An integrated software architecture for the pollution-based real-time control of urban drainage systems

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ABSTRACT

This paper presents a complete methodology for the development of an integrated software architecture, which can achieve a closed-loop application between the integrated real-time control (RTC) and a virtual reality simulation for the urban drainage system (UDS). Quality measurements are considered during the simulation and optimization process. Model predictive control (MPC) and rule-based control (RBC) are the two main RTC methods embedded in this architecture. The proposed integration environment allows the different software components to efficiently and effectively communicate and work in a system-wide way, as well as to execute all the necessary steps regarding input parameters management, scenario configuration and results extraction. The proposed approaches are implemented into a pilot based on the Badalona UDS (Spain). Results from different scenarios with individual control approaches and rain episodes are evaluated and discussed.

Keywords | Key performance indicators**,** pollution-based control**,** **s**oftware architecture, urban drainage system, water bodies protection

HIGHLIGHTS

- Closed-loop framework between the urban drainage system simulator and the real-time control module.
- Integration of the wastewater treatment plant state in the control strategy.
- Software architecture to handle operations and communication among specialized commercial software.
- Both hydraulic and quality measurements are considered during the control process.
- Implementation of the architecture to a case based on a real network.

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INTRODUCTION

Combined urban drainage systems (UDS) have a fundamental role in collecting stormwater and wastewater together and conveying them to wastewater treatment plants (WWTP) to minimize the associated pollution of the receiving environment (Butler et al. 2018). Their importance at developed areas lies in the influence over the modern society and the natural water cycle. The increasing urbanization, installation of complex infrastructure and frequent storm weather cause floodings and combined sewer overflows (CSO) due to the inability to manage high-intensity rainfalls, hence seriously polluting the receiving water bodies (Cembrano et al. 2004). New water detention and diversion infrastructure is typically installed in order to confront these challenges, but advanced control approaches are still required to proficiently operate the UDS.

Real-time control (RTC) is considered as an appropriate option among the different possible control strategies, iteratively computing the optimal control set-points through real-time measurements or even predicted values while benefiting from the development of Information and Communication Techniques (ICT) (Schüetze et al. 2004). According to the recent literature, there are numerous and different kinds of RTC approaches applied to the UDS, which can be generally classified into model-based strategies and knowledge-based algorithms. Model predictive control (MPC) (Joseph-Duran et al. 2015) and linear-quadratic regulator (LQR) (Lemos & Pinto 2012) are representative of model-based approaches which require a mathematical model of the system behaviour, together with an objective function and boundary constraints, to produce the optimal strategy. Knowledge-based algorithms do not require a model, but a complete expertise about the network characteristics. One example of this techniques is rule-based control (RBC), which considers different scenarios that may happen during the system operation by means of the assessment of if-else conditions and applies on-line predefined rules to generate control actions (Aulinas et al. 2011).

In order to validate these advanced control approaches for their application in a real system, they may be tested in conjunction with a high-fidelity simulator. This term is utilized in this work as presented in Lund et al. (2018). It behaves as virtual reality, playing the role of the sewer network (SN) and the WWTP. Typically, the implementation of a closed-loop software architecture (CLSA) for urban drainage systems is executed using a single software platform (Achleitner et al. 2007), limiting the utilization of powerful commercial tools. Most of the existing integrated frameworks only focus on the hydraulic model, so quality dynamics are not included into the optimization and simulation processes. Moreover, the integration problem is usually faced through the literature by means of the development of specialized software tools like SYNOPSIS (Butler & Schütze 2005), OpenMI (Gregersen et al. 2007), DynaMind (Urich et al. 2012) and CityDrain3 (Burger et al. 2016).

This paper proposes a methodology for the development of an integrated software architecture with the aim of achieving a closed-loop application between the RTC module and the wastewater system. The platform is prepared to allow the integration of the WWTP state in the control approaches, and therefore different individual models (Bach et al. 2014) must be coordinated. Besides, quality measurements (Sun et al. 2020) can be considered into the closed-loop. In Rauch et al. (2005), the need of integration to cope with water-quality-based approaches is remarked due to the importance of identifying the most effective action in the UDS to solve any issue affecting the receiving water body properties.

