A HIGH-PERFORMANCE COMPUTING (HPC) BASED INTEGRATED MULTITHREADED MODEL PREDICTIVE CONTROL (MPC) FOR WATER SUPPLY NETWORKS

Krzysztof GASKA [a], Agnieszka GENEROWICZ [b], Izabela ZIMOCH [c], Józef CIUŁA [d], Zsuzsanna IWANICKA [e]

[a] DSc, PhD Eng.; Institute of Water and Wastewater Engineering, Silesian University of Technology, Konarskiego 18, 44-100 Gliwice, Poland
E-mail address: *krzysztof.gaska@polsl.pl*

[b] DSc, PhD Eng.; Institute of Water Supply and Environmental Protection, Cracow University of Technology, Warszawska 24, 31-155 Cracow, Poland
E-mail address: *agenerowicz@pk.edu.pl*

[c] DSc, PhD Eng.; Institute of Water and Wastewater Engineering, Silesian University of Technology, Konarskiego 18, 44-100 Gliwice, Poland
E-mail address: *izabela.zimoch@polsl.pl*

[d] PhD Eng.; Nowy Sącz Water Networks Company, 22 Wincentego Pola Street, 33-300 Nowy Sącz
E-mail address: *jozef.ciula@swns.pl*

[e] PhD Eng.; BOŚ S.A. Centrum Korporacyjne w Krakowie, ul. Kalwaryjska 63, 30-504 Kraków
E-mail address: *zsuzsanna.iwanicka@bosbank.pl*

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Abstract

The article presents the concept of an intelligent system of multithreaded, hierarchical predictive control of water supply and sewage networks using a parallel computational architecture. The predominant element of the proposed control system over other hitherto functioning systems is the element of predicting future events (MPC model). This feature, combined with the self-learning intelligent control system, not only allows you to react to changes in sensor state, but also anticipate these changes and adjust the system in advance to prepare for predicted situation, which is particularly important in systems with high inertia as extensive water supply and sewage networks. The technologically advanced solutions proposed by the authors, ie the HPC (High Performance Computing) ICT system, including the requesting module allows (by analyzing the space of states and events in real time) to predict future behaviors of individual elements of the system and effectively react to unknown cases, supporting the making of strategic decisions.

Streszczenie

W artykule przedstawiono koncepcję inteligentnego systemu wielowątkowego, hierarchicznego sterowania predykcyjnego sieciami wodociągowymi i kanalizacyjnymi z wykorzystaniem równoległej architektury obliczeniowej. Zdecydowaną przewagą proponowanego systemu sterowania nad innymi dotychczas funkcjonującymi, jest element przewidywania przyszłych zdarzeń (model MPC). Cecha ta w połączeniu z samouczącym się inteligentnym systemem sterowania pozwala nie tylko reagować bieżąco na zmiany stanu sensorów, ale również przewidywać te zmiany i z odpowiednim wyprzedzeniem korygować działanie systemu przygotowując go na przewidywany rozwój sytuacji, co ma szczególnie duże znaczenie w systemach o dużej bezwładności jak rozległe sieci wodociągowe i kanalizacyjne. Proponowane przez autorów zaawansowane technologicznie rozwiązania, tj. system ICT klasy HPC (High Performance Computing), obejmujący m.in. moduł wnioskujący, pozwala (poprzez analizę przestrzeni stanów i zdarzeń w czasie rzeczywistym) na przewidywanie przyszłych zachowań poszczególnych elementów systemu i skutecznie reagować na nieznane przypadki, wspomagając podejmowanie strategicznych decyzji.

Keywords: **SMART City; Water distribution systems; Sewerage systems; Predictive models (MPC); Artificial intelligence; GIS; Parallel computing architecture (HPC).**

1. MARKET DIAGNOSIS – IDENTIFYING THE NEEDS OF WATER COMPANIES FOR THE MANAGEMENT OF WATER AND SEWAGE SYSTEMS

Searching for optimal technology solutions, both hard and soft (information systems) in water and waste water management requires specialized, domain knowledge, which, using advanced solutions, can be a key element in intelligent real time ICT systems. Numerical modelling allows to build systems, based on knowledge about complex systems, processes, and devices in a relatively short period of time. It is particularly important in the context of process optimization, which requires complex calculations for one case (it is impossible for technical reasons to build real models for each variant solution). This type of models is used in environmental engineering, beginning with simulation of individual devices to technical and social models of entire systems for a region or country.

