Possible concepts for digital twin simulator for WWTP

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Abstract

Application of advanced modeling and simulation technologies is essential to meet future requirements for higher wastewater treatment capacity and increased discharge water quality without large investments in construction projects.

This article describes an industrial pre-project for digital twin simulator for Veas wastewater treatment plant in Norway. The desired main functionalities of the digital twin simulator were:

- Data- and model-based management as well as decision support for process operators
- Predictive operational support and process optimization for engineers
- Testing of process modifications, control system modifications, new procedures and other changes
- Competency building and knowledge transfer between the operators and engineers

Commercially available technologies were compared according to the functional design specification and four possible digital twin simulator concepts were developed for wastewater treatment facilities.

Keywords: dynamic modeling, simulator, digital twin, water treatment, wastewater treatment plant.

1 Introduction

As growing cities produce more wastewater, climate change increases storm water intensity, and legislative requirements for the discharge water quality tightens, the capacity in the wastewater treatment facilities must be increased. In order to meet these future requirements without large investments in comprehensive construction projects, it is essential to develop innovative technology for process optimization and knowledge building in the organization.

During the past decade, research and development in artificial intelligence (Kapelan et al,, 2020), digital twins (Molin, 2021; Valverde-Pérez et al., 2021) and advanced process control solutions (Zlatkovikj et al., 2020; ABB, 2021a; Dahlquist et al., 2019) in the water sector has increased significantly. Experiences with simulators (Komulainen and Sannerud, 2018) and digital twins (Cameron et al., 2018) in the oil industry have shown good results in terms of knowledge building, process optimization and plant integrity. There is a high potential for use of digital twins at wastewater treatment plants as several commercial simulator tools and AI products are available in the international market.

Currently, the wastewater treatment plants in Viken county, Norway, are dominated by traditional control technology and do not use simulators or digital twins for operator training, process optimization, energy efficiency or other purposes.

This article describes the results of the DTS VANN pre-project, a collaboration between Veas wastewater treatment plant in Asker, Norway and Oslo Metropolitan University during 1.9.2020-31.5.2021, funded by RFF Viken (Johansen, 2021). During the pre-project, a functional design specification for a digital twin simulator for the wastewater treatment plant was developed, and available technologies were compared according to the specification. The comparison was further developed into possible digital twin simulator concepts for water treatment facilities.

The research question was “Which digital twin simulator concepts can provide a platform for 1. Online process optimization 2. Offline process optimization and modification studies 3. Operator training?”

1.1 Nomenclature

AI artificial intelligence
APC advanced process control
BOD, COD biological and chemical oxygen demand
DCS distributed control system
FDS functional design specification
OPC open platform communications (originally object linking and embedding for process control)
OPC UA open platform communications unified architecture
PAX, PIX preconditioning chemicals
P&ID piping and instrumentation diagram
PS process simulator (high fidelity)
RFI request for information
TSS total suspended solids
VEAS Vestfjorden Avløpsselskap
WWTP wastewater treatment plant

1.2 Plant description

The Veas plant is Norway's largest wastewater treatment plant and a crucial contributor to the efforts in keeping the Oslo Fjord clean. The process plant has an annual production of around 100 million m^3 of treated wastewater, about 40 000 tons of Veas-soil and 10 million standard m^3 of biogas (2019). Wastewater from the equivalent of 835 000 inhabitants (2020) in Oslo, Bærum and Asker is transported via the Veas tunnel to the treatment plant at Bjerkås in Asker. The plant is required to remove at least 70% of nitrogen, 90% of phosphorus, and organic material: 70% BOD and 75% COD.

The main processing facilities of the Veas plant include:

