INCREASING ECONOMIC EFFICIENCY THROUGH THE USE OF CYBER-PHYSICAL SYSTEMS

Zwiększenie efektywności ekonomicznej przez zastosowanie systemów cyber-fizycznych

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A b s t r a c t: Most industrial plants in Poland are still on the eve of implementing the vision of 'Industry 4.0' (Fourth Industrial Revolution), which was still conceived at Hannover Messe at the beginning of the previous decade. In the context of water management, the term 'Water 4.0' is used, which takes into account a whole range of technologies and digital tools. Its implementation relies in particular on cyber-physical systems to ensure the optimal level of network connectivity using digital tools, between virtual and physical water management facilities during their planning, construction and operation phases.The aim of this article is to identify and demonstrate the key benefits and opportunities of implementing cyber-physical systems in the context of industrial sewage management in Poland - based on selected case studies. The article has demonstrated: (1) rational management of asset renewal funds (CapEx), (2) economic efficiency of operation & maintenance (lower OpEx and TotEx), (3) maintenance planning and improved safety, and (4) various environmental benefits.
K e y w o r d s: Water 4.0, cyber-physical systems, digital twins, industrial wastewater

S t r e s z c z e n i e: Większość zakładów przemysłowych w Polsce jest ciągle w przededniu wdrożenia wizji „Przemysłu 4.0" (Czwartej Rewolucji Przemysłowej), która powstała jeszcze na targach Hannover Messe na początku poprzedniej dekady. W kontekście gospodarki wodnej używany jest termin „Woda 4.0", który uwzględnia całą gamę technologii i narzędzi informatycznych. Jej wdrożenie opiera się zwłaszcza na systemach cyberfizycznych w celu zapewnienia optymalnych poziomem połączeń sieciowych, z wykorzystaniem narzędzi informatycznych, pomiędzy wirtualnymi i materialnymi obiektami gospodarki wodnej na etapie ich planowania, budowy i eksploatacji. Celem artykułu jest – i wykazanie podstawowych korzyści i szans płynących z wdrożenia systemów cyberfizycznych w kontekście zarządzania w Polsce ściekami przemysłowymi - na podstawie wybranych studiów przypadku. W artykule wykazano: (1) racjonalność gospodarowania środkami odtworzeniowymi, (2) efektywność ekonomiczna eksploatacji, (3) możliwość planowania obsługi i zwiększenie bezpieczeństwa, jak i (4) różne korzyści środowiskowe.
S ł o w a k l u c z o w e: Woda 4.0, systemy cyberfizyczne, cyfrowe bliźniaki, ścieki przemysłowe

Introduction

As in many other European Union (EU) countries, industrial facilities in Poland are often still based on technologies from the early 21st century or older, and therefore do not yet reflect the scientific and technological advances associated with the Fourth Industrial Revolution and the vision of 'Industry 4.0' which emerged at Hannover Messe at the beginning of the previous decade. Industry 4.0 generally uses *digital twins*, wireless sensors integrated into assets, industrial internet of things (IoT), cloud computing and predictive analytics increasingly utilising artificial intelligence, i.e., automated 'machine learning'. ('Assets' are defined in this article in accordance with PN-ISO 55000:2017-09 [14]. 'Physical assets', on the other hand, are a subset of these, such as machinery, equipment and infrastructure (ibid).)

The hitherto low level of implementation of Industry 4.0 technologies in Poland is partly associated with the fact that many of the industrial plants were outsourced to Poland after our country's integration into the EU. This also applies to associated industrial wastewater treatment plants (or pre-treatment plants). Whilst municipal wastewater treatment plants in Poland have been built or extended / upgraded over the last 10 –15 years, largely through EU funding, many industrial wastewater treatment plants, and the industrial facilities themselves, are often still in the phase of being upgraded. In the case of discharge and treatment of domestic/municipal wastewater in Poland, the degree of utilisation of technologies of the era of the Fourth Industrial Revolution is often above that of the industry itself.

