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Planning, testing and commissioning of automation solutions for waste water treatment plants using simulation

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Abstract: In Germany, the EU and worldwide, the demands placed on wastewater treatment plants in terms of energy efficiency, cleaning performance, operational reliability and minimization of operating costs continue to grow. This results in an increasing demand for automation solutions with high quality requirements that are well integrated with process engineering and equipment specification. Integrated planning of automation technology in combination with mechanical equipment and process engineering requires the use of simulation tools in planning. A once existing simulation model of a plant can then not only be used for planning and optimization, but also for further questions about the life cycle of the plant. The automation concept simulated during the planning can be used, for example, as a precise requirement specification for the programming of the automation. A powerful application scenario is the virtual commissioning of the automation system.

Keywords: Integrated process design, Process simulator, Virtual commissioning, Digital twin

1 MOTIVATION

In Germany, the EU and worldwide, the demands placed on wastewater treatment plants in terms of energy efficiency, cleaning performance, operational reliability and minimization of operating costs continue to grow. This results in an increasing demand for automation solutions with high quality requirements that are well integrated with process engineering and equipment. Integrated planning of automation systems in combination with mechanical equipment specification and process engineering requires the use of simulation tools in planning (e.g. [Alex 2015]). The increasing use of simulation tools is a component of the increasingly digitized planning of plants. Digital planning documents are state of the art (drawings, documents) and are becoming increasingly comprehensive (keyword BIM Building Information Modelling). A digital model of the plant can then be maintained throughout all life cycle phases of a plant and used for different applications. If this model contains not only geometries and attributes (BIM) but also a functional dynamic simulation model, further uses are possible.

A once existing simulation model of a plant can then not only be used for planning and optimization, but also for further questions about the life cycle of the plant. The model can be used, for example, for the planning of stage expansion concepts, for the virtual commissioning of automation systems, for the continuous optimization of cleaning performance and costs, as a training simulation or as a component of a model-based control system.

A sensible application scenario is the virtual commissioning of the automation technology. This means that the fully implemented automation system (typically programmed PLCs and a PC-based SCADA system) is connected with a simulated plant for testing (see e.g. [Drath et al. 2008], [Hoffmann et al. 2010], [Wolf et al. 2015]).

Reasons for a virtual commissioning, which is already state of the art in other industries (e.g. manufacturing: [Lee and Park 2014], [Zäh et al. [2006], Drinking water: [Worm at al. 2013], are manifold:

- Protection of expensive components (e.g. lock machine technology) during commissioning or/and
- Shorter commissioning with shorter downtimes of production processes.

These reasons are not applicable for the commissioning of wastewater treatment plants. The following reasons apply to the virtual commissioning of wastewater treatment plant automation:

- Quality assurance (comprehensive test), aspect of shortage of skilled workers
- Test in shortened time: Real process with very large time constants
- Test of complex automation, e.g. SBRs
- Testing of functions for rare situations (rain weather high load)
- Test of relapse levels
- Principle function check (if no integrated planning has been carried out beforehand)
- Fine tuning of the automation concept between operator, process planner and automation engineer.

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Virtual commissioning offers itself when simulation models are created during the planning phase and tools and methods are available to perform virtual commissioning with minimal effort. The authors are currently working on the development of tailor-made tools for the water and wastewater industry.

2 PLANNING AUTOMATION SOLUTIONS USING SIMULATION

2.1 Motivation for advanced control concepts at waste water treatment plants

Despite the limitations of the biological processes of a wastewater treatment plant, there is an interesting potential for improvement through control measures. This potential can be used to improve effluent values and energy efficiency.

However, the optimal exploitation of this potential is a challenging interdisciplinary engineering task. If one follows the fate of the chemically oxidisable substances (COD) in a waste water treatment plant (WWTP), it can be seen that a large proportion is oxidized (with oxygen or nitrate). The proportion oxidized with oxygen generates the main energy demand of a WWTP. In contrast, the portion that is ultimately present as biogas can be used as an energy source (thermal and electrical). The following possibilities are therefore available as an approach to process optimisation but also to the planning of automation concepts that are intended to minimise energy requirements:

- Minimisation of the energy requirement for the provision of the required oxygen,
- Maximize pressurised air generation efficiency,
- Minimization of excess oxygen (large distance from DO saturation).

Furthermore, the amount of COD available as biogas should be increased, while at the same time the amount to be oxidized should be reduced. This can be done by:

- Optimal use of the pre-treatment and through a
- Sludge age control.

Furthermore, the proportion of aerobically oxidised COD must be reduced in favour of anoxically oxidised COD, i.e: maximum denitrification.