Hence, the development of the integrated multi-software pollution-based control architecture presented in this paper entails a further step on the path to emulate the particular behaviour of a complex water system under the influence of a certain control approach, with sufficient reliability to be capable of extracting firm conclusions from the achieved results. In addition, the effects of including quality and integrating the WWTP in the control operation can be evaluated and this information can be employed as a decision-making tool.

METHODS

The general software architecture of an integrated closed-loop framework for UDS is presented in Figure 1.

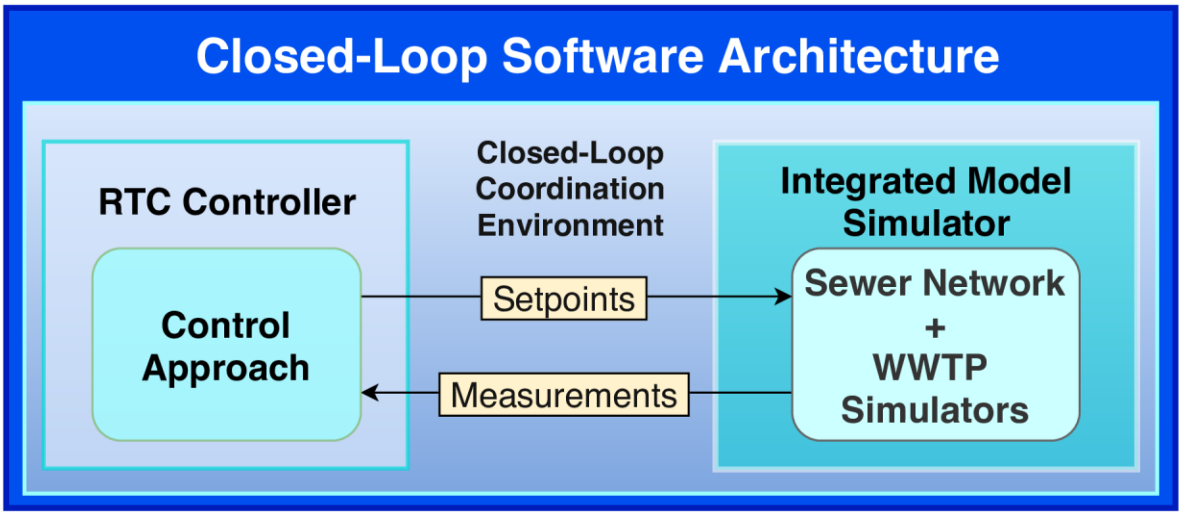

Figure 1: General scheme of the CLSA framework.

The closed-loop coordination environment enables the communication between the integrated model simulator and the RTC controller. Therefore, sewer network and WWTP simulation results are gathered, extracting the necessary data for the control algorithm operation. The real-time control software computes the next required actuators set-points, which are, in turn, applied to the simulators for the next time instant.

In this section, a detailed explanation of the different software constituents of the CLSA framework is provided, introducing the essential aspects defining each component and its operation. Those individual functionalities are linked with their role inside the closed-loop structure by explaining the coordination architecture. Therefore, a complete and hierarchic view of the proposed solution will be presented.

Integrated model simulator

The integrated model simulator consists of a set of individual high-fidelity models, representing different components of a complete UDS, whose operations are mutually influenced, as presented in Schüetze et al. (1999). In the case of this paper, the integrated model is considered to be composed by two parts: a model to emulate the complex dynamics of a sewer network and another operating as a sufficiently convenient replacement of the real WWTP.

Sewer network (SN) simulator

As mentioned earlier, a SN simulator consists of a software module which implements a high-fidelity physically-based model of the network dynamics, in the form of a set of partial differential equations. The involved hydraulic variables in those expressions may include the sewer flow rates and velocities, pressure heads, surcharge level, as well as the water depths. Besides, in this work, quality measurements are also considered in order to obtain optimal pollution-based performance. These models emulate both hydraulic and quality behaviour of the SN, through routing rain scenarios with empirical surface runoff expressions and solving the related equations (Rubinato et al. 2013). A comparison among different water network simulators is presented in Bach et al. (2014).