Process or system models are typically described by partial differential equations describing the behaviour of a given system. The computational complexity of such algorithmic models is usually so great that software engineers must apply parallel computing architecture in order to handle the tasks. Sometimes the exact nature of the problem is unknown, since our knowledge about it is derived from observation or the used software imposes a specific modelling paradigm that does not allow faithful reproduction of all the nuances of a given system.

An alternative solution that can be used in this situation is the use of advanced artificial intelligence (artificial neural networks, fuzzy collections, genetic algorithms etc.). Many artificial intelligence solutions are available in the area of industrial automation inferential, predictive and adaptive systems, having a crucial meaning in optimal control of technological processes [5, 10].

Advanced algorithms for control of industrial processes are now being used in conjunction with predictive or adaptive models [14- 15]. The main goal of controlling modern industrial equipment is to stabilize the process parameters and maintain the balance in the process management, which support the reduction of sudden and significant changes in the work parameters.

During the design of new technological process, it is important to make a list of conditions that determine the boundaries of the decision-making process. One of these areas is to consider the selection of an advanced regulation technique. The choice of a PID algorithm that foresees a regulator with a model or other method cannot be determined until the task itself is evaluated and the legitimate objectives of the newly implemented automation system are not set. The neglecting of this basic principle will expose the business to the loss of considerable resources and time.

When choosing one of the advanced methods of regulation, the three most important issues are: process variable characteristics, operational objectives, system security and use.

One of the basic principles of proper management of a modern water supply company is to have as complete information as possible on the technical condition of the water supply and sewerage network. Taking correct decisions requires the consideration of many factors that occur both at a given moment and in the future. The natural way to support this type of activity is to use the right IT tools [3, 4].

The increasing requirements of water consumers for water of proper quality, quantity, and pressure entails the reduction of current costs and water losses. The basic actions supporting these actions are:

- Active Leakage Control
- Pressure Management in water supply networks
- Speed and Quality of Repairs
- Pipe Materials Management
- Optimization of energy management in the company

The water supply system, sewage network and wastewater treatment system consists of a number of interrelated objects, such as water intake, water pumping stations, hydrophores and water supply systems, sewage treatment plants, sewage pumping stations and sewage collectors. The efficiency and operating costs of these systems depend on the proper cooperation of all their components and the control of the operation of the equipment. The introduction of predictive control in these systems will result greater efficiency in process technology and reduced operating costs for both financial and environmental systems. The proposed control system enables the integration of all existing management tools. In the case of a water supply system, these will be [4, 10, 17]:

- control of the water treatment technology process by optimizing the exploitation of equipment, adapting to the changing water demand, ensuring minimal cost of operation of the water treatment plant while increasing efficiency,

- control of the water supply network using existing (or new) hydraulic models, such as EPAnet, to provide adequate water supply, taking into account the quality of water from different sources and considering the preferences of the customers,
- Identifying both the existing technical problems of the water supply network and the anticipated futureproblems, which will allow for optimal water infrastructure maintenance and modernization,
- identification of sites of water loss resulted by leeks or illegal water consumption,
- Visualization of the entire water supply system in GIS software with the ability to modify the system in conjunction with the changes being made and analysis of future development scenarios [16].

In the case of a sewage collection and treatment system, the collections of elements that integrate by introducing a predictive control system are similar:

- control of the sewage treatment process, which minimizes the cost of treatment, considering changing sewage quality and quantity,
- Incorporation of variable atmospheric conditions into the wastewater treatment process and its adjustment to the anticipated quantity and quality of wastewater,
- control of the sewage network and its equipment based on the hydraulic model leading to minimization of energy consumption and optimization of network equipment,
- Identification of the sewerage network sections with high infiltration rates in order to support the proper planning of network renovation investments,
- Inventory and visualization of networks and devices in GIS, to support planning of sewerage network development, considering areas where the sewerage system is economically justified (the "what if" scenario).

2. INTEGRATED MULTI-THREADED SYSTEM CONCEPT, HIERARCHICAL PREDICTIVE CONTROL

The proposed system is based on a predefined component environment – ProWater Objects. NET, which is one of the ProWaterEnterpriseSolutionFramework. NET environment (author's solution). The real-time HPC (nVidia CUDA) system is a component-oriented environment with a specialized datebase of knowledge representing the elements of technological processes in the area of water and sewage management, considered as control objects. All variables related to supported devices are updated on-line through the OPC UA servers of the monitoring and control system. This system creates a platform for advanced algorithms operation, acting as the interface between the control and monitoring systems and the PLC. System configuration ensures permanent monitoring of communication connections and automatic system response in case of a failure, sudden parameter changes, etc. Key performance indicators may also be included in the system, and all calculations required for optimal system performance are performed in real-time using a parallel computing architecture. This advanced multi-parameter control system consists of a main MPC controller and individual MPC controllers for each component device.