1. Pumping of the wastewater from the Veas tunnel to the Veas WWTP facility with centrifugal pumps.
2. Mechanical treatment includes removal of bulky, large solids and garbage with screens, and removal of sand and skimming of fat in grit chambers.
3. In chemical treatment the suspended and colloid fractions are removed from the water: water is preconditioned with iron chlorides (PIX), aluminum chlorides (PAX), and polymers prior to sedimentation.
4. In biological processes Nitrogen and organic materials are removed: these processes include water screening, aerobic process in an aerated basins with nitrification filter (bacteria on granules), flow equalization, methanol addition, and anaerobic process in a basin with denitrification filter. The cleaned water is disposed to Oslo fjord.
5. Reject water from sludge treatment (after chamber filter presses) is treated to remove nitrogen. The process includes a stirred flow equalization tank, screening, air stripping of ammonia in a countercurrent column, absorption of ammonia to nitric acid solution in a counter current column. The resulting ammonium nitrate is sold to industry.
6. Actiflo-facility for excess rainwater includes the following processing units stirred coagulation tank with iron addition, stirred tanks with micro sand and polymer addition, sedimentation basin with bottom scraper, sludge cyclone. The cleaned water is disposed to Oslo fjord.
7. Sludge treatment and soil production includes the following processes fiber removal with rotating screening drums, polymer addition, dewatering with drum screen, sludge buffer tank, sludge heating, sludge buffer tank; 20 day long batch process in mesophilic anaerobic digester stirred with recirculated biogas and recirculated, heated sludge; sludge buffer tank with aeration to stop digestion; sludge buffer tank, sludge screening, lime conditioning in a stirred tank, stirred tank with polymer addition, dewatering with chamber filter press using pressure up to 250 bar, sterilization using hot membrane water (80°C); dried sludge is transported via conveyor belt system to a stirred silo, export.
8. Biogas treatment and liquefaction: gas from digesters through H_2S filter, first stage CO_2 removal in absorber using amine solution, gas pre-cooler, reciprocating compressor, second stage CO_2 removal in absorber using amine solution, gas cooler, gas drier, amine regeneration; gas cooler, gas condenser, export pump (centrifugal), export system; systems for cooling medium. The liquefied biogas is sold to industry.
9. Heat production using a pellet boiler and a biogas/oil boiler, primary and secondary hot water loops, heat pump, plate heat exchangers and centrifugal pumps.
10. Cooling medium systems with glycol, water and sea water.

2 Materials and methods

This qualitative study was conducted using the following materials and methods.

2.1 Materials

The materials for this study included:

- Piping and instrumentation diagrams (P&ID) and the distributed control system screens of the the process systems at Veas wastewater treatment plant Process areas included were water treatment, sludge treatment, biogas production, biogas refining and liquefaction and mechanical treatment of solids.
- Technical documentation and presentations of simulator and digital twin products, provided by selected vendor companies.

2.2 Methods

The methods in this study included:

- Preparation of functional design specification for Veas WWTP analyzing the process documentation (P&ID, DCS screens) and interviews with the Veas process engineers and system engineers.
- Extraction of operational challenges from the interviews with process engineers.
- Selection of possible commercial simulator and digital twin vendors.
- "Request for Information" – a questionnaire with quantitative and qualitative questions on offline/online simulator products (modules and functionalities) and digital twin functionalities based on the functional design specification.
- Comparison of available simulator and digital twin products using the companies answers to the "Request for Information", and technical material and presentations provided by the technology vendors.
- Development of possible concepts fulfilling the goals for digital twin simulator for wastewater treatment plants.

3 Results

First, a short version of the functional design specification is presented and some typical operational challenges are described. Then, the formulation of documents "request for information" and "request for project information" are presented briefly. Finally, possible solutions fulfilling the goals of the digital twin simulator are described.

3.1 Functional Design Specification

A functional design specification (FDS) was prepared for the Veas wastewater treatment processes, in short the contents are as follows:

3.1.1 Overall goals of the digital twin simulator

The overall goal of the digital twin simulator is to

- Minimize the environmental impact
- Optimize the chemical consumption
- Optimize the energy use
- Improve the quality of the products

The digital twin simulator should provide:

Goal1: Online process optimization in order to achieve better products and minimize chemical consumption and energy use. Data- and model-based predictive support for daily process optimization. To start with as a decision support tool (open-loop, operators implement suggestions manually to DCS), and in longer perspective as automatic control (closed-loop, using programmable logic controllers and advanced process control algorithms).

Goal2: Testing of possible modifications to optimize the WWTP process operation (tightening regulations, population growth, climate changes). Tool for offline process optimization, and testing of future modifications for cost-effective operation as well as providing the opportunity to utilize the margins in existing infrastructure before expensive construction projects are necessary.

Goal3: Training system that ensures effective competency building among engineers and operators.

3.1.2 Description of the Veas wastewater treatment processes and instrumentation

The detailed description of the process and instrumentation included the three pretreatment stages, the three chemical and biological treatment stages with equipment, instruments and sensors. The pre-treatment stages include inlet pumps, screening station, and grit chamber. The main treatment stages include sedimentation, nitrification and denitrification states. The water treatment processes include 45 controllers, 123 transmitters, 446 valves, 203 pumps, tanks, mixers and motors, and 16 other equipment, in total 833 objects with a total of 5214 tags in the DCS system.

