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Smart solution to improve water-energy nexus for water supply systems

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Abstract

In the last years, there has been a great interest in the complex relations between energy and water, known as the Water-Energy Nexus [1]. Natural resources, such as energy and water, enable economy growth and support quality of life. The Water-Energy Nexus is considered as one of the most important multidisciplinary challenges [2] that the global growing water market [3] has to face in the forthcoming years. Currently, many water systems are not managed sustainably enough. Water Utilities face other challenges, such as infrastructure aging and poor cost-recovery, leading to a lack of finance for O&M (Operation and Maintenance). Energy is required in all stages of water production and distribution, from pumping and treatment to transportation. Energy costs are a top-of-mind concern for water utilities, regardless of geography, size and level of water network efficiency [4]. On the other hand, Water Utilities are having a hard time to either improve their services or expand their network to unserved neighborhoods in developing countries.

The current trend of water transmission system to the creation of DMAs (District Metered Areas) offers great possibilities of non-structural solutions that use existing data and transform them into useful information to support decision making. The Smart Metering and the use of large amounts of data from a network enhance the use of software for decision support, but it is not the only way. Smart Solutions can also be applied to networks with less recorded data, which would enhance operators' knowledge to these data, turn them into useful information for decision-making either for the operation or the maintenance and network design. In this scope, a Smart Solution is presented. It is developed combining key factors of the energy consumption and the water supply into water networks management to obtain improvements from both water and energy fields. This non-structural solution increases resource efficiency and environmental performance of water distribution networks by using data acquisition and geographical visualization (real time & historical), weather and water demand forecasting, detection of networks events and hydraulic simulation of the network, and finally through a decision support system based on machine learning (pattern recognition and business rules techniques).

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As a conclusion, a non-structural solution for the Nexus issues can have a great impact on several matters (climate change, carbon footprint, WUs balance sheets, and water losses) with reasonable investment either in smart metering or networks with only a few sensors measuring.

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Keywords: Nexus, water energy; smart water networks; urban water distribution network management; Energy Management in water Distribution Systems; Water Utilities; Artificial Intelligence; Machine Learning; Pattern Recognition; Business Rules.

Nomenclature

AI	Artificial Intelligence
API	Application Programming Interface
BRMS	Business Rule Management System
BRT	Business Rules Technique
DMA	District Metered Areas
DSS	Decision Support System
ICT	Information and Communication Technologies
KPI	Key Process Indicator
PRT	Pattern Recognition Technique
WDS	Water Distribution System

1. Introduction

Water distribution systems face socio-economic, sustainability and resilience challenges, including overuse due to population growth, underestimation of the value of water, lack of coordination among actors, operational issues (ageing, leakages, quality), increasing energy prices and the need for responding to climate change issues. Much environmental data related to water are already being reported, from local to supranational level. Assessment of the resource efficiency or environmental performance of water utilities, though, still lacks a **holistic approach**.

Specifically, the **water-energy nexus** case raised the attention of water utilities, where considerable measures are taken to reduce energy consumption and increase energy recovery. Water-resource efficiency in its broader context is also of utmost importance for water utilities, which has defined water-energy nexus as one of their priority areas; it is also considered as one of the most important multidisciplinary challenges that the global water market is to face in the forthcoming years [5].

The Smart ICT solution depicted in this paper combines the key factors of the energy consumption and the water supply to improve the water networks' management in order to save water, energy and economic costs, using the renewable energy as possible and ultimately, obtain benefits in both, water and energy fields.

Given this framework, the solution provides a scalable, comprehensive and interoperable web-based Smart management platform, focused on water allocation and pump scheduling for water distribution networks. The platform provides a decision support system for short-term (operational) management of WDS based on:

- A reliable and customizable **demand forecasting system** based on DMA.
- A non-intrusive **data acquisition system**. Allows information gathering from existing SCADA systems.
- A full **spatial data infrastructure**. Including geo-database, map server and geographic information system.
- A **decision support system** to provide management recommendations. Highly innovative Artificial Intelligence and Data Analytics techniques have been developed in order to overcome the limitations of the classical approaches, mainly focused on mathematical solvers.

