the international water association

Digital Water

Operational digital twins in the urban water sector: case studies

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Abbreviations (in alphabetical order)

COD	Chemical oxygen demand
CSO	Combined sewer overflow
CWRP	Changi Water Reclamation Plant
IQR	Interquartile range
LIMS	Laboratory information management system
MPC	Model predictive control
PID	Proportional–integral–derivative
PUB	Public Utilities Board
SCADA	Supervisory control and data acquisition
TSS	Total suspended solids
WRRF	Water resource recovery facility

Foreword

Digital platforms are becoming widespread in every sector of our society: from how we manage our finances, to how we order food through a phone app. Digital tools are nowadays immersed into our daily activities and we depend on these to increase operational efficiencies and decrease timing and costs.

The water sector can also benefit from digitalisation, as this can help bring about notable improvements to water management. Increased urbanisation, flooding, drought, climate change and the need for a stable water supply are just a few of the challenges facing the water industry. Digitalisation can help address these challenges by providing real-time information which can enable the monitoring of systems performance and ensure greater confidence in decision-making.

IWA believes in the value of digitalisation and in the importance to our sector of embracing digital innovation. Through the IWA Digital Water Programme, we aim to provide the necessary tools to lead this journey towards a digital water sector. The Digital Water white paper series provides a platform to experts, allowing them to share their knowledge and experiences on different elements of the digitalisation journey, thereby leading to increased understanding of best practice.

This white paper presents case studies in which 'digital twins' have been integrated into the daily activities of water operators. Digital twins allow the operators to test different scenarios and optimise conditions in a safe environment, thus decreasing costs and the risks connected to conventional 'trial and error' approaches.

These case studies show how digital twins have been successfully used (in sewer networks and water resource recovery facilities) to face challenges such as the need to forecast systems malfunction or predict water levels. The advantages of using digital twins range from improved efficiency and productivity, up to increased benefits for society (e.g. stormwater management).

At IWA, we recognise the opportunities for our sector from embracing digitalisation and technology, and how doing so can bring about real change on the ground. Ultimately, this means delivering safer, more sustainable, and more efficient waste and sanitation services for people across the world.

Kalanithy Vairavamoorthy
Executive Director of the International Water Association

Summary

The need to handle increasing amounts of data while improving capital and operational efficiencies has directed the attention of the water sector towards advanced digital tools such as operational digital twins. Digital twins can be seen as combinations of models and real-time data that provide a digital representation of a specific part of the water system's behaviour. The aim of this white paper is to highlight how digital twins can help the water industry to improve performance of its infrastructure. The white paper presents two case studies where online digital twins are used for operational decision support: one in a sewer network and the other in a water resource recovery facility.

Introduction

Due to advances in instrumentation and the increasing availability of online data and computing capacity for utilities (e.g. via cloud computing), the development of digital twins has recently attracted large interest in the urban water sector. This interest is primarily driven by two trends in our industry: i) the increasing amount of data available at our facilities; and ii) the business drivers around both improved capital and operational efficiency targets. The amount of data available at many facilities now exceeds the amount that most operational staff can utilise in their day-to-day operations. Digital twins can take those data and present them in terms that staff can use effectively on a day-to-day basis (Garrido-Baserba et al., 2020). The second driver towards efficiency relates to the ability of a digital twin to go beyond conventional PID (i.e. proportional–integral–derivative) control, using model-based control and data-driven optimisation. This improvement has implications for capital expenditure since more reliable control can result in reductions in conservatism, and thus lower capital expenditure (Stentoft, 2020).

In a broad sense, "digital twin" refers to a digital replica of physical assets. Within the water sector, digital twins are combinations of models that provide a digital representation of a specific part of the water system (e.g., water resource recovery facilities, sewers, etc.) and utilise real-time data from multiple sources to, for example, simulate expected, desired, or critical behaviour of the physical system (Pedersen et al., 2021).