3.1.3 System integration

The digital twin simulator will be integrated with ABB's 800xA distributed control system and SCADA. version 6.1. The data can be shared via OPC server, preferably with OPC-DA, OPC-HDA, OPC-AE. It is desired that the digital twin simulator can be integrated together or co-simulated with other dynamic models, for example DHI's MIKE model of the urban drainage tunnel leading wastewater to the Veas facility.

3.1.4 Simulator specification

The simulator specification includes typical simulator functionalities for all user groups, like initial conditions, scenarios, basic functions, process equipment details and failure modes. Special functions are required for engineering simulator, operator and instructor interfaces. In addition the simulator should be run online, parallel to the real process with adaptation of the simulator model parameters, possibility for snapshots and predictive what-if-scenarios towards future.

3.1.5 Digital twin specification

The digital twin functionalities were not specified in detail, but the functionalities should fulfill the goals 1-3 listed in the beginning of the FDS.

3.2 Operational challenges – need for digital twin simulator

Based on review work the functional design specification and interviews with the Veas process engineers, the following areas of interest were identified:

3.2.1 Early warning and monitoring with virtual sensors

- General measurement quality using mass, molar or energy balance based approach
- Screens, conveyor belts and transport screws: blocking of these with solids, and faulty level measurement around these equipment due to build-up
- Basins: accumulation of sedimented particles and sludge
- Biological filters: effectivity and activity of bacteria
- Filters: fouling and timing for backwash cycle, as increased pressure difference over filter increases energy use in downstream pumps;
- Pumps: pump effect, energy use, wear-and-tear, challenges with sludge pumps
- Mixers: solids build-up/fouling, wear-and-tear, insufficient mixing of polymer
- Digesters: monitoring of the rotting process, stop in gas-circulating compressor leads to foaming;
- Heat exchangers: efficiency, heat transfer coefficients, stopping, leakage

- Tank after digesters: end the rotting process with aeration.
- Chamber filter press: many components and multi-stage sequences with high pressure and high temperature, degree of sterilization is dependent on hot water temperature in membrane water system
- Water tanks: decreasing level due to small inlet flow or leakage.
- Oil tanks: high pressure/temperature leads to process shutdown
- Gas tanks: possible hazards like leakage, emergency shutdown

3.2.2 Process optimization and/or advanced process control

- Inlet pumps: during varying hydraulic loads optimize the load sharing between eight inlet pumps.
- Chemical addition: optimize dosing of chemicals PIX, PAX, methanol, lime slurry, polymer and micro-sand based on influent quality.
- Sedimentation basins: optimize sludge pumping out of basin to avoid accumulation
- Nitrification basin: optimize aeration rate
- Denitrification basins: balance flow between the eight basins
- Nitrification, denitrification and stripping: optimize degree of purification with process parameters including backwash
- Digesters: optimize biogas production using parameters such as sludge retention time based on total suspended solids (TSS) in, sludge heating and circulation, biogas circulation and mixing; balance organic load between the tanks.
- Digesters: improve temperature setpoint tracking in digester tank with sludge heating and circulation.
- Filters: optimize pressure difference over the rag filters and dewatering of sludge in drum screens.
- Chamber filter presses: improve temperature setpoint tracking in membrane water system.

3.2.3 Operator training

- All scenarios given above, especially process optimization and advanced process control should be included to operator training.
- Emergency scenarios especially with biogas production, refining and liquefaction should be included to operator training.
- Process shutdown scenarios related to the logic in the safety and alarm system should be included to operator training. For example, pump stop in "less critical" parts of the plant can lead to full process shut down.

3.2.4 Simulation studies on possible modifications

- Case studies for increasing water treatment capacity with current equipment
- Case studies for new parallel operations (keeping in mind the limited space available), i.e. replacing existing water treatment equipment with new, more effective alternatives.
- Case studies with control system modifications.

3.3 Selection of companies

The possible vendors were selected from list of technology companies working with water, water networks and wastewater.

The following companies answered positively to the RFI: ABB, Aquasight, Aspentech, Corys, DHI, Hatch/Hydromantis, Kongsberg, KrügerKaldnes/Veolia, and Statsoft.

The following companies did not reply to our request for information or gave a negative answer: Andritz, Createch 360, Cybernetica, Envidan, EnviroSim, H2Ometrics, Perceptive Engineering, Prediktor, Royal Haskoning DHV, Xylem (Emnet).