- An interoperable **hydraulic modelling** system, making use of already existing simulation software in the water utility through and API. The model aim is to simulate the network behavior, assess recommendations and analyze measured and simulated information in real-time.
- An **events detection system** to detect anomalies and to alert the managers about events recommending solutions in real-time.
- A set of **dashboards for KPI tracking** focused on different objectives: water resource, physical, operational or economic indicators.

The overall objective is to allow water utilities to holistically manage their processes in a flexible way by maximizing water and energy savings (the so-called Nexus) and minimizing operational costs, while **maintaining quality and level of service**. Mainly, the platform provides information, KPIs, and operational management recommendations focused on: decrease the non-revenue water, improve the pressure management, detect leakages, save energy and water, and above all, improve the **Integrated Water Resources Management in terms of water resources and revenues supporting financial, social and environmental sustainability**.

2. Methodology

The platform affords support and gives recommendations to the network managers in order to improve decision-making, using real-time information and the simulation of complete operational scenarios in a friendly graphical environment.

An **operational scenario** is the set of data, information, conditions, rules and decisions associated with the operation of the network during one day. The aim of the network managers is to handle the operational scenario accurately.

The platform helps manager in each step of the operational scenario management chain, using available knowledge and providing management recommendations and information about current or likely future events. To achieve the objective the platform makes use of GIS data, network models, consumption models, real-time measurement, expert manager knowledge and AI inference engines to gain the maximum benefit from the information available. Also, the introduction of machine learning techniques allows the platform to learn about the "best practices" in operational management **providing a mechanism to promote continuous improvement processes in the whole operational scenario management chain**.

In a simplified way, the platform approach proposes the following working process:

i. Store of network measured or simulated data and operational information in a knowledge database.
ii. Proposal of operational scenarios based on the Pattern Recognition Technique (machine learning).The water manager can accept, reject or improve this scenario according to his experience.
iii. Simulation of network behaviour using a demand forecasting system, a hydraulic model and the Business Rules Techniques in order to evaluate the system with a multi-criteria approach.
iv. Results are shown as recommendations, graphics, indicators, alarms or maps in a GIS format, and can be stored in the knowledge base as a new improved operational scenario.
v. The training module allows the self-learning of the system that will take the water manager experience and his analytical capacity in order to improve the quality of the recommendations and offered results.

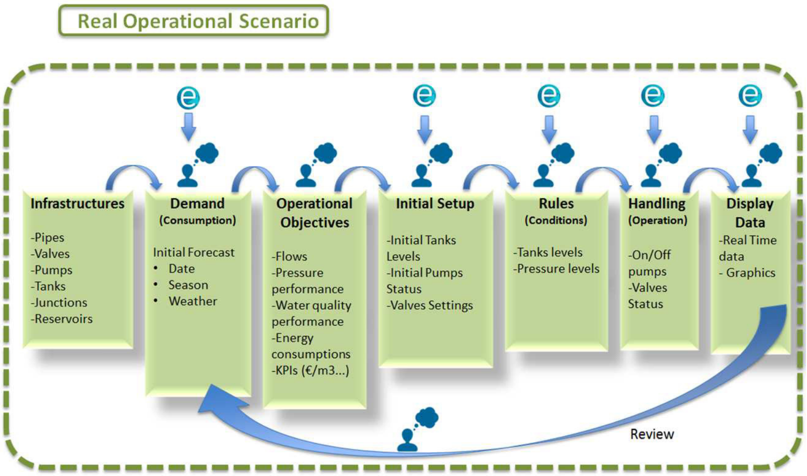

Fig. 1 Smart platform improvements in the operational scenario management

The aim is to help managers in the daily operation of the network from a holistic perspective, using multi-criteria approach to detect the inter-relations inherent to the water supply distribution networks.

Using the Smart platform, the real operational scenario is transformed in an **improved operational scenario**, in which the platform provides tools for each step of the management chain and converts the existing information into knowledge to be exploited in successive management steps and/or processes.