The largest industrial plants in Poland, especially in the energy, chemical, petrochemical and refining industries, tend to discharge their wastewater directly to the receiving waters - after treatment to comply with the regulatory standards. The other plants usually discharge their wastewater to municipal sewers after pre-treatment so that the contaminant load does not exceed the design capacity of municipal wastewater treatment plants – for compliance with the *Regulation of Minister for Construction on the implementation of responsibilities of industrial wastewater producers and the conditions for wastewater discharges to sewers*. In this instance, the mixture of industrial and domestic wastewaters is discharged after treatment (effluent) to waters.

The aim of this article is to identify and demonstrate the key benefits and opportunities of implementing cyber-physical systems in the context of managing industrial wastewater. This includes municipal wastewater that is a mixture of, amongst other things, industrial and domestic wastewaters.

The concept of Water 4.0

The term 'Water 4.0' is used in the context of water management (including water and wastewater management). Figure shows the stages of development of water and wastewater management starting with 'Water 1.0' in the times of Roman Empire [1].

As the German Water Partnership defines [9], Water 4.0 emphasises digitisation and automation and incorporates the same main characteristics and terms used as Industry 4.0. In particular, the implementation of Water 4.0 is based on cyber-physical systems to ensure the optimal network connectivity, using digital tools, between virtual and physical water management facilities during their planning, construction and operational phases.

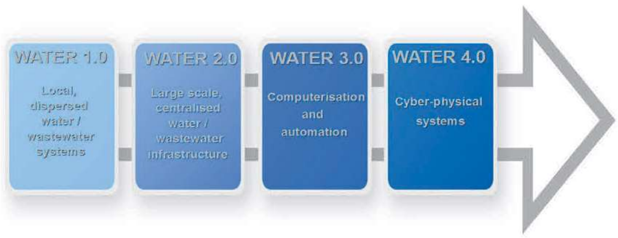

Fig. 1. Phases in the development of water and wastewater infrastructure (Source: prepared based on [1])

Water 4.0 is a new, innovative and multidisciplinary field, but not fully defined yet. Its definition and understanding are evolving along with the published case studies such as those described below in Chapter 3.

The number of topical publications is, however, limited. A previously conducted literature review is contained [12], where an attempt is also made to define this field in the context of various business processes, engineering and industry sectors of '4.0' and relevant technologies, methods and tools, as well as some of the opportunities and risks relating to Water 4.0.

Method

The research method is based on the analysis of a number of topical case studies from various countries (including Poland), which are related to the topic of Water 4.0 in the context of industrial wastewater management.

They address the optimisation of the efficiency/performance of municipal wastewater treatment plants and associated sewers which accept industrial wastewater. Optimisation reduces the number of overflows/bypasses of the wastewater treatment plant and provides in parallel, a 'protection' to the plant from the excessive flow and pollutant load, as well as ensures a consistent quality of the treated effluent.

This will reduce the impact of industrial wastewater and substances it contains, on the receiving waters.

As with the municipal sewerage systems, the same technologies, methods or digital tools can be applied to large industrial wastewater treatment plants and associated sewers, especially in the energy, chemical, petrochemical and refining industries, which are fed from numerous internal units and departments by often heterogeneous wastewater whose sources are difficult to identify.

Technology-wise, cases studies presented in Tab. can be subdivided as follows:

A. *Digital twins* with 'hybrid analytics', where hybrid analytics for the purposes of this article, involves the analysis of historical and real time data, but may incorporate a form of prediction made by digital tools and/or the operator based on the analyses conducted for the aforementioned data.

B. *Digital twins* with predictive analytics.

The case studies (as mentioned above) are based on information received from technology suppliers' publications, methods and tools. Therefore, not all details of the case studies, as well as the technology itself are available to the authors of this article. However, an earlier literature review [12] showed that case studies on Water 4.0 in scientific journals remain relatively rare.

Table presents information from these four suppliers divided into case studies using *digital twins* with hybrid analytics and *digital twins* with predictive analytics (A and B). For each of these, "Description of digital technologies and tools" is provided (1.1 - 4.1), followed by "Selected case study (purpose, method, outcome)" (1.2 – 4.2).