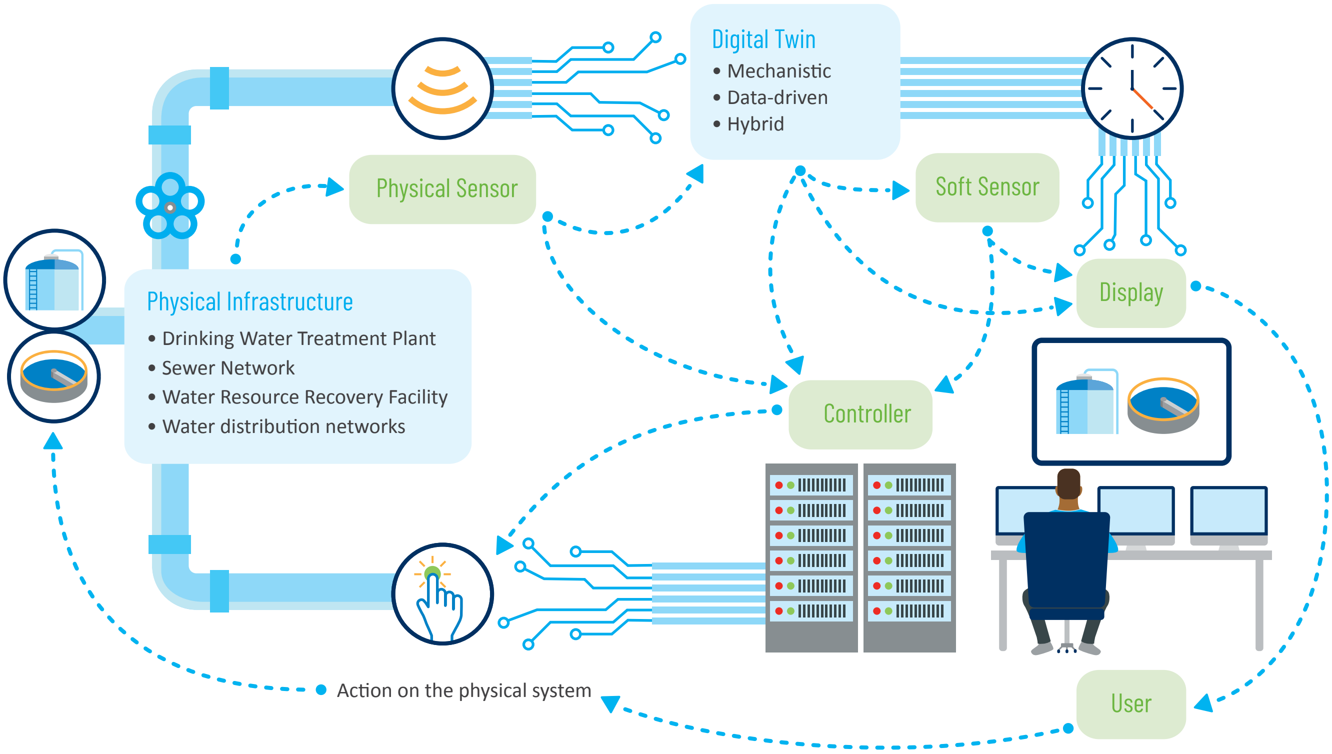

Figure 1. Basic structure of a digital twin application. Elements in blue are basic elements needed for implementation of a digital twin, while elements in green are complementary to the digital twin, ultimately to enable an action on the physical system.

While there is agreement in a broad sense about the definition, there is a lack of consensus on which elements characterise a digital twin. Some experts consider traditional mechanistic models with frequent recalibration using sensor data enough to qualify as a digital twin, whereas others consider the interaction with real-time data as a key element in an operational digital twin. In this discussion, it is important to distinguish between digital twins for operational use (relying on near-real-time data from the physical system) and digital twins for planning, design, construction or investment purposes (relying on historical data from similar physical systems or expected demands given the operational environment of the physical system under development). In some cases, digital twins are considered as soft or virtual sensors of the physical system. Thus, aspects like model complexity (mechanistic, data-driven or a hybrid combination of both), handling of uncertainty and data requirements, among others, need proper assessment to ensure successful alignment between digital twins and their intended application. Furthermore, data assimilation from different data sources remains a key challenge to be addressed. Figure 1 illustrates the most basic structure of a digital twin and its interaction with the real system and users.