In addition to the energy required for oxygen supply, energy is also required for conveying waste water and activated sludge and for mixing and preventing sludge settling. When operating pumps, attention must be paid to the design of the pumping system and an operating regime with optimum efficiency in each case.

Almost all these measures can be supported during operation by suitable control functions.

2.2 Integrated Planning of Processes and Automation using Simulation

In order to guarantee, better still improve, the process performance of the waste water plant as a task for the process engineer (civil engineer), a proper designed mechanical equipment (pump stages, diffusers, diffuser density, air distribution system, blower stagees, valve design) must be installed. In order fulfil the requirements with a high degree of efficiency, a coordinated automation system must keep the process stable, fast and load-dependent in the best operating points with the help of the equipment. A powerful tool for all tasks is the use of the simulation tool. To be able to analyse the interactions between processes, equipment and automation, a simulation tool is required that can be used to describe the interaction of all components (SIMBA$^{\#}$ see [Alex 2015]).

Process models: Reliable activated sludge models that have been tried and tested for many years are available to describe the biological degradation processes. The ASM3 (Activated Sludge Model No. 3) provides a reliable model basis for describing the processes of decomposition of carbon compounds and nitrogen (nitrification and denitrification). This simple model should provide reliable answers to most questions arising in the course of automation and process optimisation. If the detailed description of the processes of the extended biological P elimination becomes necessary, the extended ASM3 [Rieger 2006] can be used.

In the simulation tool SIMBA$^{\#}$ widely used in Germany (among others [Alex 2015]) these models and the methods for simplified application are implemented. The activated sludge models are supplemented by models of pre-clarification, post-clarification, wastewater distribution, digestion etc. in order to be able to fully describe the process engineering side of a wastewater treatment plant.

Mechanical equipment: The mechanical equipment of the WWTP (aeration, pumps, control valves etc.) must be suitably designed for the function of the plant and in particular for the function of the automation system. The aeration system is of particular importance here. The current version of the simulation system contains modules for the description of blowers and blower controls, supply pipes with typical internals, control valves (conventional and new developments) and diffuser elements (devices for the fine-bubble introduction of air into aeration tanks), which can be interconnected or combined with a process wastewater treatment plant model. Of course, the function of the automation system can also be considered in detail. Fig. 1 shows a section of a model of a wastewater treatment plant (nitrification basin) to which an aeration system is connected.

Models of ICA components: In order to be able to describe the effects of control engineering measures in the simulation, automation functions must be mapped. For many applications, it makes sense to describe the control functions as a function block diagram. A standard library of basic function blocks is available in SIMBA#. There are blocks for basic mathematical functions, signal processing, dynamic functions such as general transfer functions, characteristic blocks and standard controllers. This function block-oriented approach is particularly useful for continuous control and simple logical operations. For the description of sequence controls, however, other forms of description are useful. For the description of sequential controls different approaches are conceivable. In the newly developed simulation platform SIMBA# a Petri net-based approach is pursued. With Petri nets sequences, also parallel running, can be described graphically, whereby as subset also an automaton graph can be defined (only one mark). This description tool can be used to elegantly describe sequential processes, such as the phases of an SBR plant and alternating / intermittent cleaning processes.

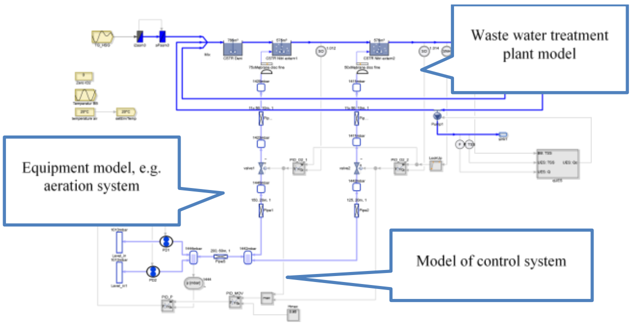

Fig. 1: Integrated simulation model of process, mechanical equipment (aeration system) and control functions

In current projects, the integrated simulation tool is proving to be particularly useful for planning and coordinating plants with more complex automation solutions:

- Sequentially operated plants (SBR plants),
- Energy-efficient aeration control (e.g. sliding pressure control),
- process cascade controls (ammonium controls, sludge age controls) and
- Model-based predictive control.