	Selected case studies involving the optimisation of control processes for the transmission and treatment of industrial wastewater
1.	**A. *Digital twins* with hybrid analytics**
	Danish Hydraulic Institute - DHI (Denmark)
	1.1 Description of digital technologies and tools

Digital tools which apply to wastewater treatment processes [2], but also with applications, for example, to water distribution networks, sewers and rivers are as follows [3, 4, 5]:

WEST – models (digital twins), simulates and evaluates physical, biological and/or chemical processes [2, 4].

DIMS.CORE – a central data depository for customised real time solutions: monitoring, reporting and control. Converts data into information. Provides data / information to global users through customised reports [2, 3].

MIKE OPERATIONS – real time data management including compliance reports together with supporting data. Online modelling for both forecasting and control [2, 5].

The subsequent case study concerns WEST.

1.2 A selected case study (objective, method, outcome)

***Water Resources Recovery Facility in West Lafayette, Indiana (United States)* [6].**

The goal was to reduce the carbon footprint by 50% by 2025 while improving the quality of treated wastewater. Only minor infrastructure redevelopment was permissible.

Modelling of the treatment plant processes was carried out using WEST that enabled different aeration control strategies to be tested in real time and in a virtual environment. Parallel optimisation of the digesters identified the potential for doubling energy recovery from biogas.

Modelling resulted in improved quality of the treated wastewater. The treatment plant also became 60% energy neutral. Operating costs (OpEx) were reduced by $293,000.

2. Endress+Hauser – E+H (Germany)

2.1 Description of digital technologies and tools

The aim of the Liquiline Control CDC81 system (supervisory system) is to achieve the set values for nitrogen and phosphorus compounds with the lowest possible: (1) electricity consumption, and (2) dosage of chemical reagents [8].

The Liquiline Control predictive control system also targets the automation of the process in order to react quickly to: (1) erroneous readings of measured values, and (2) equipment failures, e.g., blowers (remote diagnostics) (ibid).

The system utilises predictive algorithms developed on a mathematical model (e.g., [7, 8]). A few hours in advance, on the basis of the analysis of inflow to biological reactors, the system selects the settings of control devices to optimise the conditions for reducing contaminants [7].

Through continuous measurement and verification of signal quality, Liquiline Control aims to ensure stable operation of the wastewater treatment plant and adequate effluent quality parameters [8]. In the event of erroneous indications or failures, the system sets the respective control loop into an emergency state and generates an error or warning message (ibid).

Utilising the asset networks or wireless technologies, Liquiline Control transmits measurement data to a central control room for the purpose of monitoring the process and possibly changing control algorithm parameters (ibid). The system also uses a mobile communicator to allow remote access (ibid).

2.2 Selected case study (objective, method, outcome)

***Water and Wastewater Management Company in Tomaszów Mazowiecki (Poland)* [8]**

Liquiline Control system has been designed to provide full automation of processes from the raw wastewater pumping station and the septage discharge station to the sewage treatment plant located at Tomaszów Mazowiecki. Control algorithms control the processes of mechanical sewage treatment, operation of the grit chamber, fat disposal system, operation of primary settling tanks, sludge thickeners, secondary settling tanks and operation of biological reactors.

The system cooperates with monitoring devices and control devices of the treatment plant. Its main task is to conduct an on-line analysis of monitoring data and calculate the settings of the subordinate control devices.

A real time algorithm assesses characteristics of the inflowing (raw) wastewater and selects the settings of control devices accordingly to create conditions for the optimal reduction of contaminants.

The operating parameters / settings constitute the basis for the automatic execution of the nitrification / denitrification process. The operating parameters of the biological reactor such as duration and intensity of aeration and the duration of anaerobic conditions are defined.

The system algorithm operates in real time and interfaces with the SCADA system. It monitors pollutant loadings and provides emission standards for treated effluent in a predictive manner.