Digital twin applications include (but are not limited to): i) investment planning via future scenario analysis, traditionally performed with models calibrated with historical data; ii) data-driven decision support for selection of different operational strategies; iii) operator training; iv) online optimisation (e.g. model predictive control) for energy or resource savings or compliance management (e.g. to minimise carbon footprint); v) asset management and interaction with different stakeholders; and vi) sewage epidemiology (Poch et al., 2020).

Within the water sector, digital twins can support the transition towards more proactive management of water infrastructure, whereby different processes and systems can be operated to mitigate disturbances before they have adverse impacts on performance (Karmous-Edwards et al., 2019). Thus, there is large potential for economic savings (e.g. online energy optimisation), more effective protection of the environment (e.g. model predictive control for effective nutrient removal) and increased benefits for society (e.g. improved storm water management to minimise risk of flooding in urban areas).

In this paper, two examples of online digital twins for operational decision support are presented: one focuses on improved control of combined sewer overflows (CSOs) in a sewer system and the second focuses on proactive maintenance and process optimisation of a water resource recovery facility (WRRF) intended for water reclamation.

Digital twin for sewer networks

Background, motivation and purpose for digital twin

This case study describes the digital twin approach used for sewer networks in the Swedish cities of Gothenburg and Helsingborg within the project Future City Flow. The approach is similar in both cities, but this case study will focus on the digital twin developed in Gothenburg (WRRF: 900 000 PE; catchment: 240 km^2 with 20 km^2 of impervious surface; 40% combined sewers).

The utilities regularly experience high flows in the sewer collection systems leading to spills from combined sewer overflows (CSOs) that lead to 3 billion litres per year (2.2% of total flow) of untreated wastewater being discharged to the environment. The CSOs mostly occur due to large flow variations caused by heavy rainfall events. To manage issues related to CSOs and to reduce storm weather impacts on the WRRF, an operational digital twin approach was envisioned as a decision support system with online flow prediction and suggestions for control strategies (the final decision is currently made by the operator). Part of the last stage of the project (2019-2021) focuses on implementation of full model predictive control (MPC).

Components

The structure and different components of the digital twin are shown in Figure 2. The main part of the digital twin consists of a model of the sewer system built in MIKE URBAN using several different modules, including: a dynamic model for the hydraulics of the pipes and tunnels; conceptual hydraulic models to describe sub-catchments; optimisation modules for real-time control; and modules for handling of precipitation forecasts and rain gauge data quality control. The model has been calibrated manually for many of the sub-catchments in the network where rain gauges and flow measurements are available, as well as for the hydraulic model of the main tunnel system. The catchment model is re-calibrated manually to achieve better flow prediction as more sensors are added to the system over time, thus providing greater spatial resolution in the system for model calibration.

The physical infrastructure connected to the digital twin consists mainly of flow and water level sensors in the central part of the sewer system and at the WRRF that provide online, real-time updates of these measurements, as well as status from actuators (pumps, valves and gates) in the system.

The operator visualises simulation results on a dedicated website, separate from the supervisory control and data acquisition (SCADA) system, showing flows in the catchment, influent flow to the WRRF and a comparison of predicted flows with both the default reactive control strategy (based on an empirical level-flow relationship) and a recommended control strategy (provided by the simulator) (Figure 3a).