The EnviroLab.ProWater Enterprise Solution system is based on process state space model. It is implemented on a higher supervision level in order to manipulate the multiple control loops and to optimize control systems and to track changes in process variable values. The state space model is used to forecast the influence of time independent process variables – both manipulated and anticipated – on dependent output variables of the process – so regulated like unregulated predicted variables. The model allows for consideration of the dynamics of the process between the change of independent variables and the expected changes of the dependent variables. The optimization algorithm predicts the future course of the process and compares it to the operating objectives of the process. Internally, the algorithm also calculates the strategy of future decisions, saving only the current changes in the settings of the lower level regulators. This multi-stage computing process, repeated at each execution, enables the driver to plan ahead in order to ensure optimum dynamic control of regulated process variables. EnviroLab.ProWater ensures flexibility in the combination of control targets and control of limits of variable for multiple variables. Each adjustable process variable may contain a target value and/or limiting values limits can be defined as absolute minimum/maximum values or minimum/ maximum deviations from set point values).

One of the main tasks will be to develop advanced prediction control (MPC), adaptive (APC) and inferential control algorithms that will provide:

– Significant reduction in operating costs and higher stability of operating parameters than with classic PID controllers.

– Reduced time for diagnosis and analysis of processes and thus rapid response to interferences and undesired working conditions – through state domain analysis.
– Rapid response to unknown events (interfering signals) destabilizing the technological process. The EnviroLab Enterprise Solution incorporates dedicated HPC (High Performance Computing) tools, advanced prediction models for MPC and adaptive and inferential control and thus provides stable and optimal working performanceof the equipment.
– Significant shortening of the design process or modifications of the visualization and process control systems through the use of the RAD.NEnvironTcomponent.
– Significant reduction of process modelling errors, thanks to author's innovative solutions (predefined. NEnviroT intelligent real-time components – processes, objects, events), meaning that all process units can be precisely modelled and optimized to support planning and profit maximization.
– quick adaption of the drivers' operating strategies to economic and environmental goals by using innovative technology in ProWater Enterprise Solution.It allows users quickly adapt to changing economic scenarios, making it easy to design and maintain the driver.
- Significant increase in system performance due to the use of 64-bit architecture
- Real-time knowledge base optimization based on process, computational, and laboratory data
- API to C ++, Java and .NET for individual adapters and direct integration
- use of Complex Event Processing technology (complex event processing).

3. ARCHITECTURE – TOPOLOGY OF THE SYSTEM

Control in a hierarchical structure is an effective way to control complex control systems.

In the hierarchical system, the system decomposes into separate subsystems or cells, with autonomous information processing and decision-making. The main reasons for the use of control structures are:

1. The ability to decompose a complex decision problem with a large number of coordinates, the most difficult solution, a few minor simpler decision problems, a smaller number of state coordinates (smaller space of states) solved sequentially or in parallel.
2. Increased flexibility and clarity with modules easier to modify and detect any errors,
3. Shorter of computation time (quicker algorithms), thanks to the use of parallel computing architecture
4. Increased reliability of the operation of the control system.

The structure of the hierarchical system (Figure 1) consists of the main layers (Supervisor, Optimizer, and Follower) and subsystems (slow, medium and fast). Higher levels generate controls and decisions that help the lower layer perform its tasks. Layer separation is the result of functional decomposition of the control system, and subdivision is the result of decomposition of system dynamics in the time scale. In addition, it uses the available information about the system such as dynamics and interactions between its individual elements (knowledge based on control objects).

The Supervisory Control Layer (SuCL) coordinates the individual components of the water and wastewater management structure, evaluates the operational status of the system, and selects the best control trajectory. The observation of the actual control results and its comparison with the forecast allows to decide whether to change your control strategy. Hence, one of the important tasks of this layer is to switch between control strategies [6].

Optimizing Control Layer (OCL) is responsible for the generation of control trajectories for individual control variables. The MPC – Predictive Control Model is used here. This layer determines the trajectories of the set points for the lowest layer [6, 7, 12, 13, 16].

The Follow Up Control Layer (FCL) is the lowest layer and is responsible for the safety of the processes at the facility, in accordance with trajectories defined in the higher control layer. It has direct access to the controlled object and can implement advanced control strategies developed in higher layers. These tasks implement straight-line algorithms in the form of classical PID algorithms or algorithms written in logic memory of programmable PLC [6, 7, 9].

