a 49 h field test with a doubled hydraulic load for one SST

to plant-wide hydraulic conditions, the maximum additional loading of the plant is only about 30% above the design influent flow rate unless extensive upgrading for screens, grit chamber and inlet construction would be done.

SBR. The conditions for the biomass separation after the end of the biological treatment process are ideal, because of good sludge settling characteristics and the fact, that the sedimentation process is decoupled from the influent situation. So, it is possible to reach very low TSS concentrations in the effluent of the reactors even during phases of high hydraulic load. Another benefit of the discontinuous filling and emptying of the batch reactors is, that pumping stations, decant devices and connecting pipes possess high hydraulic reserves (Table 1). Due to the SBR procedural properties, a few phenomena, which could be observed in CFR (see above) during phases of combined sewage flow, could not occur (e.g. sludge shift, disturbed sludge balance).

Operation and control

The operation of CFR and SBR plants both requires automation on the basis of sensor signals and timers. Furthermore, the same measurement instruments, which are commonly used on CFR to control and/or to monitor the treatment process, can also be used for SBR plants. *Nevertheless, some differences exist:* In dependence of diurnal, weekly or seasonal variations in flow rate, load and sludge characteristics it is possible to vary the sequences of the steps, the duration of phases in a cycle and the volumetric

Table 1 Hydraulic capacity of a typical German SBR plant (5,500 p.e.) in comparison to the maximum design influent rate (100%)

Max. hydraulic capacity of … in % of maximum design influent rate	WWTP SBR
Influent pumping station	213%
Screen/Grit Chamber Module	200%
Connecting pipe: screen module – influent buffer tank	274%
Pumping station (influent buffer tank)[1]	187% – 391%
Decant devices	296%
Connecting pipe: SBR – effluent buffer tank	470%
Connecting pipe: effluent buffer tank – WWTP effluent	296%

[1]Depending on the potential difference between the pressure heads in the SBR and influent buffer tank

exchange ratio (VER, the fraction of the reactor volume, which is removed during draw, and replaced during fill) to the current requirements. This leads in principle to a high flexibility of the SBR technology. But in many cases the flexibility is not used because almost all of the existing SBR plants worldwide are using fixed time-based sequential control strategies (TSC). Until now, measuring devices are predominately used for monitoring only. But with a TSC it is very difficult to react adaptably on the rapid changing of the inflow characteristics (pollution load and hydraulic conditions). This especially applies for SBR plants without or with a small influent buffer tanks. On the other hand, TSC strategies are easy to understand and can be realized with simple ICA equipment. Furthermore, it is easy to synchronize the different SB reactors. But, in order to create a powerful integrated RTC it is meaningful to use process-dependent sequential controller (PSC), which are based on a combination of a timer-based sequential controller and feedback control strategies. According to Keller (2005) such process-dependent control systems provide an ideal way to efficiently utilize and manage the large degree of flexibility the SBR process offers. Unfortunately, such PSC strategies require modern supervisory control and data acquisition (SCADA) systems and powerful programmable logic controllers (PLC); e.g. a complex PSC strategy is based on several thousand variables (process variable, time steps etc.). Many (small) SBR plants possess out-dated SCADA and/or PLC systems, which can only handle a limited number of process and archive variables; in these cases complex integrated RTC strategies can not be implemented, i.e. older SBR plants must be extensively retrofitted with state-of-the-art ICA equipment.

In contrast to this it is much easier to create integrated RTC for CFR plants, e.g. it is possible to create complex RTC strategies for CFR plants, which are based on less than 100 variables. Thus, it should often be possible to implement integrated operational concepts even on older plants with older ICA equipment.

Other aspects

Up-scaling. Plants which are based on the typical SBR principle are limited to 50,000 to 100,000 p.e. because of operational (e.g. many reactors necessary) and economic reasons (i.e. up to now the scale of economy law is not valid for very large SBR plants). In contrast to this numerous very big CFR plants ($>$ 1 Mio. p.e.) are operated world wide.

Transparency. The principle 'All treatment steps take place in one reactor' sounds simple. In reality, the SBR technology is a complex technology. This especially applies because of the very high degree of freedom (e.g., the duration of an individual treatment step can be as long as desired, different steps can be combined diversely etc.). In contrast to this, in a normal CFR plant the degree of freedom is very much smaller.

Consequences for planning and operation

The findings presented in the chapter before are important for integrated concepts for existing plants. But still there are several countries where modern sewer system and WWTP do not exist yet and have to be planned. So it is important to consider the differences between SBR and CFR concerning integrated operation possibilities during the planning phase. In some cases these aspects may lead to the decision for or against one of the mentioned systems.