The majority of software platforms utilized for this purpose gather a particular set of functionalities apart from the network dynamics simulation:

- Network generation: sewer network simulation packages normally include a graphical user interface (GUI) which allow the user to design a new network or represent an existing one by placing the necessary components (e.g. sewers, nodes, pumps, gates and catchments, etc.). Besides that, property details for these components can be configured due to the requirements of the SN structure.

- Rainfall definition: in the case of combined drainage networks, the water input to the system comes from two main sources: wastewater and stormwater. Regarding the fact that SN control approaches evaluation relies on the performance analysis in demanding scenarios, primarily characterized by intense and/or long-lasting rainfall events, the proper definition of those rain episodes becomes a capital task. Therefore, the precipitations configuration must be considered as a prior stage of any project dealing with UDS, generating a large database of real or fictitious scenarios with enough diversity to be capable of carrying out a proper evaluation of the control strategy operation.
- Simulation configuration: several parameters must be set to achieve correct and effective simulations. Depending on the selected software, the amount and complexity of the settings may vary, though various of them need to be available at any simulator: simulation date and time, duration, rain event, build-up time (number of hours/days, depending on the simulation software units parametrization, from the previous rain event end to the starting point of the current simulation), numerical solver settings, wastewater profile (complementing the stormwater to supply the sewer network model with the total water input), control mode (apart from receiving external regulator set-points, the virtual drainage structure may employ local rule-based approaches to manage the actuators operation), hotstart file (record of a certain state of the virtual network, commonly used to feed the model as initial condition), among other.
- Results extraction: it is a mandatory feature regarding the necessity of supplying several measurements of the virtual network state to the utilized by the external controller (unless an internal local management approach is selected). Depending on the control strategy, the required input data may differ, but tank and catchment volumes and/or pollutants mass, certain sewers flow or water quality and water level at critical points are typically needed. Moreover, these results are also indispensable to perform an analysis of the virtual network representation resemblance to the modelled real system.

Wastewater treatment plant (WWTP) simulator

To consider an integrated control strategy, the presence of a WWTP model inside the simulation framework is essential. The physical, chemical and biological degradation processes that treat the pollutants contained in the water reaching the treatment plant are represented, and operation results are gathered to get information about the benefits of exploiting the integration in the considered control approach. Moreover, the collected data allows to compare the performance regarding quality measurements between pollution-based and volume-based controllers.

The WWTP simulation software packages allow the inclusion of several operational blocks representing well-known processes like pre-treatment, clarifiers, gravity thickeners or bio-reactors (each one of them defined by a set of equations) (Jeppsson 1996); whose connection and configuration implies the implementation of the WWTP model.

As in the case of the SN simulation software, several general settings are mandatory for the wastewater treatment plant operation, as e.g. date, time, duration, hoststart information, among other. Moreover, depending on the designed WWTP type and its composing elements, various parameters regarding biological aspects of the plant functioning are required. If the sewer network simulator does not provide the necessary information as a result, an intermediate process must be designed to generate the parameters for the virtual treatment plant from the available pollutants information at the SN simulation results.

Regarding the integration implementation, a certain scope for action at the WWTP model performance is necessary. The degree of freedom in the treatment facility management from an external source is a design aspect for the closed-loop framework.

Real-time controller (RTC)

Through the UDS state produced by the integrated model simulator, the RTC module must be capable of computing the set-points for the different actuators.

As previously mentioned, there are several control strategies that can be implemented to accomplish this set-point computation Thus, the approach selection ought to consider numerous aspects like its associated economic/technological cost and the network characteristics and complexity, highlighting the control degrees of freedom due to the number of accessible actuators at the system.

In addition, the real-time control module must include a component whose function consists of allowing the integration of the WWTP with the control strategy, so that the treatment facility actual state is taken into account during the urban drainage system management operation.

Control algorithm

Regarding the control strategy, model-based and knowledge-based approaches will be considered. In this work, about the former, an algorithm based on MPC is utilized as example (it is extensively described in Sun et al. (2020)); whereas regarding the latter, a rule-based scheme referred to as RBC is introduced. A review about these and other approaches can be found at García et al. (2015). In both cases, hydraulic and quality dynamics are considered into the RTC controllers.

The distinctive features of these two control approaches will be presented, stressing issues like necessary input information or required software resources; as well as highlighting their advantages and drawbacks from the integrated UDS closed-loop architecture point of view.