OCL is divided into three sublayers (slow, medium and fast) corresponding to different dynamics of technological processes in the water supply system and dynamics of interfering inputs. The basic tasks of the slow control sub layer are based on the determination of trajectories of pressures and flows.

The medium control sub layer generates trajectories

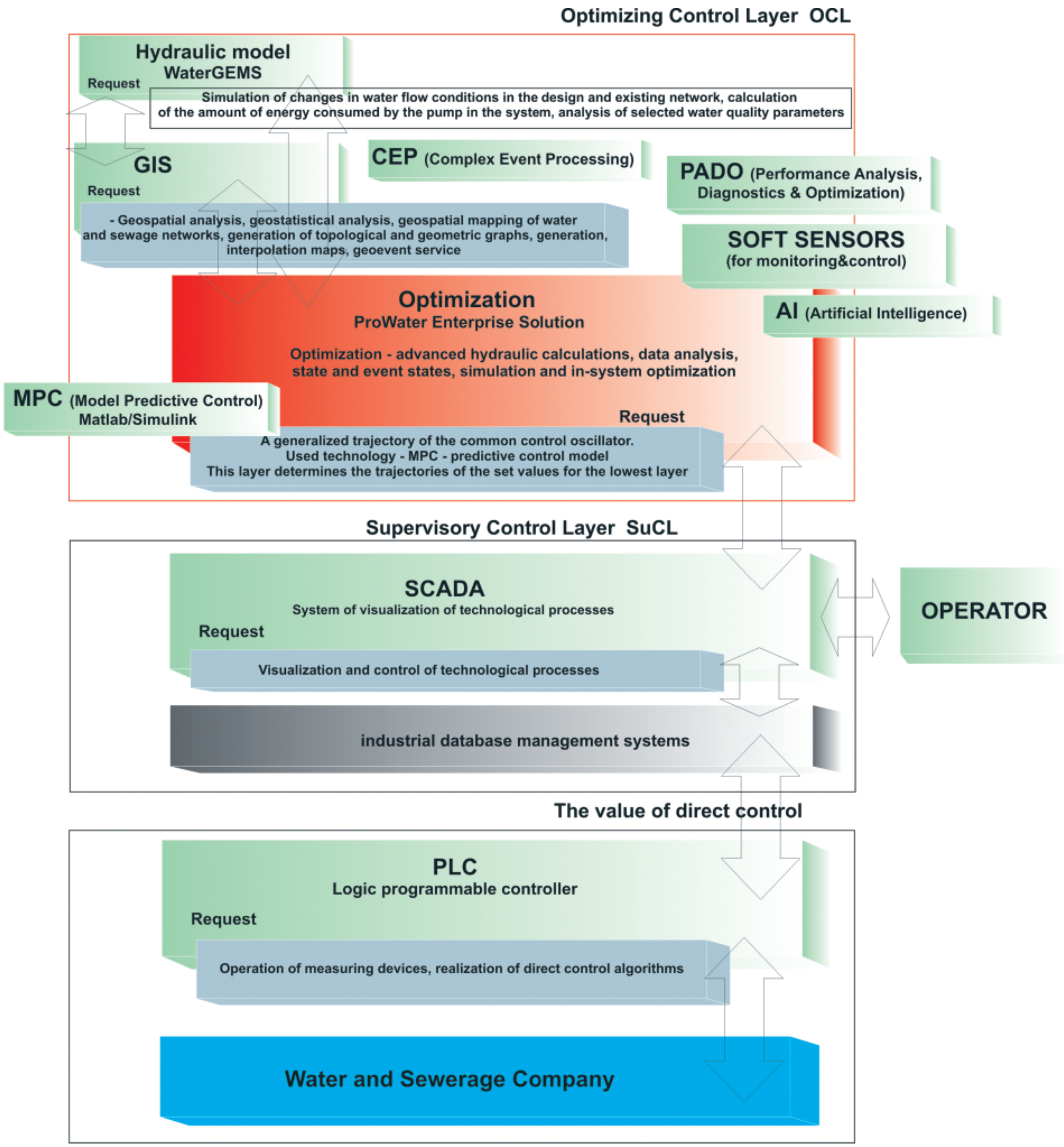

Figure 1.
Architecture / Topology of the System

for output variables controlling the control process, using the MPC model in the full range of the water supply (sewerage) system.

