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An integrated modeling approach to optimize the management of a water distribution system: improving the sustainability while dealing with water loss, energy consumption and environmental impacts

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Abstract

There is a strong link between water and energy in municipal water systems then the Alliance to Save Energy coined the term "Watergy" [1].
Each component of the integrated water system contributes differently to the energy balance. With regard to urban water distribution systems (WDS), the pumping energy cost represents the single largest part of the total operational cost, also magnified by every litre of water lost to leaks. Even a small increase in operational efficiency may result in significant cost savings to the water industries.
Therefore the inefficient management of water distribution systems results not only into depletion of water resources but also into energy consumption that increase CO_2 emissions related also to the treatment of water volumes greater than needed, with use of excessive chemical components and consequent higher environmental global impact.
The research outlined in this contribution was born with the aim to develop appropriate methodologies and tools to support the optimization of the WDS performance, in terms of water saving and reduction of energy consumptions and consequently environmental impacts. The integration of advanced WDS hydraulic modelling with a material and energy flow analysis is proposed

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herein, where the output of the hydraulic simulations permits to get more accurate input for a metabolic analysis of the system. Next phases of this research will test the integrated model under different scenarios, aimed at quantifying the environmental impact of different WDS management solutions by means of selected indicators.

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Keywords: Water distribution system; metabolic analysis; energy consumption; leakages; environmental impacts

1. Introduction

The current state of many existing urban water distribution networks is inadequate to cope with the change of the conditions that drove their design: primarily the ageing of infrastructure, population growth, increasing of urbanization but also the more recent factors of climate change and environmental pollution. The main problem is represented by the increasing of water losses and, consequently, the loss of energy (and cost of energy) spent for pumping, treating and conveying that water [1]. The inefficient management of the water resources means increase the risk of supplying insufficient quantity of water of inadequate quality to users.

Therefore, it is required, according with the Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000, an integrated water cycle management tacking into account efficiency, effectiveness and economic criteria. Effectiveness requires providing a specified amount of water with sufficient pressure, and efficiency means doing it at the lowest cost [2]. There is then a necessity to develop methodologies and tools to support efficiency and safety of water distribution system (WDS).

The paper presents the ongoing research of a more comprehensive project, which aims at coupling the advanced hydraulic analysis of a WDS with the resources input-output analysis of the water supply system. The main objective of such research is provide methodologies and tools for the optimization of the performance of the WDSs, in terms of water saving and reduction of energy consumption and consequently environmental impacts.

1.1. Relationship between water losses and energy

The possible connections (nexus) between water and energy are vast and ever changing, but the knowledge of these links in both the production and consumption of water is necessary for optimizing the impact of using these resources [3]. The Alliance to Save Energy coined the term "Watergy" to describe the strong link between water and energy in municipal water systems [1].

In the last decades, the electricity prices is increased causing the major interest of water utilities to energy recovery and saving by searching for optimal solutions for energy management in integrated water systems. Each solution is linked to water system characteristics and, in particular, to the resources availability and quality, to the network topology, to the topography of served area and processes in the treatment plants. Each component of the integrated water system contributes differently to the energy balance and some procedures are currently available for identifying the best energetic configuration [1]. In the WDSs the large part of the total operational cost is represented by pumping energy cost which is also magnified by every liter of water lost to leaks before reaching the consumer. Water lost includes not only the value of water as limited resource but also the added value for the treatments to make water drinkable, then the expenses of treatment chemicals, the cost of running the distribution service and also social impact of leakages which might prevent for providing sufficient supply service to customers. . The presence of water losses also contributes to unnecessary capacity expansion, to the acceleration of infrastructure deterioration that means more risk of new leaks and then loss of energy related to increasing leaks, creating in this sense a vicious cycle. In addition, the energy wasted in leaks involves an environmental burden related to many impacts associated with energy production and consumption, including greenhouse gas (GHG) emissions, acid rain and resource depletion [4]. Therefore, even a small increase in overall operational efficiency may result in significant savings to the water industries.