We also invited presentations from ABB Västerås about MPC solution for a WWTP facility in the FUDIPO EU-project (Dahlquist, 2021), from ABB Italy about advanced process control for WWTP facilities (ABB, 2021a) and collaboration with DHI in the Singapore PUB project (ABB, 2021b) and ri.se about digital twin projects for WWTP facilities (Molin, 2021; Valverde-Pérez et al., 2021).

3.4 Request for information

To get an idea of the dynamic simulation modules and digital twin functionalities the available commercial tools have, a request for information (RFI) was sent to the companies. The request of information included three sections, Veas plant description, a multiple-choice questionnaire on dynamic simulation modules and system integration, and open written questions on system integration and digital twin functionalities. The multiple-choice part was divided to five categories:

Generic dynamic simulation modules including: Pipelines with two phase flow (liquid and solids), Pipelines with two phase flow (gas and liquid), Control valves, on/off valves, manual valves, safety valves, Centrifugal pumps (water), Eccentric U-pump (sludge), Heat exchangers: plate, spiral and tube, Fans, Stirred tanks, Buffer tanks, Cyclones, Pellet boiler, Biogas boiler, ESD/PSD system.

Wastewater treatment-specific dynamic process modules including: Grit chambers, Sedimentation basin, Basin/reactor with nitrification filter and aeration, Basin/reactor with denitrification filter, Continuous stirred tanks with chemical, sand or polymer additions.

Sludge treatment dynamic process modules including: Digester tank (anaerobic sludge rotting), Buffer tank with air inlet from bottom, Chamber filter press

Biogas specific dynamic process modules including: Gas coolers, CO_2-absorbtion and stripping columns, Gas compressor (piston and screw), Gas drying/H2O removal: absorption in silica gel, H_2S-filter, Flare system, Gas cooler (plate heat exchanger), Gas condenser, Pump (LNG, glycol), Expansion drum, Coalescer (oil droplet removal), Drum for gas/liquid separation

Mechanical processing and transportation of dry solids dynamic process modules including:

Screens, Screws (transport of solids), Conveyor belts, Flip-flops, Containers, Fiber/rag removal with rotating screening drum

System integration including:

Communication via OPC-DA/HDA communication protocol, two-way communication with third party process modeling software, online simulation and requirements for communication outside Veas firewalls.

Open-ended questions

- Supported system integration protocols
- Maximum amount of signals
- References to previous projects with system integration to a control system like ABB's 800xA
- References to previous projects with system integration to third-party simulation software.
- Experience with co-simulation
- Description of digital twin functionalities for WWTP

4 Analysis: Possible solutions with commercial tools for WWTP

The information gathered from FDS, interviews with Veas engineers, presentations and discussions with the companies were merged and compared with the goals Veas has for the digital twin simulator.

4.1 Goal1: online process optimization

The first goal of the digital twin simulator is to provide online process optimization. If the decision support system is to suggest manual control actions to process operators, either an online simulator covering the whole plant or an AI tool for specific operational cases can be implemented.

An online simulator based on high-fidelity process models, gives holistic approach to the whole plant operation and covers more than cases in AI tools, i.e. the process interactions. Available online simulator simulator tools include DHI's TwinPlant (DHI, 2021a), Hatch's Mantis.AI (Hatch Hydromantis, 2021a), and Kongsbergs K-Spice Assure (Kongsberg, 2021a; 2021b). All of the online simulators can be run with ABB's 800xA DCS simulator (ABB, 2021c) for example using OPC-UA protocol.

Data-driven, artificial intelligence or model-based tools use real-time data to monitor selected process units and assist process operators. Products like Aquasight's Apollo (Aquasight, 2021), Veolia's Hubgrade (Krüger Kaldnes Veolia, 2021), or Statsoft's TIBCO (TIBCO, 2021) can be applied case-based for process units with largest potential for cost savings. Examples of research projects on digital twins, virtual/ soft sensors based on artificial intelligence and models can be found from (Molin, 2021; Valverde-Pérez et al., 2021)

If closed-loop control is desired, advanced process control packages like ABB's APC (ABB, 2021d) can be applied case-based to cover the process units with largest potential cost savings in energy and chemicals. In order to minimize the model mismatch between the simplified model in the APC algorithm and the "real process", an online simulator or an extended Kalman filter can be used to update the model parameters. Examples on MPC applications for wastewater treatment plants can be found from research projects (Dahlquist, 2021) and commercial projects (ABB, 2021b).