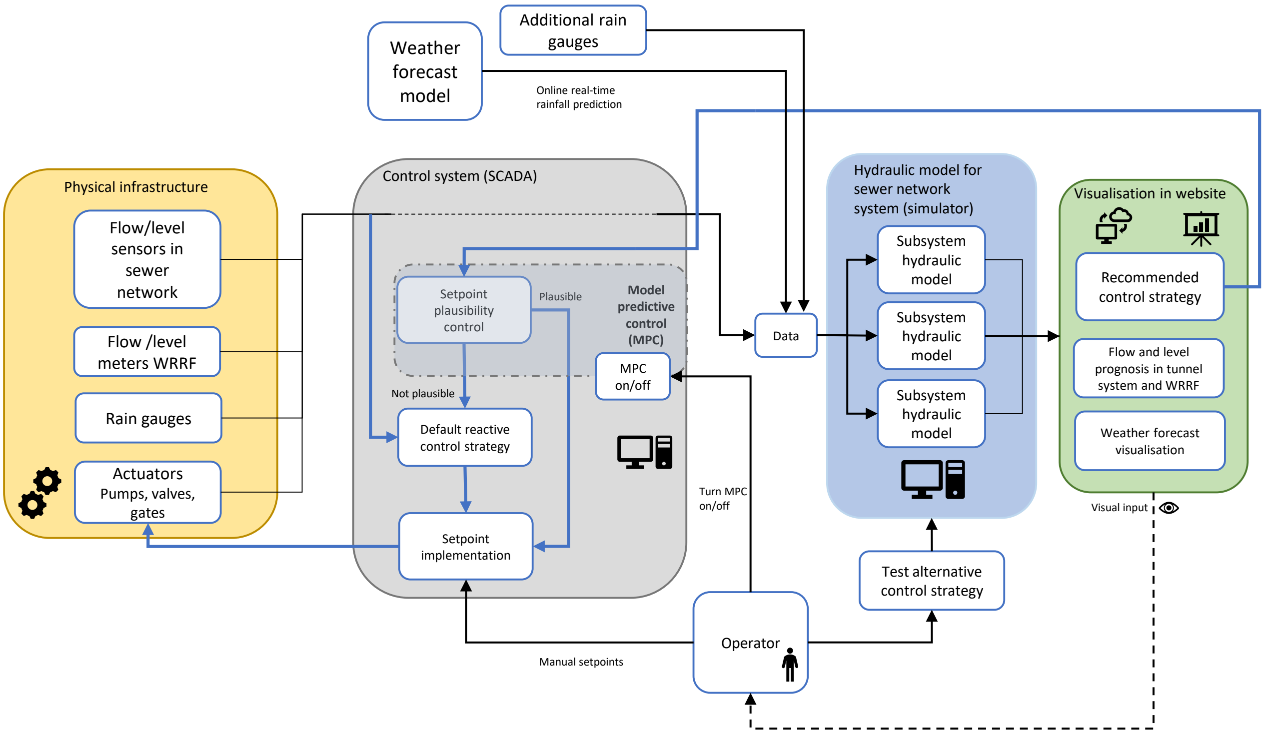

Figure 2. Sewer network digital twin structure and components in the current implementation as well as with model predictive control (work is now underway with the goal of implementing full real-time model predictive control).

Both sets of predictions are for the next 2.5 days, based on the latest weather forecast. The recommended control strategy is updated every hour, resulting in new recommended set points. The operator then has the option to implement the recommended control strategy or to test their own strategy in the simulator and evaluate those results. The future MPC will include plausibility control of the recommended control strategy before final implementation. If the plausibility check fails, the controller will revert to the default reactive control strategy.

To determine the recommended control strategy, the controller uses an algorithm to optimise a pumping scheme to achieve inflow to the WRRF that is as constant as possible during the next 12 hours, while considering boundary conditions such as allowable water levels in the sewer (to avoid CSOs), pumping capacity, pumping conditions etc. To avoid discrepancies between current measured values of flows and water levels in the sewer network and pumping stations and the corresponding values in the model, corrections are required. Data assimilation techniques are therefore used to initialise the model using real time data from the sewer network before each simulation and to adjust the forecast according to identified patterns of deviations between measured and simulated values.