The complexity of finding the optimal operating strategy stems from many concurrent factors. During a typical operating cycle, the electricity tariffs and consumers demand can significantly vary; at the same time, minimum water levels have to be maintained in the tanks to ensure reliability of supply, e.g. in case of failure scenarios. Due to the non-linearity of the hydraulic behavior, the simulation of such system requires advanced simulation models permitting the realistic analysis of both normal and abnormal (i.e. pressure deficit) scenarios including also pressure-dependent leakage modelling [5]. Finally, the number of possible operating strategies becomes huge for systems with more than a few pumps and tanks.

The most promising areas for intervention within water supply systems can be summarized as:

- Improving regular operation system through advance strategies for pressure and flow monitoring;
- Improving the pumping system in terms of efficacy (i.e. sufficient pressure) and efficiency (i.e. providing the same performance at lower energy expenses);
- Reducing leaks, by implementing effective pressure control strategies (e.g. using pressure control devices);
- Automating system operations.

2. Methodology

The WDSs are complex systems, with many different design and operational options available to a decision maker, including optimal pump management, effective pressure control or even rehabilitation/renewal works. In addition, optimal WDS management should match a large number of aspects and goals to consider, involving technical, economic, environmental and social perspectives, which are often conflicting with each other. This makes such problems tackle as multi-objective optimization problems (e.g. [2]), which can be solved using evolutionary-based optimization algorithms, e.g. Multi-Objective Genetic Algorithms - MOGAs. Indeed, MOGAs permit to take into account many available options, formulated as both continuous and discrete variables, where different and conflicting objective functions are used to drive the search towards a set of optimal trade-off alternative solutions. In this context, the WDS hydraulic model permits to evaluate the performance under alternative design and operation combinations.

The purpose of this research is the developing of an integrated tool to simulate the real behavior of a water distribution system considering also the various flows of water, energy, materials, costs and chemical components involved to optimize the sustainable WDS management. The term of metabolism has been applied outside the biology discipline to refer to these flows and conversion processes of material and energy that occur in the urban or industrial system because of the development and operation of the system: it is normally used the metaphor which considers the systems literally as organism [6,7,8]. Stokes [9] developed a conceptual framework that identifies and shows the interaction between the various modeling elements that have an impact on WDS cost and GHG emission optimization. The various parts that it is necessary to taking into account to develop the coupled model will be shown through this framework, considering also other involved flows.

2.1. From Stokes Framework to the coupled model

Stokes structured his framework in four different components with corresponding sub-component that include

- *infrastructure component* to represent the physical WDS elements that allow the fresh treated water to reach the consumers and those elements to evaluate accurately pumping operational costs and GHG emissions associated with a WDS (electricity generation and the supply infrastructure);
- *option component* to represent the options available to decision makers when optimizing the design and operation of a WDS and then to find the solution to minimize costs and GHG emissions (design and operations of the WDS);
- *analysis component* to consider both the simulation and evaluation options available during the optimization of design and operation of a WDS and to reach the more accurate trade-offs between costs and GHG emissions (simulation and evaluation) and
- *government policy component* to represent the policies and governance external to the control of a water utility that can have a significant effect on both the design and operation of a WDS and the evaluation of its associated costs and GHG

emissions. The policy types considered are climate change policy, economic discount rate policy and emissions discount rate policy.

Each of these consists of a number of related elements. The components are linked to one each other to represent the flow of information throughout the system. (See Fig. 1)