The task of the fast control sublayer is to force the control trajectory defined by the average control subset on the object. This sublayer is responsible for meeting the system input control requirements while minimizing power consumption.

The operation of the MPC predictive algorithms is based on the knowledge about the future behaviour of the regulated variable in order to determine the value of the control variables. In order to predict the future values of the controlled parameters, the mathematical model of the control object (control object model) uses the previous control signal values and disturbance values (past, present and future) [1- 3, 10]. Basic advantages of predictive control are the following:

– possibility of application for both linear and non-linear objects / processes,
– the construction of SISO (Single Input Single Output) and MIMO (Multiple Input Multiple Output) control systems
– consideration of the limitations of process variables,
– incorporation of the internal interaction in the control object by using the object model (the regulator "knows" the object by the control object model).
– incorporation of time delays variable of control objects,
– optimization of the economic indicators related to control.

The MPC algorithm takes into account different types of restrictions:

– limitation of the values of control variables,
– limitation of the increments values of control variable
– limitation of the output variables
– limitation of technological variables that are formulated analogously to constraints on output variables.

The implementation of advanced hierarchical predictive control in the real system requires some solutions, to make changes to the existing measurement and / or hardware and software infrastructure, and to adapt ICT infrastructure.

Implementation of new control method requires proper configuration of the automation system [17]. It is assumed to introduce a hierarchical system of three-layer structure. The direct control layer will be used to control the executive devices in the water supply system, the supervisory control layer will be responsible for supervision and data acquisition.The third layer -the optimization control layer will consist of an additional computer unit implementing complex prediction control algorithms in the parallel computing architecture (NVidia CUDA) using specialized scientific applications (Matlab / Simulink, PADO, CEP, Neurosolution), including innovative solution.

The proposed ICT architecture encompasses several PC units, including units with increased computing power, used for acceleration of hydraulic calculations of diagnostics and analysis of state-space and events domain in water and wastewater systems.

The basic working unit is equipped with a SCADA system consisting of visualization software and an industrial database. The communication server collects the process data from the drivers and transfers to ProWater Enterprise Solution (Matlab) or MatLab [6, 8, 12].

Advanced computing unit is used for advanced hydraulic calculations, data analysis (Big Data Analytics Research), state space and event domain analysis, simulation and multi-parameter optimization of the operation of water / sewage system. The installed ProWater Enterprise Solution environment. NEnviroT includes two areas – ProWater.Engine (domain for complex computation and application control) and ProWater.WorkSpace (data space) [11].

The supervisory system is SCADA, which sends NetDDE commands to ProWater.Engine and ProWater retrieves process data via OPC UA or ODBC to ProWater.WorkSpace. Then the calculations are performed and the results are sent by the OPC UA to the SCADA system.

4. THE STRUCTURE OF A VIRTUALIZED KNOWLEDGE DATABASE ON OBJECT AND PROCESS CONTROL (MPC)

The expert system supporting the monitoring, control and management of technological processes in water and wastewater management systems is based on the EnviroLab Enterprise Solution Platform component environment. The NVviTT Framework is an advanced technology platform for integrated industrial software (with built-in dedicated modules.) The system is scalable in a virtualized modular structure (IFL+CASK+CLOUD). It sets new directions and standards in process simulation, process research and algorithmic control of technological processes, utilizing the latest ICT solutions and advanced predictive and adaptive control models, including laboratory (ACD / Labs, LIMS). The author's innovative solution – the .NavviTT platform, in addition to known solutions, applies real-time knowledge database updated from different, often dispersed sources (process data from SCADA, homo, heterogeneous, structural and non-structural). Uses a number of innovative data processing tools, including validation and statistical analysis.

One of the key elements used in the proposed EnviroLab_Enterprise_Solution is the application of virtual sensors in PLCs to increase the reliability of automation systems by providing rapid response to damage [19]. Virtual sensors are especially useful in situations where is not possible to measure the process variables (measurement is too expensive; no sensor can be installed in the plant or no suitable measurement method is available).