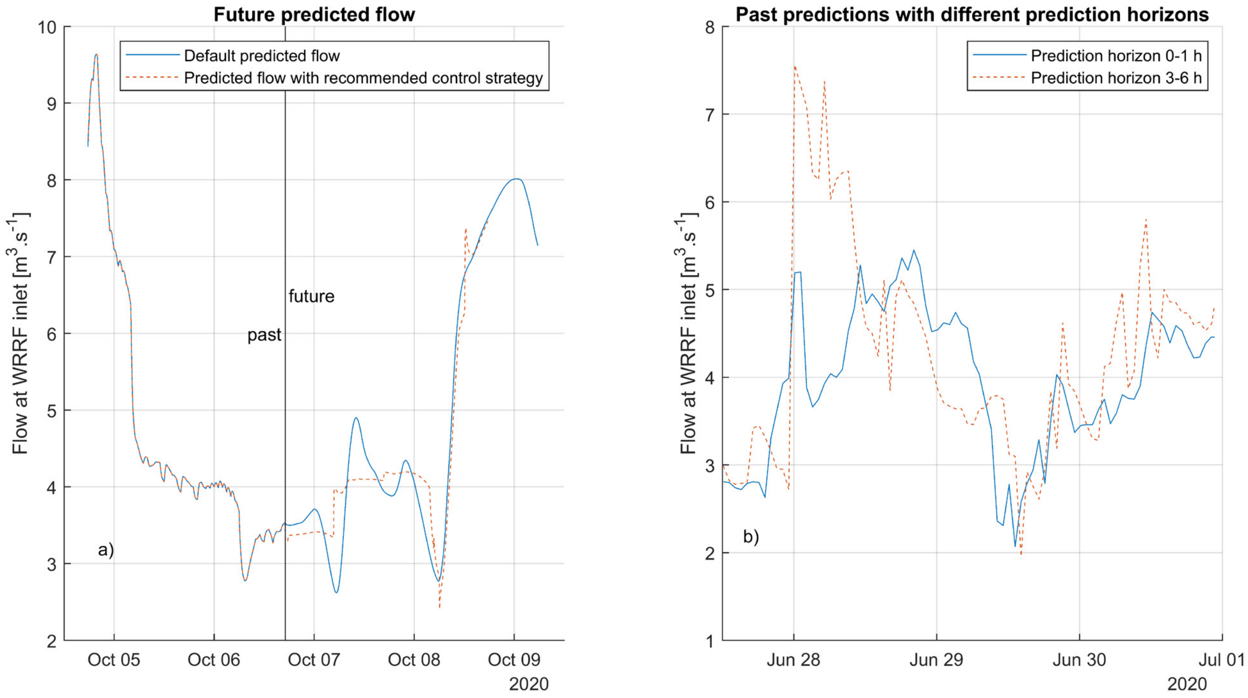

Figure 3. a) Example of model predictions for influent flow to the WRRF using the default control strategy (solid line) and the recommended control strategy suggested by the model (dashed line); b) Example of past model predictions with different prediction horizons (0-1 hours and 3-6 hours).

Challenges

Predicting the future in such a varying system is always a challenge. Since accurate flow and level predictions depend on accurate rain forecasting, this has presented a major challenge due to the uncertainty of weather forecasting models.

Another challenge is to represent variations in extraneous water from different sources (such as direct inflow, infiltration water, drainage water etc.) for different hydrological events both in the short term and the longer term. This requires a modelling approach that allows an accurate representation of the urban hydrology and of extraneous water impacts on the sewer system, not only for single events but continuously in time, using both hindcast and forecast data. Figure 3b illustrates the effect of the prediction time horizon on predicted flows by showing past predictions of WRRF inflow with two prediction horizons (0-1 h and 3-6 h in advance). The curves display the mean predicted flow values for the specified interval after the time of forecast which are saved at the time in the middle of the interval (i.e. the curve tagged “prediction horizon 0-1 h” shows the prediction made 0.5 h earlier for the mean flow during the next hour after the time of forecast, while the curve tagged “prediction horizon 3-6 h” shows the prediction made 4.5 h earlier for the mean flow in the period 3-6 h after the time of forecast).

A large rainfall event was initially predicted to occur on 28 June, as suggested in the 3-6 h curve, but the rainfall volume and WRRF inflow were predicted to be much smaller when predicting 0-1 h in advance.

Data management has also been a challenge, mainly to create a secure and robust data transfer. Specific issues include: time stamps when combining data from different systems (e.g. because of daylight savings time); ensuring data quality for precipitation data; managing the size of files for weather data which was initially too large for efficient transfer; and integration of SCADA system, which normally only handles historical data, with local databases and interfaces for storage and visualization of future predicted scenarios, respectively.

A critical part of the digital twin is the connection between the user and the models. An important aspect has been to develop confidence in the digital twin among the operators in the control room. A model that is sufficiently accurate and whose limitations are well understood is therefore important. A related issue has been the question of how to display uncertainty in predictions to the user (since weather predictions can include many different scenarios and many pumping strategies can be tested).