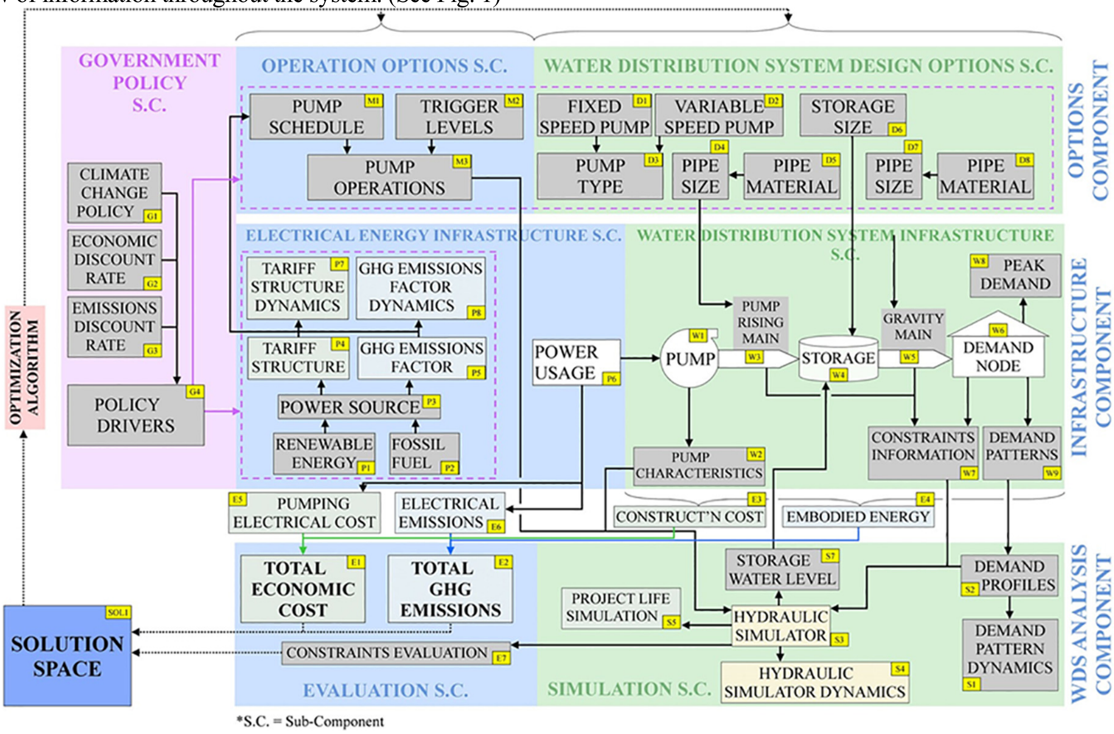

Fig. 1 The water distribution system cost-emission nexus framework of Stokes

In order to investigate the effects that each component has on the solutions to reduce GHG emissions and cost, the multi-objective optimization algorithms provide an efficient means of searching a set of optimal or near optimal solutions.

Specific parts of the framework (electrical energy infrastructure sub-component) are included for the evaluation of costs, but also to evaluate GHG emissions: connected with electricity generation and depending to the source of generation, whereas emissions intensity is represented by the emissions factor. The coupled model that will be realized, will consider in the same way the other emission factors connected with the various impact categories. The impact categories, usually considered in this type of analysis, are built taking into account as principal standards, ecology, health, resources and social effects. The ecology refers to the effect on population and ecosystem, called ecological effects. The human health and safety effects are included among the standard of health. For the resources, energy and materials it is considered their depletion. Social effects mean impact on all human activities that interact on the system and then it is considered the habitat degradation. In this manner, the specific characteristic effects are defined and chosen, as follow: global warming, ozone depletion, acidification, eutrophication, photochemical oxidant formation, human toxicity, marine eco-toxicity, terrestrial eco-toxicity. There are another impact category to emphasize that raw materials and energy are non-renewable resources: the abiotic depletion. The evaluation will be done not only for the direct and indirect consumption of electricity, but also connected to the production phases of pipe, pump and the other types of elements involved, also the chemical products used in the treatment plant.

Stokes in his framework considered as options subcomponent, the options directly connected with pumping operations explicitly, using pump scheduling, or implicitly using storage trigger levels. The integrated model will incorporate also other management devices, such as flow control and pressure control valves. Moreover to be more realistic, the hydraulic model have to simulate the state of the WDS by taking into account not only the water losses as burst, but also the background leakage, i.e. diffuse outflows along pipes due to deterioration caused by aging and external factors/forces (e.g. [5,10]). Indeed, although bursts are characterized by higher leakage rate, they product higher impacts on WDS hydraulic behavior, thus being easier identify and repair. Vice versa, background leakages represent limited leakage rates, thus running for longer time involving also huge volumes of lost water (and energy); therefore the realistic hydraulic modeling of background leakages is of direct relevance for medium-long horizon planning of actions in WDS.