The guidelines defined by the operator (in this case the technologist) are crucial in the configuration of the system / master system for running the nitrification / denitrification process. It defines the control area for the host system. It specifies the ranges of variation for individual parameters. It also defines the required parameters of the treated effluent at the reactor outlet and the process parameters. The master system, on the other hand, ensures that the treatment process progresses in an optimal way.

Any anomalies that may occur in the performance of measuring probes and actuators are monitored in real time. In a possible emergency, the system can automatically take predefined actions, but the final decision is ultimately left to the operator.
Automation of the aeration process reduces operating costs (OpEx). One of the main benefits of the system is the reduction in electricity costs.

B. *Digital twins* with predictive analytics

3. **Xylem (United States)**

3.1 Description of digital technologies and tools

The following description and case study apply to Xylem's BLU-X method / tool. BLU-X is applicable, amongst other things, to catchments of municipal sewage treatment plants. Xylem refers to its methodology as decision intelligence. The method is based on big data and its purpose is to improve decision-making and make recommendations for both the operation and planning of new infrastructure [18].
BLU-X is based on advanced analytics which allows the water utility / operator to make optimal decisions, for example to ensure resilience to climate change, as well as to optimise costs (ibid). By understanding how external factors (e.g., weather) interact with operating parameters and analysing an enormous number of scenarios in real time, the organisation can then manage the uncertainties / risks associated with asset planning and ensure cost efficiency (ibid).

Catchments of municipal sewage treatment plants [18]

- Digital twins of the sewerage system optimises, controls and coordinates all system assets in real time. It identifies any potential failures and malfunctions for critical assets with the use of diagnostic tool data and machine learning.
- Intelligent pumping systems transmit information in real time and can thus assist with maintaining the operational reliability.
- As Xylem reports, digital twins can be helpful in optimising the process, reducing energy consumption and ensuring process stability, throughput and treated effluent quality.
- If integrated with real time control of the sewer system, digital twins can optimise the volume of wastewater entering the treatment plant.

Decision intelligence **[18]**

This functionality provides data integration, analytical and visualisation capabilities so that the operator (water utility company) can: (1) control the intelligent system that has been installed, and (2) use the gathered big data.

3.2 Selected case study (objective, method, outcome)

City of South Bend, Indiana (United States) **[18, 19]**

The objective was to avoid potential costs of $1 billion associated with legal requirements to reduce frequent storm overflows from the City's combined sewers with industrial wastewater.
The City of South Bend has implemented a BLU-X Intelligent Sewer tool based on wireless sensors linked by SCADA system and machine learning (artificial intelligence) to provide decision support and process control.
The disposal of industrial wastewater through the sewerage system into the Saint Joseph River has been a key issue in relation to the heavy industry that historically existed in the city (e.g., Singer Sewing Company). More recently, the region has re-attracted new industries and has become a technology hub (industrial zone).
The City has implemented the Xylem tool for the catchment area of the sewage treatment plant to reduce overflows from storms (4-8 million m^3 per year) and to optimise the existing combined sewers.
Initially, real time monitoring was installed and implemented on the basis of 120 sensors located within the catchment area of the municipal sewage treatment plant of the City. Following a thorough analysis of the data in 2012 conducted jointly by the City and Xylem, real time decision support system (RT-DSS) based on BLU-X was implemented. It considered sensors and valve actuators, which made possible to 'trade' the available sewer capacity (as with the stock exchange) to prevent wastewater overflowing.
BLU-X RT-DSS transmits information: to operators on SCADA screens, to field workers on smartphones and tablets, to the City engineering staff through web portals. (Operators are able to take control of the system at any time.)
Consequently, the City has reduced storm overflows from the combined sewer system by over 70% and concentrations of E. Coli in the Saint Joseph River by 50%. As a result, the compliance costs have been reduced by more than $500 million.