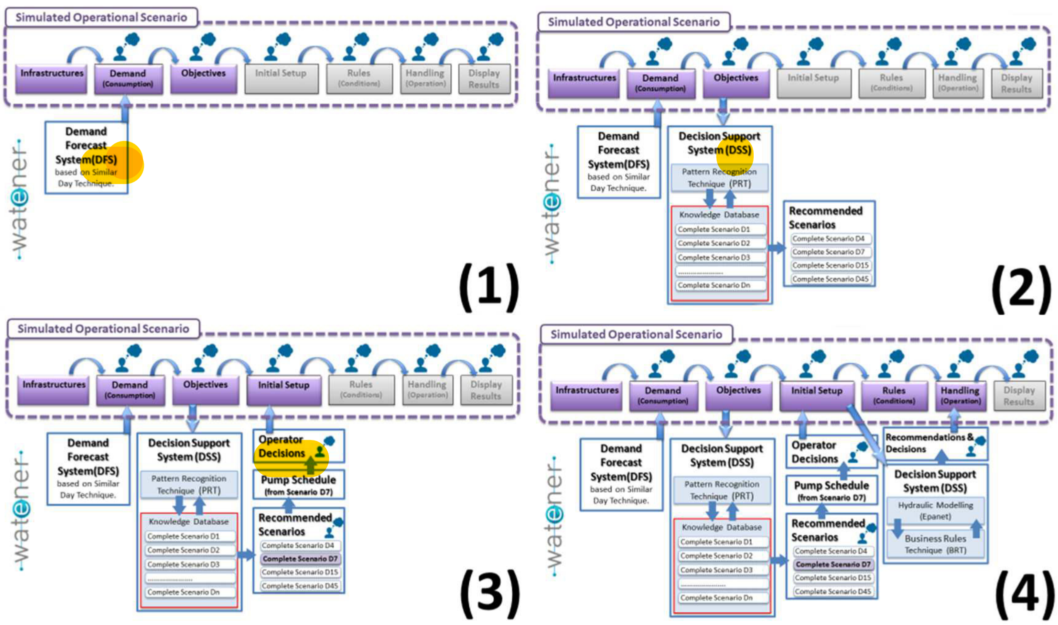

Fig. 2 Improving operational scenario using Smart solution

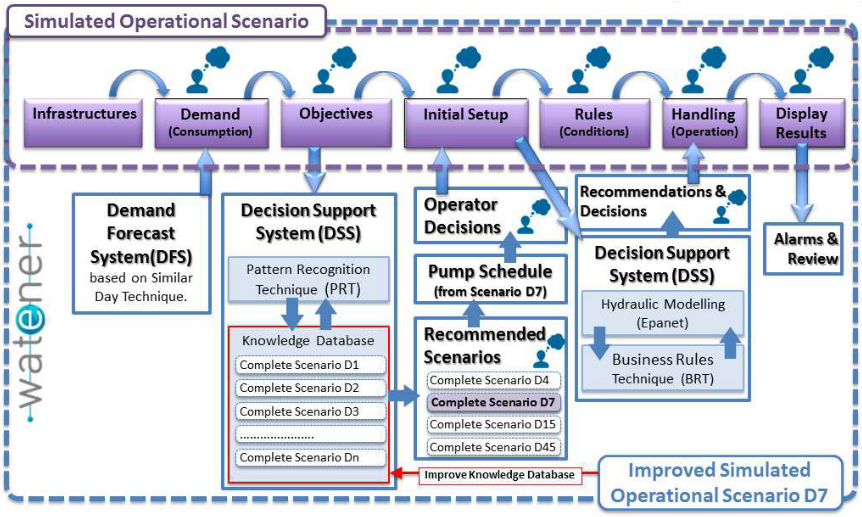

Fig. 3 Improved operational scenario using Smart solution

Initially, network managers propose a set of objectives to be carried out during the management of the water supply network. In the step (1), the platform computes consumption forecasts in each DMA, and provides tools to calibrate and configure the forecasting process. During following step (2) the pattern recognition engine search for past operational scenarios similar to the current, and recommend a strategy to operate the network based on multi-criteria assessment (for instance a combination of water saving, energy saving, overall economic cost, leakage prevention, etc.). Next step (3) provides tools for the managers to evaluate recommendations and choose different strategies, test them with the hydraulic model (EPANet or already existing one) and obtain performance indicators in terms of water and energy consumption/saving, economic costs and other socio-economic indicators. Also, the machine learns from the manager, improving the knowledge base by adding new operational strategies more effective and/or managing different real operational scenarios (for instance, a new strategy to handle a scenario with one tank unavailable and good energy usage). Finally, step (4) and final (Figure 3) track the network operation, providing continuously real-time alerts and data about what is happening, possible events and deviation from the objectives set by water managers at the beginning.