3. Remarks for the development of the coupled model

Stokes framework has shown the complexity of a water distribution system which behavior depends on each of its numerous elements. It should satisfy the basic quality and quantity requirements of supplied water during its entire lifetime for the expected loading conditions. However, it should be able to tackle also the abnormal conditions such breaks in pipes, mechanical failure pumps, valves, and control systems, including malfunctions in storage facilities and inaccurate demand projections.

The main objective of this work is the coupling of a hydraulic simulation model of a water distribution system (WDS) with a resources input-output analysis, reaching by following intermediate objectives/steps:

- selection of appropriate hydraulic model to be used and further developed, if needed, to simulate the hydraulic behavior of the network to describe different operational conditions, once the boundary conditions (i.e. operational/management scenarios) are defined;
- evaluation and application of a selected model to evaluate material and energy flows in a given domain, i.e. the so called metabolism models;
- definition of an optimal efficiency - control system framework which include the above mentioned models;
- study of the hydraulic variables to capture, during the simulation of real networks, the flows of water, energy, materials, costs and chemical components to be then modelled with metabolic analysis;
- selection of a list of various scenarios of management, demographic grow or climate change and different technical solutions;
- testing and validation of the model through study cases.

3.1. Hydraulic model

The selection of the hydraulic model for the simulation of a WDN was driven by some needs. First of all a realistic simulation/prediction of burst and background leakages. Among the types of simulation, there are the classical demand driven and the more recent pressure driven. In a demand driven simulation model, the demands are assumed as fixed at nodes of the WDNs model, irrespectively on network head/pressure status. This is a statistical assumption, but, as outlined in Bhave [11], for a correct service a statistical significant number of orifices are actually functioning above a minimum pressure, which is not the case of pressure-deficient conditions (e.g. due to climate change, increase of population and asset deterioration). In this case, leakages are either kept as a percentage of fixed nodal demands or are simulated as free orifices at nodes (e.g. using EPANET2) [12]. Nonetheless, it was demonstrated that such simplification is nether realistic nor consistent with energy and mass balance through the network [13], which are of primary importance for assessing the impacts of WDS operations.

In the most recent pressure driven simulation, the demands are no fixed but they are generally dependent on the pressure status of the network. Consequently, they permits to include pressure-demand relationship for all water demand components including customers' demand and leakages. In this type of simulation, leakages are more realistically modelled as a function of the network pressure [5].

The hydraulic model have to be able to simulate the behavior of the water network, under many possible uncertain situation management, demographic growth or climate change and different technical solutions that could change its normal operating conditions. Laucelli et al. [14] had shown how these uncertain scenarios would be analyze using a pressure driven approach rather than a demand driven one. The reason is that the last one underestimates the hydraulic network capacity and does not predict the water demand that can be realistically supplied to customers under pressure-deficient system functioning. In fact, from a water management perspective, the factors that could change the working conditions of a WDS result into an abnormal hydraulic behavior that could put the system in crisis, due to the peak demands in warm seasons and ageing of pipes.

For these reason the chosen model that help in this to simulate the behavior of a water distribution network is the WDNetXL [15].

3.1.2 WDNet XL

WDNetXL is a system tool to support analysis, planning and management of WDSs, using MS-Excel as data management interface. The MS-Excel interface helps users to manipulate the various parameters working with tables including various elements of a real water distribution network.