2.3 Support for commissioning of automation solutions

In order to enable the simple transfer of control algorithms, which have been developed and tested using simulation, into practical applications, a special block has been developed in SIMBA#, whose function can be defined via one of the standardized PLC programming languages (IEC61131 ST - Structured Text [IEC 61131-3 2002], see Fig. 2).

```
(* NH4 controller
(* Example IEC 61131 ST block
(*************************************************************
(* ifak e. V. Magdeburg, 23.12.2012
(*************************************************************
(* FUNCTION_BLOCK NH4c  *)

FUNCTION_BLOCK NH4c
VAR_INPUT
        nh4:    REAL;

END_VAR
VAR_OUTPUT
        o2set:          REAL:=1.0;              (* the DO setpoin
END_VAR
VAR
    i:          INT;

END_VAR
    o2set:=0.5 + (nh4-0.5)*3.0/2.5;
    IF (o2set<0.5) THEN
        o2set:=0.5;
    ELSE
        IF (o2set>3.5) THEN
            o2set:=3.5;
        END_IF;
    END_IF;
END_FUNCTION_BLOCK
```

Fig. 2: Ammonium-Control implemented as “Structured Text”

This is a high-level language (Pascal-like) that can be used to formulate the control code. However, this approach can also be used to implement algorithms of any complexity. The developed and tested function block can later be handed over as source code to the implementing engineers and then either serves as a unique function description or the code is copied directly into the PLC programming environment.

Even difficult control tasks can be solved with model-based control. There are many different variants, but all of them have in common that a simplified model of the process is used as a component of the controller. An example is a general non-linear predictive controller (non-linear MBPC). The internal model of the controller is created as a separate simulation model with the same simulation environment and given as a parameter to the MBPC block. A predictive controller uses an internal model of the controlled system to calculate the controlled variable curve for a given sequence. The calculated control and manipulated variable curve is evaluated in a quality functional.

With the developed simulation platform all these variants can be tested. A more detailed description can be found in [Alex 2015].

3 TEST AND VIRTUAL COMMISSIONING CONTROL

3.1 Coupling Automation System with Simulation

In order to connect a real automation system (PLC + SCADA) against a simulated process, different technical possibilities exist. If all process data is exchanged via a digital fieldbus, the real field devices (on the bus) can be replaced by simulated devices. Bus-specific and relatively complex fieldbus participant emulation systems are required here. Alternatively (see e.g. Guerrero et al 2014), the interface at which the real process is exchanged for a simulation can also be pushed into the PLC (Fig. 3).

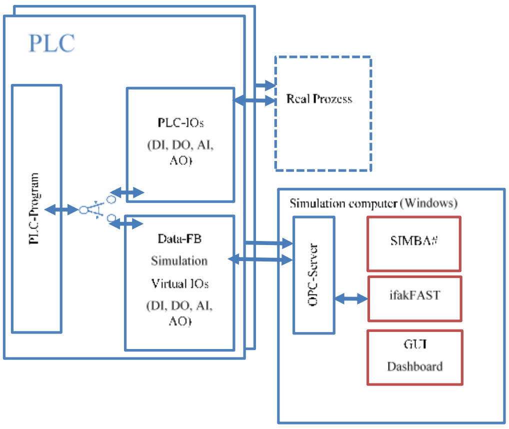

Fig. 3: Replacement of the real process by a simulation model

In the PLC program, the real I/O variables (DI, DO, AI, AO or more complex data blocks that are exchanged with complex field devices (drives, fans, etc.) via fieldbuses) are duplicated as virtual IOs. The virtual IO data blocks are used for testing the PLC program. For real operation, the physical IO variables are switched over. This requires little additional effort on the PLC programming side. This variant is favoured here because it is more manufacturer-independent and requires less effort.

The model of the plant must be simulated in real time (if necessary with n-fold acceleration). The physical control, e.g. in the form of a PLC, interacts during the test with the model of the plant instead of the real plant, so that scenarios can also be tested that would normally only rarely occur in the real plant.

As a prerequisite for the practical feasibility of this approach, the logical signals in the plant model must be linked with the physical IO signals of the automation system. This is usually done by mapping between logical signal names and OPC tags (if an OPC server is used for data exchange), which in turn are assigned to the signals in the controller.

ifak*FAST* is used as a runtime system for the organization of real-time simulation and data exchange with the automation system. The open middleware platform ifak*FAST* (Framework for integrated automation and simulation technologies) has been developed in recent years as part of several research and industrial projects [Hübner et al. 2013]. The goal of this development is to support the implementation of solutions aimed at monitoring and optimizing the operation of process engineering processes. The application focus is in the field of water management plants and processes, in particular waste water treatment plants. The ifak*FAST* platform is available as Open Source (https://fast.ifak.eu). Fig. 4 shows a structure used to test a load management controller.