Main innovations were done in the structure of control algorithms, their temporal complexity and the speed of technological process stabilization (followed by optimization). It is crucial to have specialized domain knowledge, dedicated and structured base of knowledge about the expert system, which is logically and physically divided into three independent modules with different functionalities (Fig. 2, 3):

Figure 2.
EnviroLab Enterprise Solution Logical Structure

IFL – Integrated Field Laboratories

Advanced model of virtualized laboratory space supporting the process of building and updating the knowledge base of expert system (CASK layer), calibration, validation, testing of MPC / APC control models, event models – by incorporating laboratory test (process, technological, analytical). IFL environment, through the introduction of the IFL.NEnviroT module is a dedicated tool, including LabResearch_Architect.NEnviroT, which is an expert support system (using LabView, LIMS, ACD / Labs) to conduct research and interpret analysis results. The built-in IFL.NEnviroT advanced research wizard tool allows to integrate lab resources and create a virtual environment – the infrastructure of dispersed labs – by preceding elements of diagnosis, identification, and formulation of a research problem, including the test program required to build a knowledge base for control objects for drivers predictive MPC, adaptive APC, including neural model learning and calibration, validation of object models, events, and real-time updates of knowledge base.

CASK – Cyberinfrastructure, Analytics, Simulation and Knowledge (Expert system in the CASK layer) includes the following functional modules:

- **EnviroLab.AdvancedProcessControl** (integrated diagnostics and optimization toolkit and advanced APC process control, predictive control of MPC processes)
- **EnviroLab.EnvironmentalMonitoring**(an advanced HPC solution that simulates pollution propagation and optimizes process parameters to reduce negative environmental impacts).
- **EnviroLab.EnterpriseSolutions** (open and scalable NET-based platform that utilizes the latest information technology and modular plug-in solutions) dedicated standard. EnviroLab.NEnviroT – provides SDK, API, and many other dedicated / domain tools – which allows to modify or extend applications, standard models by editing the source code of the class representing the given object, process, etc.

Cloud-GRID – technology

Highly integrated companies are constantly searching for ways to get faster and more efficient data retrieval from industrial installations. One of them is the use of data-driven solutions in the so-called cloud computing, using remote communication through HMI operator interfaces. In the concept of modern industrial networks Industry 4.0 employees and managers have free and remote access to object-level system data. This allows for more efficient resource management, monitoring and control of the machines.