Finally, as a transversal step, the platform transforms all the information into knowledge and exploits it in an **events detection system**. The events system runs in background at any moment and provides alerts about current or likely future events useful for network managers. The **events represent the knowledge**, and are detected using **anomalies, representing information**. The platform is extremely flexible to inform and alert about different event types and to use different algorithms to detect anomalies.

Event: "something that should be notified because it can affect the main objectives of the water utility"
Anomaly: "a detection of unusual values in data"
Alert: "the notification of an event to a person or a machine"

3. Decision Support System: from information to knowledge

The potential of enhancement of energy efficiency when jointly considering water and energy systems is highly significant according to governmental studies in the USA [6] and in the EU [7]. Considering water distribution systems, it can help increase the energy efficiency in comparison to handling the problem in the electric and water networks separately [8]. However, considering them together also poses challenges and scheduling optimization issues. Even though there are a lot of research and pilots focused on energy efficiency and in water supply costs for separated, there are a limited number of pilots or research done considering both together, besides addressing other technical and economy aspects, different from the scheduling optimization problem at which the Smart platform described aims.

From a system intelligence point of view, different water management situations are usually handled with specific reasoning procedures or models, but no efforts are reported **in combining multiple inference engines in a single platform**, addressing several water supply and distribution chain management needs. The DSS combines the BRT and PRT techniques in order to support the water manager in efficient resource allocation and energy improved usage throughout the water supply distribution network. In addition, the BRT approach applied to pumping management constitutes a breakthrough in this research field, which nowadays is mostly based on defining complex optimization models. In the energy consumption case, the complex interrelation between variables in order to distribute water using efficient energy strategy (e.g. maintain the correct pressure in the scenario) makes the creation of a suitable model that performs competitive parameters difficult [9] [10]. This kind of complex problems are the cases to which cognitive technology (e.g. pattern recognition) offers suitable results by simplifying the problem of vast amount of interrelated variables into an experience-based approach where the benefits occur by learning from past experience (already managed operational scenarios) [11].

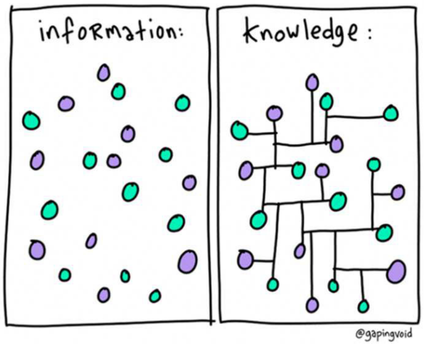

Fig. 4 Information vs Knowledge (Source: gapingvoid llc)

Summarizing, the AI techniques described are highly flexible to be used for several purposes related to water supply networks management, and the combination of them provides a powerful method to firstly, transform information into knowledge and secondly, to consume this knowledge helping in handle operational scenarios.

3.1. Business rules technique (BRT)

Business rules describes the policies, norms, standards, definitions and restrictions existing in any organization which are essential to reach the objectives of the mission. **Regarding to water utilities, they are expressed in terms of water allocation, water consumption, energy consumption, economic costs, infrastructure ageing, environmental requirements, etc.** The other relevant concept in addition to business rules is the **fact**. A fact is something that is known in a real scenario, in this case, the facts are the infrastructures information and the existing data, which may be measured or simulated; naturally, the reliability of the data is other fact. The Smart platform provides a knowledge base to store, maintain and manage business rules and an inference engine to track and check if the rules are being accomplished or if any kind of deviation occurs.