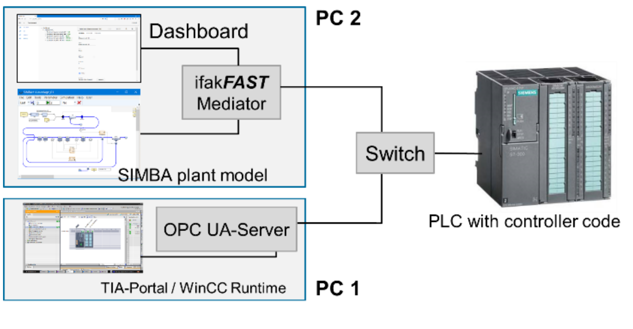

Fig. 4: Test environment for virtual commissioning

A Siemens PLC is used, which is programmed in the TIA portal. WinCC or a SCADA from another supplier could be used as SCADA. Here the OPC UA Server available in the scope of WinCC was used as data interface between simulation and PLC. For newer PLC variants, some internal OPC UA servers are available, which could then be used as an alternative data interface. The simulation software exchanges data with the ifak*FAST* mediator, which in turn communicates with the OPC UA server. A web dashboard is available as a component of the ifak*FAST* framework for operation and visualization of the virtual commissioning.

3.2 Requirements simulation system

In a simulation system suitable for virtual commissioning, interface blocks must be provided for linking the simulation model serving as the process with the IOs of the PLC. Two variants are conceivable for the transition from planning to commissioning. In variant 1, the simulation model also contains a model of the control functions (see Fig. 5).

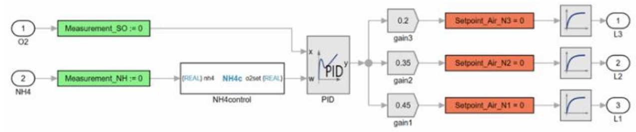

Fig. 5: DO and Ammonia control blocks

This model is used to plan process automation, and can then be seen as part of the specifications for the control system. The interfaces between process and automation system are marked by corresponding interface blocks. Measured variables of the process (green measurement block) and manipulated variables (red setpoint block) are defined. To use the model for virtual commissioning, the controller model located between these interfaces is ignored and the function is taken over by the real PLC. The interface blocks communicate with corresponding variables in the ifak*FAST* mediator, which then communicates these variables with the interface to the PLC. In the ifak*FAST* framework, different interfaces can be used for communication with the PLC (e.g. OPC DA, OPC UA, Modbus, databases).

In variant 2, the simulation model (Fig. 6) does not contain an automation model; the simulation of this model is only possible to a limited extent (constant manipulated variables) without a connected PLC.

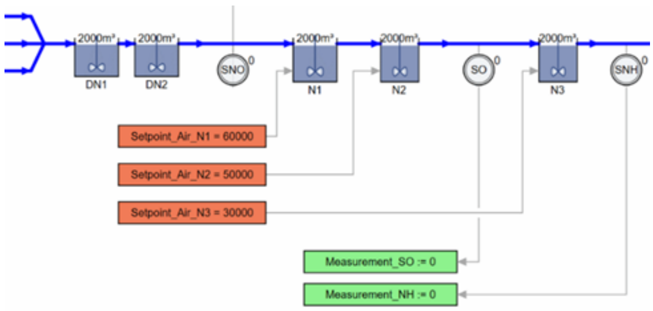

Fig. 6: Process model without control functions and with interface blocks toward PLC

For a simpler porting of automation functions that are developed and tested in the simulation (variant 1), the simulation system provides control blocks which are programmed using a standardized PLC programming language (IEC61131 ST). This code can then be copied directly into the PLC development environment (e.g. TIA Portal Siemens).

The simulation software can then be executed in real time, whereby a scaling factor can be specified, with values >1 a corresponding acceleration of the time progress (time lapse) is realized, with values <1 defines a deceleration (slow motion).

With a further option (Connect to SCADA) it can be determined whether a data exchange of the simulation via ifak*FAST* to the PLC/SCADA is performed. If this option is switched off, the delimitation blocks (see Figure 6) transmit the signals, if this option is switched on, the data are sent to or read from the PLC and the signals of the controller of the simulation are ignored. The frequency of the data exchange can be parameterized. All data is read and written synchronously.

Further operating options and functionalities are required in order to test automation systems comfortably. The following requirements must be considered:

- Convenient specification of test scenarios (static and test sequences)
- Automated execution of tests
- Analysis of target and misconduct
- Loading and generating test output states
- Documentation of test runs.

These functions are currently under development. Within the framework of two ongoing pilot projects, requirements are collected and first versions of the test environment are developed.