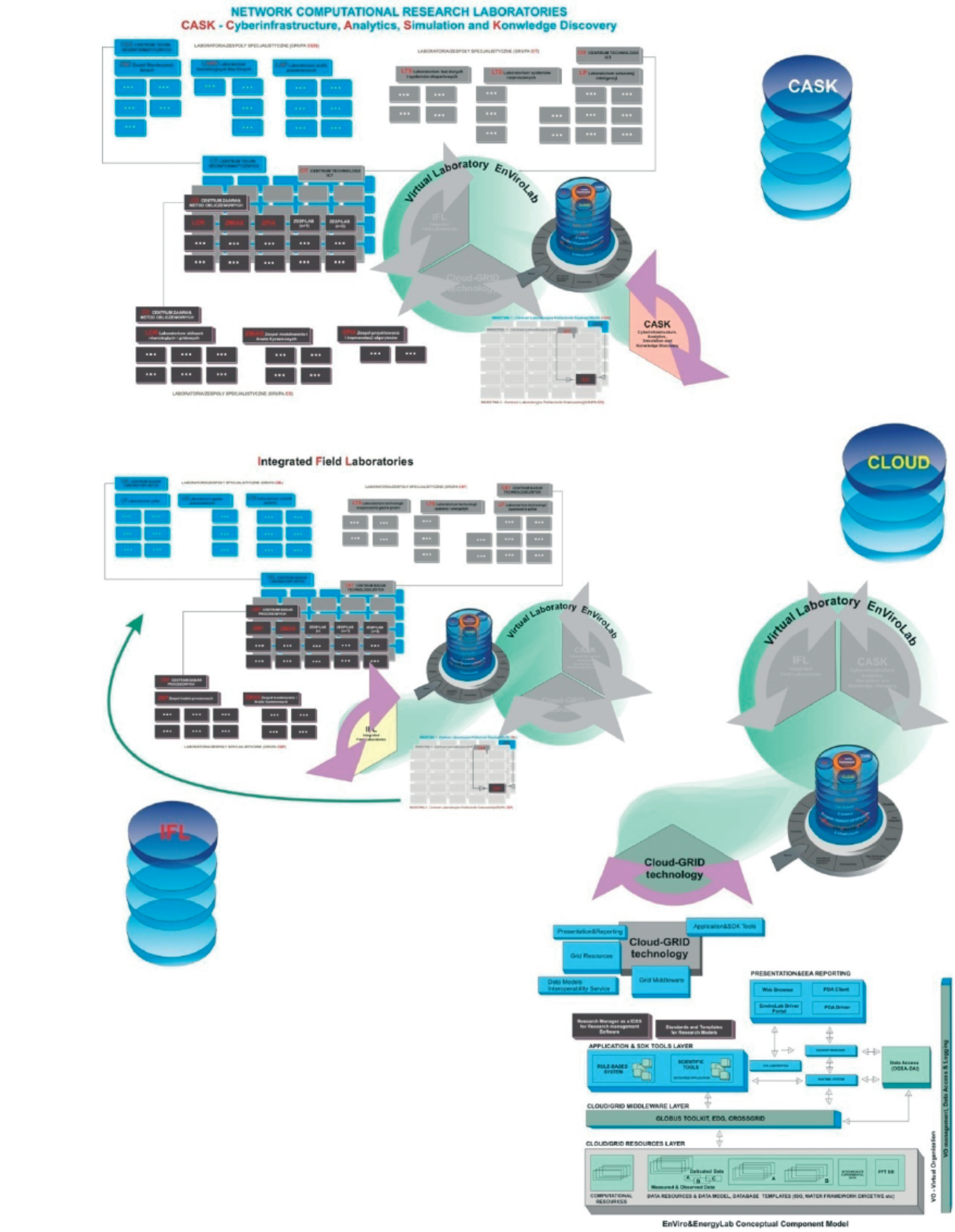

Figure 3.
Logical structure of a virtualized knowledge base about objects and processes (EnviroLab Enterprise Solution)