Hydraulic reserves. For both systems it is essential to have the hydraulic capacities for integrated operation. Concerning the mechanical part (screen, grit chamber, grease trap) of the plant hydraulic reserves have to be considered in the same way. But especially for a CFR plant the dimensioning of connecting pipes and channels in the biological part (including SSTs) must have reserves for higher hydraulic loads. In special cases (e.g., scum and foam problems) it may be helpful to keep reserves in the secondary settling tank (depth and surface area). In contrast to CFR, the SBR has usually hydraulic reserves because of dump fill strategies. But during planning it must be taken into consideration that the VER is adaptable and the decant devices should have a higher hydraulic capacity than usually. Furthermore the cycle duration should be flexible, because it has to be shortened in case of higher hydraulic load. Therefore it is important to have storing capacities in the influent buffer tank which should already be regarded while planning. There is no need to enlarge the effluent buffer tank (if one is necessary at all) in order to run the plant, but a bypass is essential to handle higher hydraulic loads.

Instrumentation, control and automation. The requirements on ICA for integrated operation are considerably higher for SBR plants than for CFR. In CFR plants the amount of return sludge should be flexible, which means mainly that pumps and connecting pipes have to have reserves. Additionally actuators must be adaptable and operate in a wide range.

In a SBR it is essential to have a high flexibility in cycle duration and time of the different phases. At least special timer-based sequential control programmes are necessary or even better a process-dependent RTC strategy. That means that the selection of the automation is very important already during planning. In order to allow complex RTC strategies and/or to react on different inflow load situations, the SCADA and PLC of a SBR plant must be able to handle several thousand variables.

In the case of SBR, it is helpful to control the aerated phase by NH4 analyzers to minimize the aerated phase without exceeding the official effluent limit. For CFR plants, NH_4-N analyzers are essential for plants with a low (aerated) sludge retention time. In the case of aerobic digestion CFR plants, a NH_4-N analyzers is not necessary under normal effluent requirements (>5 mg/l). To avoid a sludge displacement from a SB reactor into the effluent, the authors strongly recommend to control settle and draw phases by using online sludge level probes and/or TSS (and/or turbidity) probes. By using these devices it is easily possible to close the decanter immediately (approx. 1 min) in case of a sludge displacement danger. In contrast to a SBR plant, on a CFR plant it is not possible to close the effluent in case of a sludge displacement. So, it is not possible to use the settler to full capacity. Thus, it is recommended that a sludge level probe is used as a secondary clarifier to monitor the variation of the sludge level and/or to identify critical load situations as early as possible. An additional turbidity/TSS probe in the effluent can be helpful in both systems to monitor the concentrations of suspended solids, but in case of CFR plants this parameter it not suitable for RTC.

As already mentioned, SBR can hold treated wastewater for testing before being released. By using online sensors and analyzers for NH_4-N, NO_3-N and PO_4-P, it is also possible to skip over the decant phase completely (e.g., in case of inadmissible high effluent concentrations). In case of very low effluent limits for organic carbon (<40 mg/l COD in a grab sample) it can be useful to control the decant phase by using online sensors for organic carbon (e.g., a combination of a SAC and TSS probe). To enlarge the biological treatment time to the disadvantage of the settling time is not possible in CFR plants.

Simulation. For integrated planning and operation dynamic simulation can be a helpful tool. The biological treatment processes should be simulated using a detailed model.

Table 2 Cash costs of the new RTC strategy (economic life: CSO: 50 years, measurement equipment: 8 years, real interest rate (without inflation): 3% p.a.)

	CSO tank 550 m^3	RTC
Investment costs	US$ 390,500	US$ 53,900
Reinvestment cost	US$ 47,000	US$ 140,000
Operational costs	US$ 83,000	US$ 238,000
Savings (emission tax)		US$ −173,400
Cash costs	US$ 520,500	US$ 259,000
Savings in total		US$ −261.500

According to the authors' experience Activated Sludge Model (ASM) No. 3 (IWA, 2000) is suitable, because in a batch process/CFR plant large anoxic and anaerobic zones can exist. Further, it is important to use module for SBR plant and/or secondary clarifier, which are able to simulate sludge settling processes in detail. In order to evaluate the plant limits in simulation as good as possible, the control strategies as well as the characteristics of important devices (e.g., pumps, decant devices) and plant components should be modelled in detail. For integrated modelling of small and medium catchment areas it is recommended to use sewer pollution load models which are able to simulate first flush effects. Thus, the model should feature accumulation and wash-off functions and/or optional sedimentation and remobilization of sediments.

Economical aspects

Integrated strategies are reasonable, because in many cases investment and operational costs could be saved. Table 2 shows for a 5,000 p.e. SBR-plant that savings in the region of US$ 250,000 are possible by using a real time control strategy (RTC) for integrated approaches. Due the increase of the treatment capacity during phases of combined sewage flow it is possible to reduce the emissions caused by combined sewer overflow events significantly (e.g., COD emissions: $\approx -25\%$, number of overflow events: $\approx -23\%$): In this manner, one can refuse in the building of another CSO storage tank with 550 m^3. Furthermore the RTC- strategy leads to lower effluent values, which save emission taxes.