Model predictive control (MPC)

MPC is a model-based control strategy that employs the prediction of the system response to compute a set of suitable future control actions for a certain time horizon, using a simplified mathematical model of the system dynamics and an optimization process to minimize a certain cost function J. Its definition is essential and mainly includes an analysis of the different desired goals, like minimization of the floodings and/or combined sewer overflows spilled to the water receiving bodies (in both quantity and quality), the WWTP efficient usage, safe and smooth operation of sewer network and WWTP, etc. All these objectives are represented by a term in the cost function, where each element is multiplied by its associated weight. The non-linear optimization problem associated to the MPC can be expressed as:

$$
\begin{aligned}
&\underset{\boldsymbol{x},\boldsymbol{u}}{\text{minimize}}\ \ J(\boldsymbol{x},\boldsymbol{u},\boldsymbol{w})\\
&s.t.\ x(t) = x_0;\\
&x(k+1) = f(x(k), u(k), w(k));\ k = t, \dots, t + H - 1;\\
&h(x(k), u(k), w(k)) = 0;\ k = t, \dots, t + H;\\
&g(x(k), u(k), w(k)) \leq 0;\ k = t, \dots, t + H;\\
&x_{min} \leq x(k) \leq x_{max};\ k = t, \dots, t + H;\\
&u_{min} \leq u(k) \leq u_{max};\ k = t, \dots, t + H;
\end{aligned}
\tag{1}
$$

where $x(t)$ corresponds to system states at time step t, typically representing water volume and pollutants mass in tanks; $u(t)$ is the vector of control actions at time step t (it depends on the studied network); and $w(t)$ represents the disturbances at time step t (normally related to rain intensity and runoff). Function $f(\cdot)$ mainly includes mass and volume balance equations, while $h(\cdot)$ and $g(\cdot)$ represent the general constraints of the MPC problem, and u_{min}, u_{max}, x_{min}, x_{max}, are the control actions and states physical limits. Constraints are given by the capacity of tanks/WWTP and flow limits at pipes/actuators. Finally, k is an index that represents time, which goes from the current time instant t to $t+H$ (or $t+H-1$ considering $f(\cdot)$), where H is the optimization horizon.

Therefore, the utilization of an optimization specialized software would be necessary if the MPC approach is considered, and a simplified model of the SN should be derived in order to implement the modelling equations at the optimizer. These conceptual models involve network components like nodes, pipes and tanks, as well as the evolution of their associated variables, like flow, total suspended solids-TSS (it is considered as a pollution representative in this paper; see Woodward & Curran (2006) for more information about this quality indicator), volume and mass. They mainly consider the flow and mass balances at the nodes and the tank volume and mass evolutions. Other elements like weirs may need custom models for the considered SN.

The set-points for the network actuators are derived from the optimization results. The achieved data for a certain set of sewers at the simplified model, at the first time step in the horizon, is evaluated by means of a flow-to-setpoint function. It allows the conversion of the corresponding flows into reference values for the position of the actuators. This function depends on the network characteristics and it must be meticulously designed.

Besides, as the optimization scheme employs the SN simplified model to emulate its dynamics by means of the implemented equations, information regarding the water inputs to the network is required. This knowledge may come from a conversion function that transform the rain forecast into the flow reaching the network by each one of its basins.

Rule-based control (RBC)

RBC consists of a decision-making approach that exploits gathered knowledge about a system features to generate a certain set of rules that defines the cause-effect relation for a specific problem. The obtained set-point explicitly depends on the fulfilment of a settled group of conditions involving variables directly measured at the considered system.

In the case of urban drainage systems, variables (involving tanks level or volume, water level at critical points for flooding prevention, quality measurements at certain sewers or nodes, CSOs, etc., as well as wastewater treatment plant inflow capacity in integrated strategies) must be evaluated to generate proper regulator values affecting the different system actuators.

As discussed in Aulinas et al. (2011), this system knowledge is usually converted into if-else structures like decision trees, although this implementation presents some disadvantages for complex networks, like the less flexibility and lack of reasoning capabilities. Other approaches which result more suitable for complex water systems rely on fuzzy logic based schemes as presented in García et al. (2015).