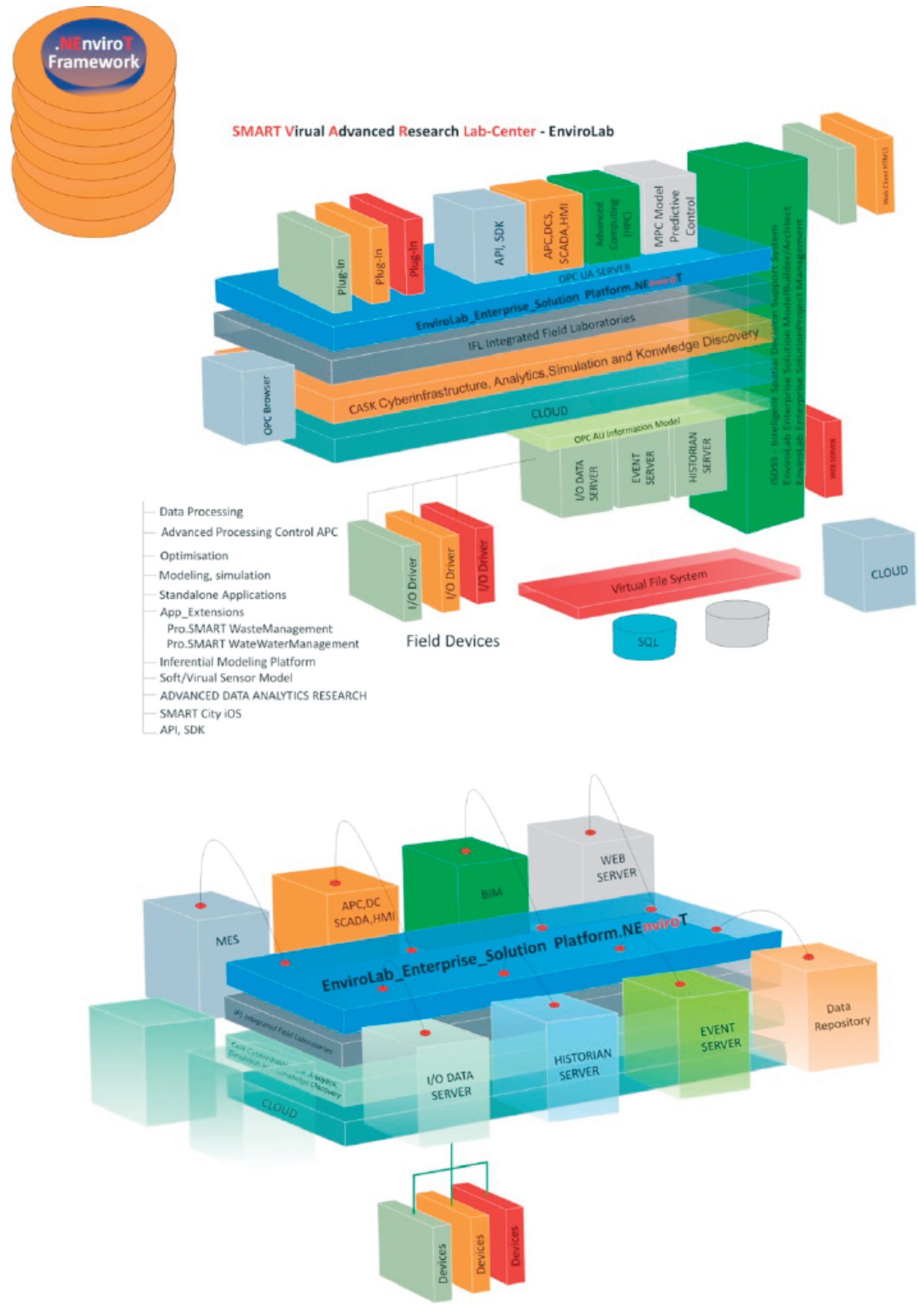

Figure 4.
ProWater Enterprise Solution Framework – EnviroLab. NEnviroT

EnviroLab.NEnviroT was built on the basis of .NET libraries that use 64-bit architecture. The environment enables the use of "plug in" technology to ensure complete customization of the application to the customer needs and the integration of external components, complementing the rich set of functional modules available as standard.

EnviroLab.NEnviroT is based on client / server architecture applying OPC UA technology. The environment also offers integrated communication controllers designed to exchange data with external devices (PLC, fieldbus, distributed IO).

The .NEnviroT platform is based on the environment of intelligent components of process models, events (Complex Event Processing), objects, test models. Crucial meaning for the precision of mapping of real processes, objects and events has the knowledge base – updated, analysed and validated in real time based on data from various sources (homo / heterogeneous, p / non-structural etc.) computational (eg. CFD modelling).

The expert system is based on precisely defined models of control objects, where the knowledge base of processes, state spaces, and device performance is built on the basis of expert knowledge and advanced ICT systems. Unlike other solutions, it provides complete and integrated environment which incorporates advanced IFL, modelling and simulation (CASK) components by moving some of the CLOUD computing solutions.

The adopted technology of system construction provides maximum flexibility (the ability to expand the system with new modules and thematic databases) and scalability (the ability of the designed system to function efficiently in a growing number of users and increasing volumes of data being processed).

5. CONCLUSIONS

The dynamic development of information and communication technologies determines economic development in various sectors of the national economy, including water and sewage management.

The most important element of the solution proposed by the authors is adding to the existing ICT systems (integrating GIS, SCADA and hydraulic models) the optimization control layer (including MPC prediction control model). In existing systems, the highest level in hierarchical control of water supply networks is the supervisory control layer. The superiority of the proposed solution, relative to existing ones, results from the application of Predictive control model MPC, which integrates knowledge base on control objects and processes and state space and event domains models. Through the application of evolutionary strategies, the MPC control algorithm is less sensitive to signal errors, while the use of PADO (Performance Analysis Diagnostics & Optimization) and Complex Event Processing (PADO) technology generates optimal control trajectories for the supervisory layer. Furthermore, a parallel computing architecture (NVIDIA CUDA technology) is used to accelerate numerical computation. The knowledge base for control objects is updated in real-time from SCADA supervisory systems. The multi-threaded, hierarchical control of the water distribution process will run in the background – parallel to the real system, carrying out a huge number of simulations in state space and event domains – learning (from the real-time knowledge base updated from SCADA, GIS, GeoEvent Service, hydraulic models, control objects, state space models, and real-time events, constantly improving the quality of control [18, 19]. State space and event domain models are part of the knowledge base for objects control.

The main advantage of the proposed control system over other existing functions is the element of predicting future events (the MPC model). This feature, coupled with a self-learning intelligent control system, not only allows to react to changes in the sensor state, but also anticipates these changes and correct the system in advance to anticipated changes, which is especially important in systems with high inertia such as extensive water and sewage networks.

The tools built in the integrated system include support for hydraulic modelling and calibration (recalibration), water and sewage network planning, power optimization, leak and damage detection, network diagnostics.

The multi-threaded, hierarchical control of the water distribution process (through the application of technologically advanced solutions) runs in the background – parallel to the real system, carrying out a huge number of state space and event domain simulations – learning from the real-time database updated from SCADA, GIS, GeoEvent Service models, hydraulic models, control models, state space models, and real-time events and improving the quality of control. The state space and event domain models are part of the knowledge base for control objects. The acceleration of hydraulic computation and multiparameter simulation of the water supply network is implemented using technology. NVidia CUDA.

The presented concept of smart monitoring and management of dispersed water and wastewater systems in metropolitan areas is a response to today's challenges in the context of SMART Cities' sustainable urban management, including sustainable resource management, in terms of increasing efficiency resources.

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