Concretely, this Smart platform provides a **Business Rules Management System**. BRMS consists of a general purpose Rule Engine and a software layer on top providing business user focused systems for rule creation, management, deployment, collaboration and analysis. Further adding to this value is the fast evolving and popular methodology "Business Rules Approach", which is a helping to formalize the role of Rule Engines in the enterprise.

A **Production Rule System** is Turing complete [12], with a focus on knowledge representation to express propositional and first order logic in a concise, non-ambiguous and declarative manner. The brain of a Production Rules System is an **Inference Engine** that is able to scale to a large number of rules and facts. The Inference Engine matches facts and data against Production Rules - also called Productions or just Rules - to infer conclusions which result in actions.

A Production Rule is a two-part structure for reasoning over knowledge representation. The term "**Production Rule**" originates from formal grammars where it is described as *"an abstract structure that describes a formal language precisely, i.e., a set of rules that mathematically delineates a (usually infinite) set of finite-length strings over a (usually finite) alphabet"*. The alphabet used here is the **first-order logic** (also known as predicate logic or quantification theory), which is a collection of formal systems related to mathematics, philosophy, linguistics and computer sciences. It uses quantified variables over (non-logical) objects. The first-order logic provides a formal, well defined (in terms of computer sciences) and computable way to describe the syntax to define business rules (policies, norms, standards, restrictions, etc.) and facts (infrastructures and data).

The process of matching the new or existing facts against Production Rules is formally called **Pattern Matching**, which is performed by the Inference Engine. Pattern matching **is the process to transform information (rules and facts) into knowledge (What is happening? What is likely to happen? Any possible solution?)**.

Returning to the water scope, the Smart platform provides a set of tools to: (a) define business rules (policies, norms, standards, restrictions, etc.) and facts (real infrastructures, measured data, simulated data) and (b) search for relations in data using rules to provide new information about **events detection** and **management recommendations**.

The table and figure below depicts a very simple example about how the BRT detects the event *"Tank T level low"*, sends an alert to the operator and provides the recommendation *"Begin pumping with Pump P for 1 hour"*.

Table 1. Set of business rules and facts.

BUSINESS RULES	FACTS
R1 "Tank has a minimum allowed level"	F1. "T is a Tank"
R2 "Pumps has a Flow-Head curve"	F2. "P is a Pump"
R3 "A Tank can be filled using a Pump"	F3 "D is a DMA"
R4 "A Tanks is emptied by a DMA consumption"	F4 "T is emptied by D consumption"
R6 "Pump fills Tank using the Flow-Head curve of a Pump"	F5 "T min allowed level: 8m"
………	F6 "P Flow-Head curve is FH_P"
	F7. "Measured data: Tank T level 8.1m."
	F8. "Next hour D consumption forecast: 1,900 m^3"....

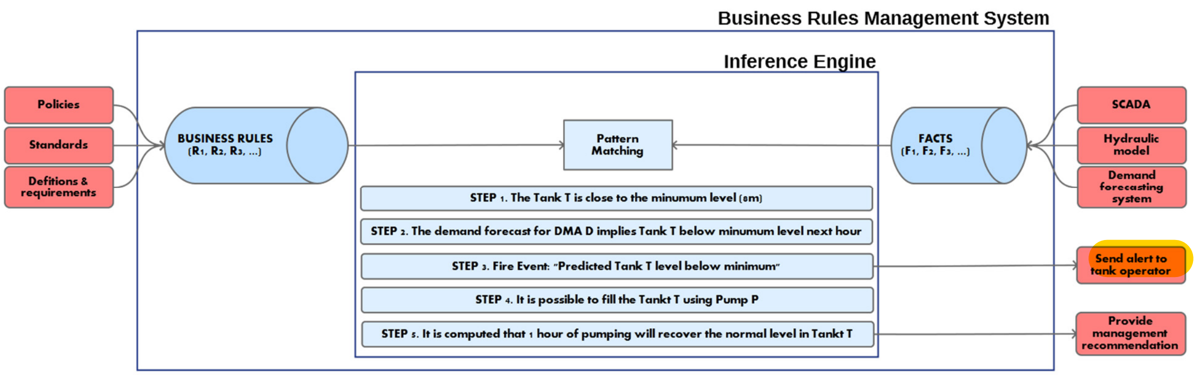

Fig. 5 Simple BRMS inference process

3.2. Pattern recognition technique (PRT)

Additionally, the Smart solution contains **pattern recognition** and **machine learning** algorithms to purvey capabilities for: (i) given an operational scenario (from past, present or future), find the most similar scenarios already managed in the past, (ii) apply a multi-criteria analysis to evaluate similar operational scenarios and obtain the most suitable management strategy and (iii) learn from the network manager in order to improve the knowledge and consequently, enhance the recommended management strategies.