Results and benefits

The digital twin allows for increased confidence in decision making as the effects of a change in control strategy can be visualised quickly. Simulations of the real-time control strategies indicate that CSO spill events can (ideally) be reduced by 50% in the Gothenburg case. In Helsingborg, CSO spill events have already been reduced by 32% before implementation of MPC, by thoroughly studying the sewer system and exploiting opportunities that emerged. Benefits at the WRRF include: i) a more constant influent load which leads to more stable treatment processes; ii) lower risk of reaching critical load situations (e.g. by pumping water from the tunnel system before large flows are expected, so that more volume is available for attenuation, thus avoiding large flow peaks that can be hard to handle); and iii) an increased margin for handling issues with pumps or accumulation of material in the coarse screens at the inlet of the WRRF. A major benefit with MPC is that the control system takes into account both current conditions and predicted future conditions.

Digital twin for a water resource recovery facility

Background, motivation and purpose for a digital twin

Jacobs has partnered with PUB, Singapore's National Water Agency in an R&D project to create a digital twin of the Changi Water Reclamation Plant (CWRP). This digital twin will provide new insights into the ongoing operations and maintenance of the facility, supporting increased productivity and enhancing operational resilience.

The digital twin is currently envisioned as an advisory tool without direct control capabilities, which can grow into control functions as staff gain confidence in the tool. It has automated data inputs directly from both the SCADA system and the laboratory information management system (LIMS), as well as auto-calibration and soft sensor capabilities. This model is expected to assist PUB in simulated scenarios to test and calibrate strategies to enhance the plant's water quality as well as optimise its energy and chemical consumption. The use of the model is also in line with PUB's goal of tapping smart technologies to increase productivity and improve resilience in operations. A process flow diagram of both CWRP and the digital twin simulation is shown in Figure 4.

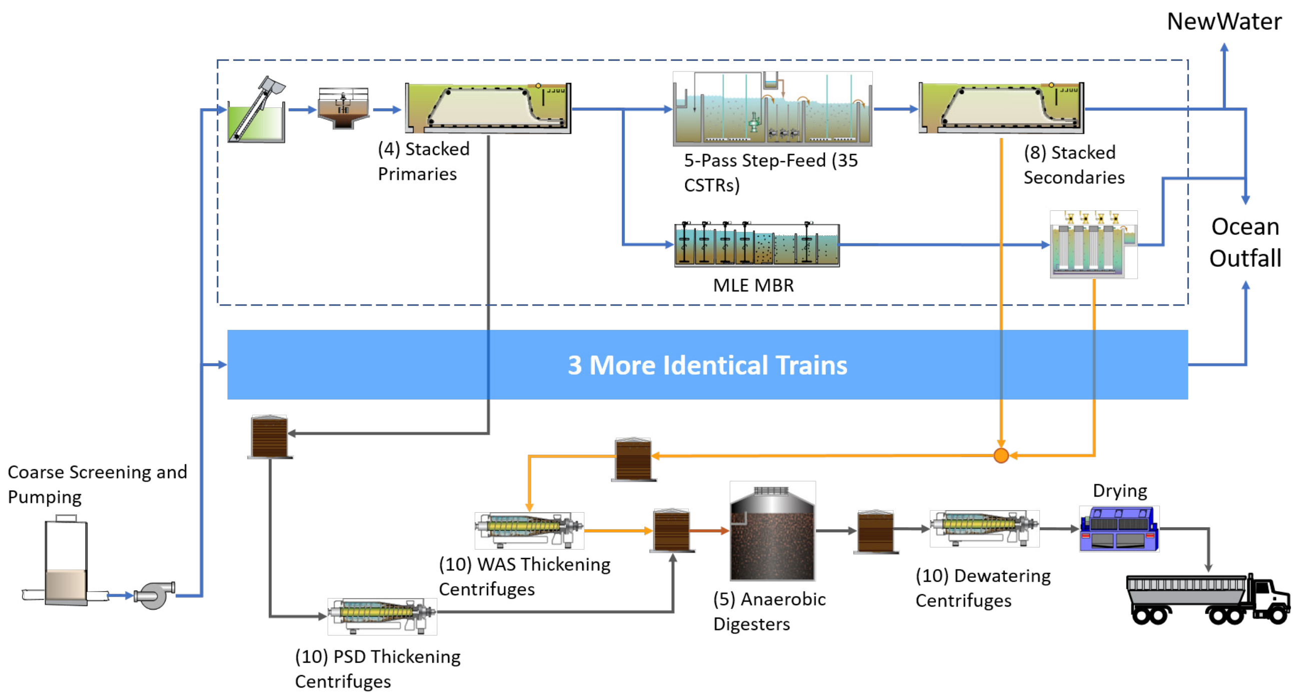

Figure 4. Process flow diagram of Changi WRP and scope of digital twin simulation (inside dashed line). The digital twin includes the four water treatment trains.