3.3 Coupling Level and Time Lapse

During the virtual commissioning of the automation system, it must be determined on which logical level the switching between the real process and simulation should take place. The lowest level in a fieldbus architecture is the fieldbus. Real fieldbus participants can be replaced by simulated participants. The next higher level is the IOs of the PLC. For a valve, these are, for example, binary signals to start the actuator, limit switches, etc. If separation is provided at this level, then the simulation model must also provide models of the field level (valves, drives, pumps) with all actually available IO signals and the behaviour of the corresponding components. The coupling is simplified if the logical coupling level is set even higher, now the PLC program switches over to the process controller level. Here PLC variables, the set point positions for valves, speeds for drives and scaled measured variables are used as interfaces. The advantage of coupling at this level is,

- that significantly fewer signals have to be exchanged
- No special component models of the field level must be available in the simulation model, and
- the data exchange with a longer sampling time is possible.

A disadvantage of the coupling at this high level is that functions of the IO level (gate valves and pump controls) cannot be tested. In many cases, however, this can be accepted if one assumes that for these IO functions frequently tested typicals are used.

A bigger challenge is the virtual commissioning of the automation in a shortened (or extended) time scale. The vast majority of PLC models do not provide access to the real time clock and the actual time provided as a variable or function for commissioning to run faster or slower than the real time. Here one must either accept that a test can only be carried out in real time, or modified PLC programs with special function block libraries must be used. The testing of wastewater treatment plant PLC programs is much more convenient and efficient if testing can be carried out in time-lapse. Many processes on KA have time constants in the range of minutes, hours, day up to week, correspondingly long test phases must be considered. For example, complex SBR systems are operated with cycles between 4 and 8 hours. Testing these cycles in real time is correspondingly lengthy.

There are different approaches for running a PLC program in fast motion or slow motion. A deceleration is arbitrarily possible from the point of view of computing time, an acceleration is only possible up to a certain ratio (approx. 10-fold) if acceptable cycle times are adhered to. In addition to this limitation due to the performance of the PLC, the PLC program must also handle the changed time scale correctly. All time-dependent functions (switch-on/switch-off delays, dynamic filters, PID controllers, etc.) must take time scaling into account. Two ways are possible here. Variant 1 provides a special function that provides the system time, which can switch internally between real time or scaled time, and which must be used in all time-relevant FBs. This can only be realized for self-defined FBs. As a rule, FB libraries supplied by the manufacturer will not be able to access this function. In the case of the development of operator, office or industry FB standards, however, this path is accessible. For variant 2, all variables that represent time periods must be manipulated with the scaling factor (on/off delays, controller time constants, cycle times, etc.). This method can also be used with existing FB libraries, but scaling is necessary in many places, there is corresponding programming effort and the danger of overlooking variables is high.

4 APPLICATION AND SUMMARY

The methodology described is being tested in various ifak projects. In order to promote the use of the "virtual commissioning" tool in the waste water industry, a test rack was set up (Fig. 7). Two PCs and a PLC are located on the test vehicle. The following software solutions run on it

- Simulation model process (wastewater treatment plant with equipment)
- Automation simulation model
- SPS development system
- SCADA runtime and development system
- ifak*FAST* as interface between automation system and simulation

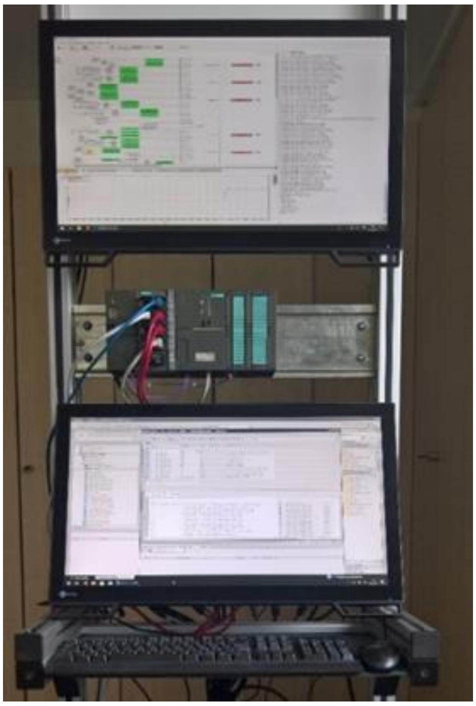

Fig. 7: Test rack for virtual commissioning

With the solution presented, dynamic simulation can not only be used for the integrated planning of wastewater treatment plants, mechanical equipment and control, but can also be used with little effort for a "virtual commissioning" of the automation system.

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