The computational bases of the PRT are a mix of different AI methods which includes: (i) Knowledge Discovery in Databases [13] which allows a similarity comparison through a large amount of data using variable reduction techniques, (ii) Windowing [14] in 24 hours to adapt time series to the inference process allowing quick aggregation and comparisons, (iii) Hierarchical Clustering and Data Mining [15] to find patterns in unstructured information and (iv) a persistence method to provide machine learning capabilities.

Regarding the automatic comparison of operational scenarios, a scenario is classified given a set of similarity characteristics called patterns. The tool is flexible and customizable to be useful independently of the level of monitoring or the information available in the water utility, allowing adding and modifying patterns. Some of the most common patterns used are depicted in Table 2.

Table 2. Patterns to compare operational scenarios.

Characteristic	Description
Total demand volume	Compares the total consumption of two scenarios
DMA demand volume	Compares the consumption in one DMA of two scenarios
Demand peak	Compares the consumption peak volume
Demand peak time	Compares the similarity of the moment of the demand peak
Tanks availability	Check if a tank is available/unavailable in two scenarios
Pump availability	Check if a pump is available/unavailable in two scenarios
Pipe status	Check the similarity of the status of a pipe (open/close)
………	……..

When the system has to search for the most similar past scenarios to the current one, it computes a similarity coefficient for each scenario stored in the knowledge base in relation to the current. This coefficient is a combination of the similarity coefficients for each pattern, including the possibility to introduce a threshold in the pattern to consider feasibility. Finally, is returned a list with the N scenarios more similar to the current.

Secondly, a multi-criteria analysis is performed using a combination of PRT and BRT inference to select the best management strategy from the similar scenarios list. PRT compares a set of KPIs (regarding to energy consumption and water demand/supply) and is used to evaluate the efficiency. Meanwhile, BRT is used to evaluate the feasibility of the scenario (pressure management, storage levels, energy and water consumption issues, etc.).

Thirdly, the platform shows to the network manager the list of feasible management strategies for the current operational scenario, and also, informs about the efficiency of each one in terms of water supply/demand and energy consumption by KPI comparison. At this moment, the network manager can perform changes in the management strategy and evaluate the effects through a simple visual environment.

Finally, the platform stores in the knowledge base the new management strategy and performs a hydraulic simulation to compute simulated KPIs (flows, energy consumptions, storage levels, etc.) as performance indicators of the future operational management. During the operation stage, the platform will re-compute KPIs from measured information and will compare then with the simulated ones. To end the process, the strategy adopted is stored and available to be recommended in future operational scenarios.

4. Conclusions

Smart tools for water supply networks management offer a variety of advantages as opposed to the classical approaches, highly focused on mathematical models. Besides, the big-data/data-analytics paradigm is not enough, because of it hasn't the ability to include the knowledge gained during the improvements of the operational management. AI methods help to handle the expert managers' knowledge and are flexible to allow the enrichment of the operational strategies over time, helping in a continuous improvement of the management strategies.

On the one hand, pure mathematical solutions don't take into account the changing environment of the daily water network operation. The AI contributes to management improvement by including machine learning techniques capable to evolve following the new knowledge gained during network operation. The platform has the ability to accommodate to policy or directives changes, knowledge improvements or infrastructural modifications during time.

On the other hand, the Smart solution provides a flexible way to perform the analysis needed to carry out a holistic management of the network; AI methods described are independent of the monitoring level, the network infrastructure or the water utility specific objectives. They only depend on the knowledge of the network managers and provide a mechanism for maintain and improve management strategies by allowing the addition of variables and rules in the multi-criteria analysis to be performed during the daily operational management.

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