Components

The digital twin includes dynamic semi-mechanistic models of the CWRP whole plant hydraulics, controls, and processes. Hydraulics and controls are simulated within Jacobs' Replica™ simulator. Processes are modelled using Dynamita's Sumo© whole plant simulator with direct communication between Replica and Sumo. The inputs to the digital twin are only those currently available at the facility. Data driven influent predictions are used as part of the digital twin functionality for predicting plant performance up to five days into the future.

The influent soft sensor workflow of the digital twin is illustrated in Figure 5. Input data to the model are first conditioned by removal of "bad" data, defined as negative or zero data that are not consistent with other related data. A historical test is then made to remove all data that are not within normal variations (± 2.5*log normal interquartile range, IQR). The digital twin inputs from SCADA are the various flows measured in the facility, the online primary effluent ammonia values, air rates to the various bioreactor zones and other relevant operational setpoints. From the data, in combination with the LIMS data, a dynamic raw sewage influent file is generated, thus creating a soft sensor of the actual influent to the facility. Air rates and operations set-points read from SCADA are directly input into the digital twin.

The initial calibration of the digital twin was done manually; control and hydraulics calibrations were based on actual measurements. The process calibration was first done in a steady state, then dynamic calibration was done based upon the first six months of a full data set. The digital twin also included limited auto-calibration while running. This was accomplished as measurements became available where, for example, primary effluent laboratory total suspended solids (TSS) and chemical oxygen demand (COD) data were used to calibrate both the primary clarifier TSS removal and the soluble COD/COD fraction in the raw sewage based on the most recent performance data.

Challenges

The largest challenge in this project is speed of computation, as results are needed for both current operation/model comparison functions, scenario evaluation, and future predictions using Monte Carlo techniques. This must be accomplished within 24 hours of receiving the relevant data. For example, the process (Sumo) model is over 40 MB in size and the Replica hydraulics and control model is over 170 MB in size, thus giving an indication of the model complexity.