Royal HaskoningDHV - RHDHV (Netherlands)

4. **4.1 Description of digital technologies and tools**

Aquasuite 'virtual operator'

In accordance with the available information, the virtual operator is a tool based on artificial intelligence (automatic machine learning) that has been designed for water and sewage companies and various industries [15]. It makes predictions (predictive control) based on historical data and external information and then automates real time repetitive actions (monitoring and control) (ibid). Hence, the virtual operator improves efficiency ('calms' and 'aligns' the processes of the network and the treatment plant) which will allow the physical operator to focus on more relevant tasks (e.g., strategic) which will increase productivity and ultimately reduce costs (e.g., OpEx) (ibid).

The virtual operator monitors, analyses, visualises (cockpit) and regulates the efficiency of water and sewage management. Based on probe data, weather forecast information and other data/information, it ensures predictions with an accuracy of up to 97% (ibid).

The virtual operator consists of two components: (1) 'analyst', (2) 'autopilot' (ibid).

The virtual analyst conveys real time capacity, flow, load and quality data from SCADA, PLCs, process databases and probes connected via IoT, and comparing them with the past data (ibid). Data visualisation enables the (physical) operator to focus on the proper tasks and make prompt decisions on the basis of available information (ibid).

Auto-pilot is a self-learning and predictive tool that allows (as described) to prevent a problem before it happens by monitoring performance and responding appropriately should it be required (ibid).

The Aquasuite virtual operator applies to processes and is applicable to five products/tools [15, 16], including but not limited to:

- Sewers / wastewater collection and transmission (FLOW)
- Wastewater treatment (PURE).

This article focuses on FLOW.

Sewerage system / wastewater collection and transmission

Virtual Operator (FLOW) can predict, identify and reduce storm overflows from combined sewers. It links weather forecasts with real time process data to forecast future wastewater volumes and their impact on the sewer system (RHDHV 2020).

It may monitor and control pumping stations to optimise the performance of the sewerage system (ibid). It also anticipates and reduces the flow / peak loads coming into the wastewater treatment plant and could bypass the plant (ibid).

FLOW uses a hydraulic model that allows prediction to be made based on current conditions [13]. Prediction of flow during dry weather is made with the use of a heuristic method and adaptive prediction model, which was previously used by RHDHV in optimising the drinking water treatment process (ibid).

4.2 Selected case study (objective, method, outcome)

Vallei en Veluwe Water Board (WSVV) (the Netherlands) [13]

This case study focuses on predictive and prescriptive methods to improve and optimise wastewater treatment processes. This was done within the context of undetermined peak flows associated with rainfall, which inflowed into the treatment plant and consequently poor quality of treated effluent, as well as bypasses of the treatment plant, which had an impact on the receiving waters (eutrophication).

In order to maximise the quality of the treated effluent, the WSVV had previously applied an effluent treatment phase (or tertiary treatment by means of sand or disc filters). The hydraulic capacity of this phase was lower than the maximum hydraulic capacity of the treatment plant (i.e., secondary treatment). This resulted in frequent bypasses of this phase during rainfall periods. Such peak flows were also associated with peak loads of total oxygen demand (TOD) and total solids (TSS).

Optimisation of the inflow to the wastewater treatment plant was carried out by using predictive control rather than conventional measurement of wastewater levels at the pumping stations. The implementation of predictive control is done using flow prediction during dry weather and "flattened" flows / peak loads based on weather forecasts. As opposed to control based only on the measurement level, predictive control waits for the situation to change by anticipating the available sewer retention so as to flatten the inflow to the treatment plant (without additional storm overflows from the combined sewers). In this regard, the FLOW predictive controller was used as a pilot project.

Predictions of flow during dry weather along with weather forecasts were key factors for the FLOW controller. On the basis of these factors and real time measurements of the level and outflow from the pumping station to the sewage system, a forecast was made along with an optimisation of the available sewer retention which allows the reduction of overflows.

Both dry weather flow and weather forecasts along with level and outflow measurements were the input data for the FLOW controller. The current situation (i.e., utilised sewer retention) was continuously calculated on the basis of the level and application of the relevant curves from the sewer models. The prospective situation (i.e., channel retention to be utilised) was predicted on the basis of capacity/volume optimisation techniques.