Wastewater treatment plant (WWTP) inflow capacity calculator

The information about the WWTP state is crucial for any considered regulator generation approach within an integrated architecture, since the selected control strategy must take this knowledge into consideration when deriving the controller set-points for the next time instant.

There exist different approaches to improve the wastewater treatment plant operation under demanding conditions:

(1) Increasing the WWTP inflow depending on its capacity instead of using a maximum inflow considered for the worst-case scenario (Müller & Krauth 1998).

(2) Increasing the WWTP inflow, but bypassing the extra flow to be introduced into the secondary clarifier (Ahnert et al. 2008).

The first strategy is selected due to the larger leeway for action considering the integration of the WWTP state during the real-time control operation, since the second approach considers wastewater treatment plant internal procedures which are beyond the scope of this article. Thus, an inflow capacity computation module, henceforth referred as capacity calculator, must provide the plant state from measurements produced by the virtual reality UDS: input water flow and quality results from the sewer network simulator, as well as the current state of the WWTP, which is derived from the information achieved by the WWTP simulator.

This maximum capacity applies to the plant entrance, but it may be computed considering the primary or secondary clarifier state, depending on the control objective, plant management goal and the facility layout. Therefore, the manner to design this WWTP inflow capacity calculator may vary among different projects.

Finally, this capacity value is provided to the control algorithm, so the way it handles this information about the wastewater treatment plant state may differ among distinct RTC strategies:

- Considering MPC as the selected control approach, the wastewater treatment plant inflow capacity knowledge must be utilized to compute an objective function term that increases the penalty as the difference between actual WWTP inflow and the mentioned capacity augments.
- Regarding RBC, the wastewater treatment plant information may be used to evaluate a condition or for the explicit computation of a certain actuator set-point. The integration scheme would depend on the RBC algorithm definition.

Closed-loop coordination environment

To develop a complete closed-loop framework from the different presented ingredients, a binding element must be employed to host the intra-application operations and accomplish the necessary inter-application functionalities. The scheme of the complete architecture is presented in Figure 2.