4.2 Goal 2: offline process optimization and modification studies

Testing of possible modifications to optimize the WWTP process operation for future requirements requires a holistic tool that covers the interconnections of the whole wastewater treatment plant. This can only be done with high/medium fidelity process simulators. The functionalities of six different commercial simulator products were compared according to the functional design specification and the request for project information. The modeling score, presented in Table 1, were calculated based on the vendors answers to the request for information. Only GPS-X modeling tool from Hatch Hydromantis (Hatch Hydromantis, 2021b) covers all the wastewater treatment, sludge treatment, biogas production, biogas refining and liquification. An older version of the Indiss Plus modeling tool from Corys (2015) covers the different process stages excluding some parts of the sludge treatment and mechanical processing, conversion to the new modeling tool will be necessary. The WEST modeling tool from DHI (DHI, 2021b) covers unit operations in general WWTP processing, wastewater treatment, sludge treatment and biogas production, but lack most of biogas liquefaction and mechanical processing. The K-SPICE modeling tool from Kongsberg (2021c) is developed for oil and gas processing and lacks ions, pH and solids. Therefore, it can calculate rough approximations for unit operations in general WWTP process, wastewater treatment, sludge treatment, biogas production and mechanical processing. K-SPICE covers well the biogas refining and liquefaction processes. The Apollo process modeling tool from Aquasight (2021) was not well enough described and demonstrated well enough to compare with the other products. The documentation and presentation from Aspentech also lacked necessary information about the AspenPlus modeling tool and APM solutions tool for WWTP unit operations (AspenTech, 2021).

4.3 Goal 3: operator training system

Training system that ensures effective competency building among engineers and operators should also rely on a holistic view of all the Veas processes, because fluid/mass flow and heat flow between the different parts of the wastewater treatment plant are heavily interconnected. High/medium-fidelity process model with a virtual replica of the distributed control system will give realistic look-and-feel for the training system. It is possible to build case-based training scenarios with partial models, like data-driven AI models, but these will most likely not be able to replicate the interconnected nature of the WWTP processes.

Table 1. Dynamic simulation modules from process simulator vendors.

Process modeling product	*AspenPlus*	*Apollo*	*GPS-X*	*IndissPlus*	*K-Spice*	*WEST*
Vendor	*Aspentech*	*Aquasight*	*Hatch*	*Corys*	*Kongsberg*	*DHI*
Total modeling score (max 5)	**1,4**	**2,6**	**5**	**4,3**	**2,5**	**3,2**
General process modules	0,4	0,7	1	1	0,8	0,7
Wastewater treatment	0	1	1	1	0,2	1
Sludge treatment and biogas production	0	0,7	1	0,7	0,2	0,9
Biogas refining and liquefaction	0,8	0	1	1	1	0,4
Mechanical processing	0,2	0,2	1	0,6	0,3	0,2

Table 2: Overall assessment of simulator tools, AI tools and APC tools according to project goals. PS=process simulator, CB=case-based

	Process simulator (PS)	DCS simulator	Online simulator	AI tool	APC
Goal1a: Online optimization with manual control	Partly	With PS	YES	CB	CB
Goal1b: Online optimization with closed loop control	No	No	No	No	CB
Goal2: Offline optimization and modification studies	Yes	With PS	No	No	No
Goal 3: Operator training	Yes	With PS	Partly	No	No

5 Conclusions and further work

5.1 Overall assessment of possible digital twin simulator concepts

Possible digital twin simulator concepts fulfilling the goals are:

- offline process simulator with DCS simulator (G2, G3) and online simulator with decision support interface (G1 manual control)
- offline process simulator (G2, G3) and online simulator with decision support interface (G1 manual control)
- offline process simulator (G2, G3) and AI-based decision support system (G1 manual control)
- offline process simulator (G2, G3) and advanced process control (G1 closed-loop control)

In order to fulfill goals 2 and 3, it is recommended to base the digital twin simulator on a high/medium-fidelity process simulator. To add realistic DCS functionalities in the simulator, a DCS simulator should be considered. In order to fulfill goal 1 with manual control, it is recommended to add an online simulator with decision support interface, or an AI tool for the most-profitable cases. In order to fulfill goal1 with closed-loop control, it is recommended to implement advanced process control for most-profitable cases. The overall assessment is further illustrated in Table 2.

5.2 Research and development possibilities

Future work is recommended for development of virtual sensors, process optimization and advanced control for cases given in Section 3.2 using data-driven and model-based algorithms. The algorithms can be effectively tested with a high-fidelity process simulator to quantify the environmental and economical benefits, and to increase the operators trust before implementation in the plant. Possibilities within vocational education research include evaluation of the learning process during the process simulator commissioning and training, and evaluation of the effects to life-long learning, work-place competency development, workplace safety and working environment.

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