The basis of the WDNetXL system is a robust hydraulic and topological analysis modules that includes pressure-driven modelling of various components of the demand in each node [16]. Leakages are modelled at both node level (e.g. simulating pipe bursts dependent on nodal pressure) and pipe level (e.g. background leakages dependent on average pressure along pipes). The simulation of variable level tanks in steady state simulation is achieved by coupling mass and energy balance equation. This permits to overcome the known instabilities of EPANET solver in tank simulation [17] and some problems in overall network mass balance. In addition, WDNetXL permits the pressure-driven simulation of water demand delivered to buildings with multiple floors as well as of water supply through private water storages at each single node, which can be of direct relevance for WDSs in Mediterranean areas. In addition, WDNetXL simulation permits to simulate remote real-time controlled (RRTC) pressure control devices like Pressure Control Valves or Variable Speed Pumps.

As a remarkable feature for the integration with the metabolic model, the convergence of hydraulic simulation results is verified from both energy and mass balance perspective, thus preventing form inconsistences and misleading conclusions in the analysis of water and energy fluxes to be carried on in the next steps.

Finally, the versatility of WDNetXL and the integration with the OPTImized-MOGA [18], make WDNetXL an ideal platform to implement customized solutions through a virtuous cycle between users, researchers and developers.

3.2 Metabolism model

For the climate change, the environmental impact became a factor of growing importance in decision making for municipalities, recognizing the need to design networks to make them more compatible with their natural and social environments [19]. Therefore, the integration of the hydraulic model with an input-output analysis of a WDS is necessary because of the optimization of a WDS will be done not only minimizing the design and operating costs (normal activities of management associated with the normal operating of a WDS) but also considering adequately the environmental costs. The processes happening in the WDS, analyzed and quantified in term of water, energy and materials, will be result optimized also from a sustainable point of view.

Among the analytical methods generally used in this type of analysis, there are the LCA Methodologies (LCA – Life Cycle Analysis). They represent a group that, for a proposed definition of SETAC (Society of Environmental Toxicology and Chemistry) is a methodology to evaluate environmental charges connected with a product, process or activity, identifying and quantifying material and energy consumptions and the environmental emissions.

3.2.1 Dynamic Metabolism Model

During the 7FP European project TRUST [20], the Norwegian University of Science and Technologies (NTNU) has developed a metabolism model called Dynamic Metabolism Model [21]. The model, in a Life Cycle Analysis perspective, allows analyzing the water system of the city to evaluate its energy consumptions and environmental impacts. The model applies the urban metabolism concept to the water system: the city is showing as an ecosystem, that transforms the input flows of energy and material into useful energy, physical structure and waste [6]. All resource flows, involved into the system, are simulated. The model is a set of Excel files, some of which with various worksheets: 1. Notes, assumptions and guidelines, 2. User control, 3. Annual files and 4. Final results comparison. The Annual files consist of as many sheets as the subsystems that form the urban water system (a water-wastewater system): raw water sources, water treatment, water distribution, wastewater transport and wastewater treatment. The others worksheets describe the system and background data of chemicals, materials and energy, necessary to evaluate energy consumption for their production and also the specific emission factors pertaining to the defined environmental impact. Between the other excel files there is one useful to present a brief description of the changes in the variables over time (1.Notes, assumptions and guidelines), and an interactive Excel file to define the foreseen and wanted changes and alterations to implement in the years to come (2.User control). The last one imported the performance indicators grouped at the end of each individual annual files and categorized into 'economic', 'social', 'environmental' and 'functional'. They are normalized and plotted as a graph [20,21].

The structure of this model permits to analyze not only the whole system but also each subsystem as independent to the other. Then among the various sub-systems, the integrations was done considering in particular the Water Distribution worksheet of each annual files.

4. Conclusions and research outputs

The paper was born with the purpose to present an ongoing research project dealing with the developing of an integrated model able to support the decision makers in the aim of managing a WDS taking into account various aspects: distributing water with adequate quality and quantity, also during the abnormal conditions minimizing design, operating and environmental costs. As shown above the advanced hydraulic model in WDNetXL will be integrated with the Metabolism Model. Besides the features that make them suitable for integration, it is to remark that also the integrated model will is being developed to work in MS Excel environment. This is a relevant aspects that will facilitate next transfer to all possible stakeholder (e.g. technicians and water utilities) as well as the integration with other data management platforms already in use.

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