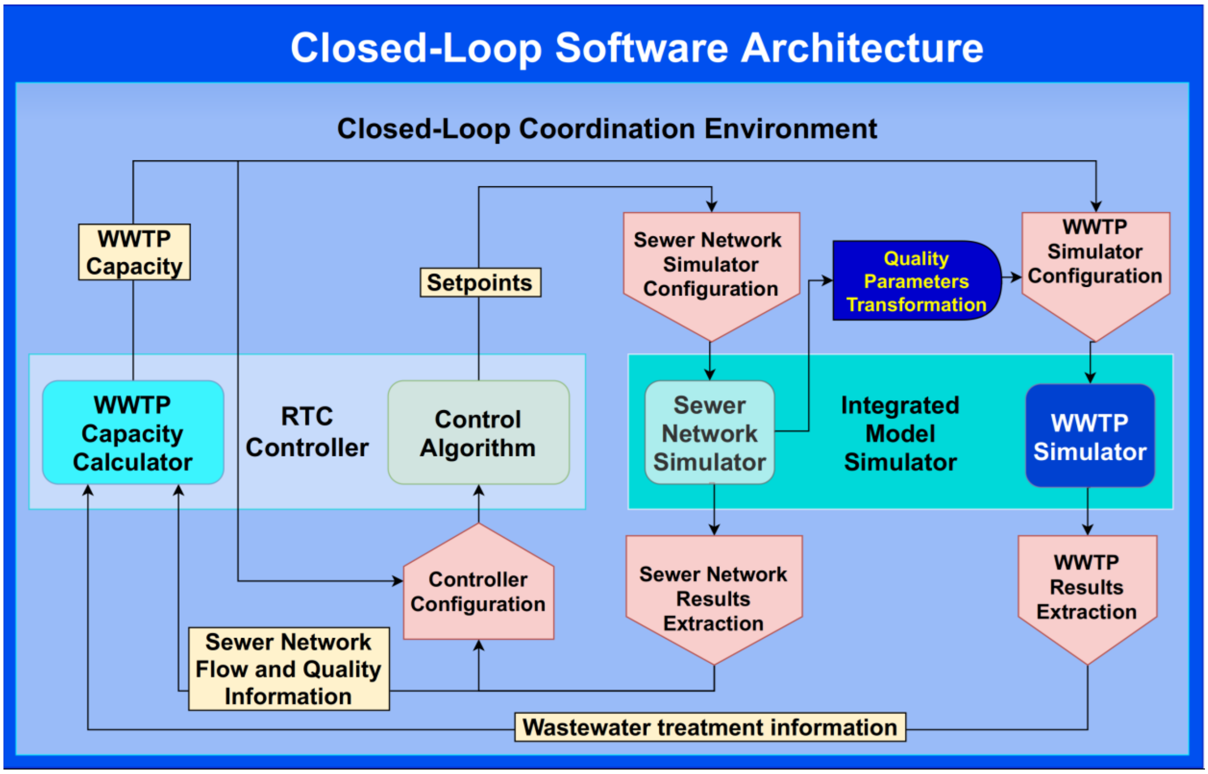

Figure 2: Detailed scheme of the CLSA framework.

The closed-loop approach implies the coordination of the different functionalities forming the framework. The sewer network simulation is configured, considering the event date, rain forecast and network initial state as internal configurations settings of the sewer network simulator, and the actuators set-points as external inputs to the simulation software. Then, this simulation is executed and the achieved results are extracted.

The information about the water quality, required for the WWTP simulation, is obtained from a quality transformation process (referred as Quality Parameters Transformation in Figure 2). It is supplied with the gathered hydraulic and hydrologic results from the SN simulation, and generates the required chemical and biological parameters for the WWTP simulator. The inflow capacity of the wastewater treatment plant, used by its simulator, is computed by a capacity calculator (WWTP Capacity Calculator in Figure 2) from the previous treatment plant state and current sewer network information. After the WWTP detailed simulator launching, the resulting data can be gathered to compute the inflow capacity in the next iteration. Finally, the RTC algorithm must be fed with the required SN results such as flows, quality and initial volumes; the capacity for the WWTP and, depending on the control approach, a rain forecast and previous control module results.

The outcome of running the controller is a set of data that has to be converted from SN flows to actuator set-points to configure the next step sewer network simulation. The selection of the coordination environment highly depends on the software elements performing the presented individual tasks:

- It must hold complete compatibility with all the applications, to carry out their launching and pull off the required communication demands.
- Files management involving numerous formats is indispensable to fulfil data inputting, software configuring and results extraction/presentation assignments.
- The importance of elaborating a closed application varies according to the purpose of the CLSA framework development, e.g., academic research and proprietary software; and the set of possible coordination software environments may be reduced if considering a professional application. However, a simpler environment may be enough for more relaxed development demands, so that the involved tasks are accomplished without including application layers to the solution.

However, the main tasks involving the closed-loop execution are conceptually identical regardless of the selected binding platform: virtual reality simulation preparation and control approach data feeding, as it is represented in Figure 1.

Different programming languages like MATLAB® (Joseph-Duran et al. 2015), Python (Urich et al. 2012), as well as combinations of both of them (Riaño-Briceño et al. 2016); have been considered through the literature for this moderation task.

CASE STUDY

The case study consists of a realistic pilot based on the Badalona UDS. It considers a combined sewer network (represented in Figure 3 by the area that is highlighted in blue) and a WWTP that treats the collected water and releases it to the Mediterranean Sea. There is a single detention tank in this drainage network (DLES in Figure 3), which stands out due to its importance considering the control problem. It is conceived to be voluminous enough to be capable of fully storing the vast majority of the water coming from rainfalls. Additional information about the case study pilot characteristics, structure and location can be found in Sun et al. (2020).