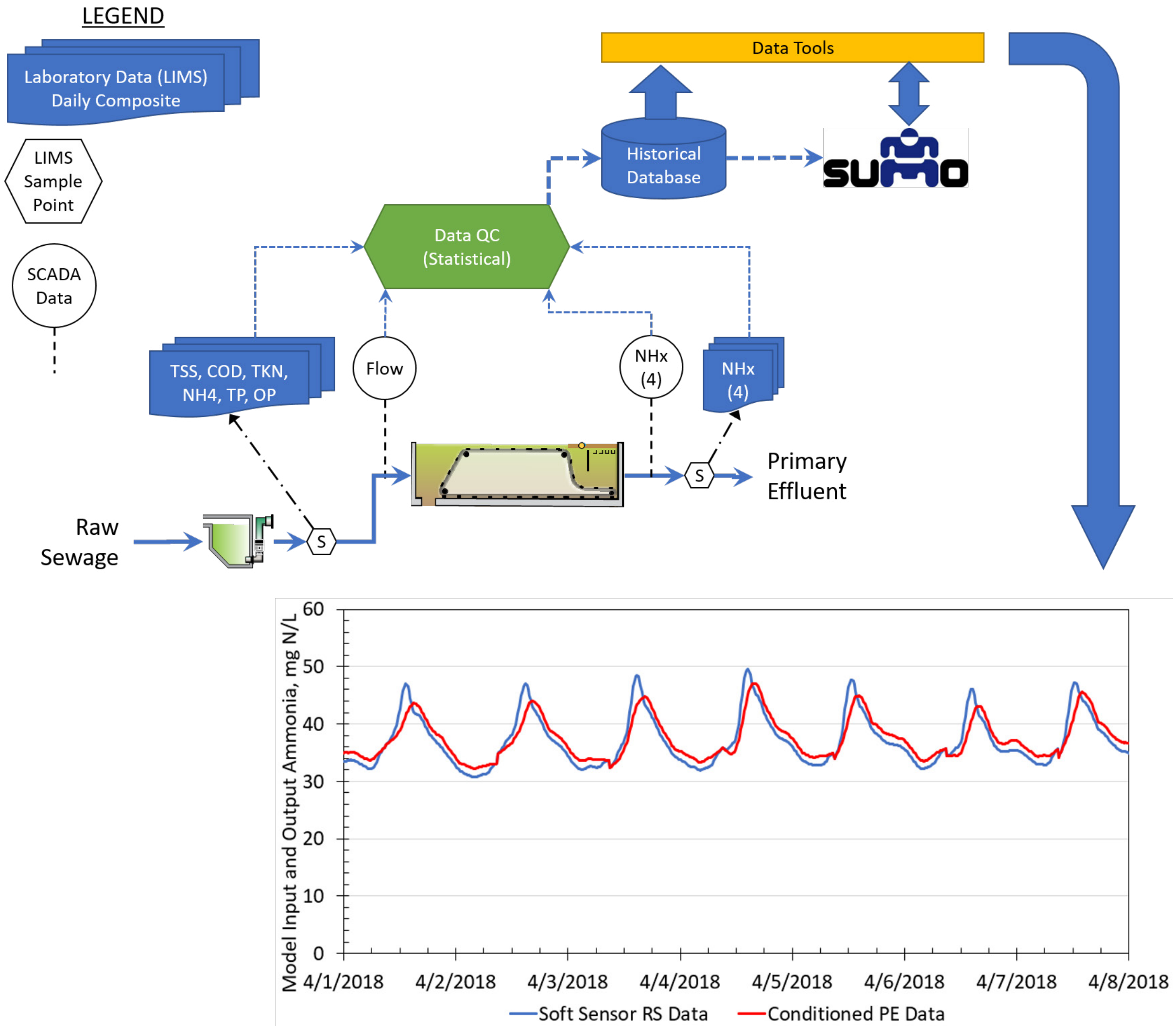

Figure 5: Data flow schematic within digital twin for influent load development for the influent "soft sensor"

Results and Benefits

There are three primary functionalities of the digital twin. First, comparison between model predictions and measured data can be used to highlight areas which require particular attention by operators and maintenance staff, thus minimising their efforts. For example, a warning will be issued if one of the primary effluent online ammonia probes differ significantly from the others and the model or if the laboratory primary sludge total solids does not match up with the model results. For the latter, a check of the primary sludge flow meter or confirmation of the laboratory results would be required. The second use of the calibrated model includes evaluation of various operational scenarios, both operator-defined, and fixed. Lastly, the auto-calibrated model can be used to predict the likelihood of future events at the wastewater facility up to five days in the future, a "wastewater weather forecast" that operations can use to help proactively operate the facility.

Conclusion

The case studies presented in this work demonstrate the water industry's eagerness to move to digital solutions such as digital twins to improve the performance of infrastructure. This white paper demonstrates that large potential savings can be derived from better process automation, online optimisation, fault detection, maintenance and more proactive operation. However, there is no "one recipe fits all" for digital twin applications, and this may hinder the rate at which the full potential of this tool can be realised. Good practice protocols need to be established to support digital twin developers. The protocols should provide answers to the following questions:

- Purpose of the digital twin: what are the objectives and the expected gains? Can the objectives be attained with the existing infrastructure and available data?
- Data: what is the impact of data quality and quantity on the applicability of a digital twin? How to feed data to it? How to calibrate it?
- Model: how to identify the right modelling approach for a given objective? What is the right level of detail (granularity) in a model? How to be confident that model predictions are acceptable for a digital twin? How to handle model uncertainty?
- Robustness of the digital twin: how does the digital twin continue to evolve? How to perform model validation using available online data?

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IWA connects water professionals in over 130 countries to find solutions to global water challenges as part of a broader sustainability agenda. IWA connects scientists with professionals and communities so that pioneering research provides sustainable solutions.

In addition, the association promotes and supports technological innovation and best practices through international frameworks and standards. Through projects, events, and publications, IWA engages with its members to stimulate innovative ideas and content in support of IWA's vision of a water-wise world.

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