Conclusions

Integrated approaches for combined sewer systems and WWTPs possess numerous economical and ecological advantages. In principle, integrated operation strategies are possible for CFR as well as SBR plants, especially when the specific requirements are considered during planning. Nevertheless, there are major differences between CFR and SBR concerning the boundary conditions.

SBR plants are very well suited for integrated operation and can even be superior in performance and flexibility compared to CFR plants. This refers especially to small and medium sized plants up to a population equivalent of approx. 60,000. However the implementation of an integrated operation for combined sewers and SBR plants requires more sophisticated RTC strategies and/or ICA equipment. Due to the cycle based operation of SBR plants this leads to an increasing complexity of the treatment process and highly trained staff will be required to run such plants. Nevertheless, it can be stated that SBR plants feature a significantly higher potential for integrated concepts in many cases.

One advantage of CFR plants is the possibility to implement integrated strategies much more easily than in existing concepts. This especially applies to plants which do not feature state of the art ICA equipment. However, the hydraulic boundary conditions are often more restricting than in SBR plants.

For both types of plants, the non-observance of the mentioned requirements during planning and reconstruction can make a later implementation of integrated operation impossible and/or may have serious technical and financial consequences on the full-scale implementation. Consequently, the authors recommend considering the discussed requirements in order to use the numerous economical and ecological advantages of integrated operation.

References

ATV (1997). *Auswirkungen der Mischwasserbehandlung auf den Betrieb von Kläranlagen (Consequences of combined sewer flow treatment on the wastewater treatment plant operation)*, Arbeitsbericht der ATV-Arbeitsgruppe 2.12.1 (Report of ATV-Working Group 2.12.1). In: Korrespondenz Abwasser, No. 8, pp. 1419–1428.

Ekama, G.A., Barnard, J.L., Günthert, F.W., Krebs, P., McCorquodale, J.A., Parker, D.S. and Wahlberg, E.J. (1997). *Secondary settling tanks: theory, modelling, design and operation*, Vol. 6. Scientific and Technical Report No. 6, IWA Publishing.

Hernebring C., Mark O. and Gustafsson L.-G. (1999). *Optimising operating strategies for sewers and wastewater treatment plants by use of RTC and integrated modelling*, 8th International Conference of Urban Storm Drainage, Proceedings, Vol. 1, pp. 418–425, Sydney, Australia.

Hoppe, H., Weilandt, M., Orth, H., Erbe, V., Podraza, P., Halle, M. and Londong, J. (2004). *Linking simulation of sewer, wastewater treatment plant and river quality management for immission based water quality management*, NOVATECH 2004: Sustainable techniques and strategies in urban water management, Proceedings, Vol. 2, pp. 1575–1582, Lyon, France.

IWA (2000). *The Activated Sludge Models (1, 2, 2d and 3), IWA Task Group for Mathematical Modelling for Design and Operation of Wastewater Treatment*, Scientific and Technical Report No. 9, International Water Association (IWA), IWA Publishing, UK.

Keller, J. (2005). *Sequencing Batch Reactor Processes for Biological Nutrient Removal*, Proceedings, IWA Conference on Biological, Nutrient Removal, Cracow, pp. 245–256.

Krebs, P., Merkel, K. and Kühn, V. (1999). *Dynamic Changes in Wastewater Composition during Rain Runoff*, Proceedings 8th ICUSD, Sydney, Australia, pp. 920–927.

Rauch, W. and Harremoes, P. (1999). Genetic algorithms in real time control applied to minimize transient pollution from urban wastewater systems. *Water Res.*, **33**(5), 1265–1277.

Seggelke, K. and Rosenwinkel, K.H. (2002). Online-Simulation of the WWTP to minimise the total emissions of WWTP and sewer system, *Wat. Sci. Technol.*, **45**(3), 101–108.

Simon, J., Wiese, J. and Hansen, J. (2004). *Integrated Approaches for Combined Sewer Systems and Wastewater Treatment Plants*, 4th International Conference on Urban Drainage Modelling, Proceedings, pp. 365–372, Dresden, Germany.

Steinmetz, H., Wiese, J. and Schmitt, T.G. (2002). Efficiency of SBR technology in municipal wastewater treatment plants. *Water Sci. Technol.*, **46**(4–5), 293–299.

Wiese, J., Simon, J. and Schmitt, T.G. (2005). Integrated real-time control for a sequencing batch reactor plant and a combined sewer system. *Wat. Sci. Technol.*, **52**(5), 179–186.

Wilderer, P.A., Irvine, R.L. and Goronszy, M.C. (eds) (2001). *Sequencing Batch Reactor Technology* Scientific and Technical Report No. 10, IWA Publishing.