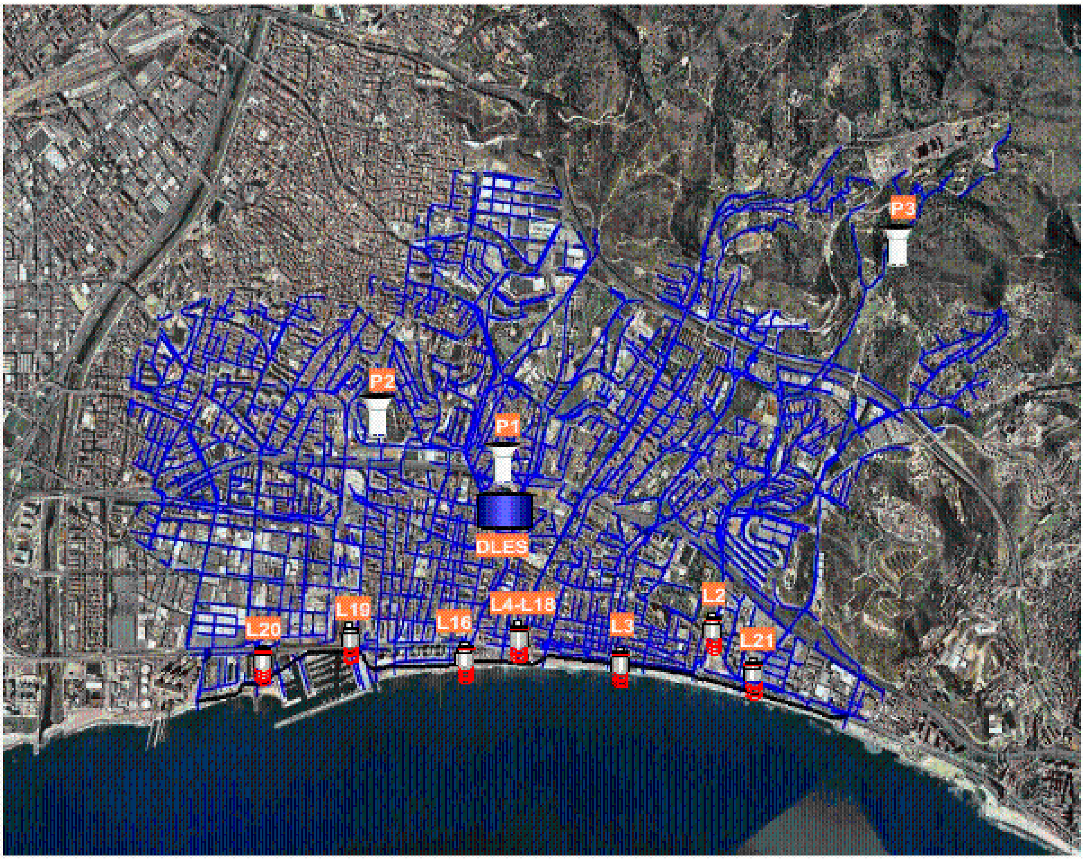

Figure 3: Map of the Badalona SN. The tank is marked as DLES, while the LX elements are CSO points (Sun et al. 2020).

When high-intensity rainfalls occur, the stormwater together with the sewage water may exceed the WWTP inflow capacity, so polluted water would reach the receiving body by means of the CSO, economically, environmentally and socially harming the area.

The local control strategy is based on two operative modes, both implementing a rule-based system that checks several SN hydraulic measurements. The anti-flooding approach is utilized as the main operation mode, basing its functioning on the water level at the most critical point of the network. Besides, an anti-CSO approach is also implemented, but due to its simplicity, the scope for action is large.

In order to improve the currently implemented local control strategy in the Badalona UDS, three different control approaches using the proposed closed-loop software architecture are developed:

(1) Volume-Based Model Predictive Control (VBMPC): model-based strategy characterized by the main role of the CSO volume spilled to the environment during the optimization process. Despite the wastewater treatment plant integration is possible due to the utilized architecture, the feature is not exploited by this approach for the comparison with the next strategy.
(2) Pollution-Based Model Predictive Control (PBMPC): the only differences with respect to the previous approach are the inclusion of the quality (TSS mass) during the optimization process and the integration with the WWTP.
(3) Rule-Based Control (RBC): a set of simple rules is defined with the aid of various decision-trees. They consider both hydraulic and quality features of the network state as well as the treatment plant inflow capacity, hence entailing a further step with respect to the local control approach. Its development is based on the gathered knowledge about the UDS characteristics during the development of the previous control approaches.

Therefore, the CLSA framework presented in this work must be implemented to be capable of applying the desired control strategies and assess their potential benefits. The coordination application that hosts the activities of the different software components has been programmed in Ruby, due to the facility of connection of this programming language with certain exploited commercial tools.