Channel retention was modelled as separate reservoirs. The reservoir inflow prediction was calculated as the sum of the dry weather flow rate and the rainfall water runoff prediction. The outflow from the reservoir was predicted on the basis of capacity optimisation. To do so, total retention was also optimised taking into account two constraints: (1) critical levels in the sewer, (2) the requirement to empty the sewer before the next significant rainfall.

This case study demonstrates that, in most cases, peak inflows to several WSVV wastewater treatment plants have been flattened and, at the same time, the number of bypasses of the tertiary treatment / further effluent treatment has been reduced (and without causing additional storm overflows). The effectiveness of the primary and secondary treatment has also improved. This resulted in lower concentrations of nutrients (phosphorus) in the treated effluent along with a reduction in energy and chemical reagent consumption (i.e., OpEx).

Results

The use of Water 4.0 technologies may improve the efficiency of the sewerage system and therefore the quality of the treated wastewater (effluent). Regardless of whether the industrial facilities themselves are upgraded to the Industry 4.0 standard or not, the benefits of upgrading the industrial wastewater treatment plants / pre-treatment plants themselves, as well as the municipal sewerage system receiving industrial wastewater, can therefore be summarised as follows: (1) rational management of asset renewal funds (CapEx), (2) economic efficiency of operation & maintenance (lower OpEx and TotEx), (3) maintenance planning: and improved safety (occupational health and safety), and (4) various environmental benefits (e.g., ensuring the required effluent quality). ('TotEx' (Total Expenditure) is the sum of CapEx (Capital Expenditure) and OpEx (Operational Expenditure) over a defined period [11].).

Discussion

The greatest benefits associated with the implementation of technologies of the era of the Fourth Industrial Revolution may be obtained by industrial plants discharging wastewater effluent directly into the receiving waters, especially in those plants where the state of repair of assets still leaves much to be desired. The benefits will, of course, be even greater when the implementation of Water 4.0 technologies is combined with the renewal of wastewater infrastructure. As with the industrial facilities themselves served by wastewater treatment plants, it is possible to gradually implement technologies of the Fourth Industrial Revolution era (e.g., [12]) what increases the economic efficiency.

One of the constraints associated with the low level of application of Fourth Industrial Revolution technologies in this country is generally a quite low level of investment directed towards the implementation of innovative solutions, as well as generally a low level of interest in the contemporary methods of physical asset management and reliability engineering. Popularising the use of the ToTex methodology in accordance with ISO/TS 55010:2019 [11] for the purpose of estimating the costs and benefits of operating facilities (assets), would probably change this unfavourable situation.

It is also worthwhile noting that Poland is a country at risk of water scarcity, especially since nearly 1/3 of the rivers in Poland have non-class water with a 60% contamination index [17]. Water deficits will become even greater with climate change. Water 4.0, through improving the efficiency of process water usage and industrial wastewater treatment (including water reuse rates), can also reduce our carbon and water footprint and certainly improve the resilience to climate change.

Summary

The process of absorption of Water 4.0 related technologies in water and sewage management (both municipal and industrial) in Poland is progressing quite slowly for various reasons. It would have a number of benefits demonstrated and illustrated by a number of case studies, viz: (1) rational management of asset renewal funds (CapEx), (2) economic efficiency of operation & maintenance (lower OpEx and TotEx), (3) maintenance planning and improved safety, and (4) various environmental benefits.

The above-mentioned benefits are shown in this article with the help of selected case studies in the context of cyber-physical systems (digital twins). While some of the case studies refer to municipal sewers, the same digital technologies and tools could be applied to large industrial wastewater treatment plants and their sewage networks especially in the energy, chemical, petrochemical and refining industries, which often receive heterogeneous wastewater from internal units and departments and their sources are difficult to identify.

One of the constraints related to the hitherto insufficient level of new technologies applications in the country is generally quite low level of investments aimed at the implementation of innovative solutions, as well as generally low level of concern for modern methods of material assets management. Properly carried out financial analyses, considering TotEx and OpEx in particular, could change this unfavourable situation.

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