Following the structure of Section ‘Methods’, the individual software elements composing the closed-loop framework for the case study will be presented; closing the exposition by defining the binding platform used to synchronize the previous elements.

Integrated model simulator

The elaboration, configuration and calibration of the integrated virtual reality simulator based on the Badalona UDS were developed as part of the LIFE EFFIDRAIN (LIFE14 ENV/ES/000860) project. The description of the integrated model simulator must be divided into its two different composing ingredients.

Sewer network (SN) simulator

The demonstration SN, used as virtual reality for the simulation of the hydraulic and hydrology dynamics of the UDS, was developed using InfoWorks Integrated Catchment Modelling (or simply InfoWorks ICM).

The SN hydraulic and sediment transport dynamics are based on the 1D Saint Venant equations and the Velikanov model (Zug et al. 1998) respectively. The virtual network includes 14280 nodes and 15055 sewers approximately, together with 4 gate elements to control the amount of water entering the tank (there is a pair of InfoWorks ICM gates for each gate at the real network, as they convey water by two possible paths: to the tank or down to the network), and a pump for its emptying. The detention tank is included among the sewers, due to the impossibility of representing it as a node due to problems with the sedimentation phenomena.

Both the gates and the pump, which compose the sewer network complete actuators set, are managed by means of a regulator whose origin may be internal to InfoWorks ICM, via its local control scheme, or external, coming from the approach selected for the CLSA framework.

The simulation software presents the mentioned functionalities in Section ‘Methods’, Subsection ‘Sewer network simulator’:

- Network generation at InfoWorks ICM: as previously commented, the definition of the virtual SN is part of a larger project that started with simpler network versions, even using a different sewer network modelling software, and ended with the latest improvements considering new data for calibration, gathered from Supervisory Control And Data Acquisition (SCADA) systems and measuring devices installed at the real network in the frame of external projects. Therefore, a deep explanation of this task goes beyond the scope of this paper.
- Rainfall events definition at InfoWorks ICM: to generate the stormwater information, historical data regarding rain scenarios occurred during the last years at Badalona was employed. This knowledge can be converted into rainfall databases which are accessible from the InfoWorks ICM user interface. Then, during the simulation configuration, the selection of a certain precipitation dataset allows the user to assign the correct rainfall pattern to the particular simulated event. In the Badalona-based pilot, the alert criteria to classify the distinct rain scenarios, established by the city hall, was utilized to select a set of episodes ranging from small to large rainfalls.
- Simulation configuration at InfoWorks ICM: events are prepared to be simulated once the previously commented aspects of the SN definition have been generated (network, rain database, wastewater

profiles, etc.), as well as others like the time step duration, corresponding to 5 minutes for every simulation of the case study. The configuration process can be carried out manually, by means of the InfoWorks ICM GUI; as well as via external source, which is the main interest for this paper.

- Results obtained from InfoWorks ICM: it provides numerous sources of information about effectuated simulations regarding hydraulic and quality results, as well as computation performance. The simulation results files, generated in .csv format, present node and sewer related variables like water depth (or height), flow rate and velocity, TSS, volume, pressure head and sedimentation depth.

Wastewater treatment plant (WWTP) simulator

The WWTP detailed model is implemented using the commercial software GPS-X, which allows the mathematical modelling, control and management of wastewater treatment plants. GPS-X provides a large suite of tools that allow to generate complex treatment plant models, run simulations and analyze the results.

The design, creation and implementation of the model of the plant consists of a prior task respect to the purpose of this paper. In this case study, the Besòs WWTP was employed as reference for the detailed virtual reality plant, including the same processes but scaling them considering the input flow to the designed model to be a 14% of the real one (this resizing of the plant is required because the real WWTP treats water from different locations, whereas the case study only considers the Badalona area, which represents a 14% of the total). The modelled plant counts on a simplified sludge line without biosolid treatment. The water line is formed by a gravity clarifier as primary treatment, an aerated reactor and a conventional decantation as secondary treatment; and a biological treatment based on the Activated Sludge Model ASM1 (Henze et al. 2000).

Apart from various simulation settings which depend on the selected episode, different input parameters are required depending on the designed GPS-X model characterization, being related to the biological processes executed in the treatment operation. Regarding the Badalona-based pilot, the selection of the ASM1 model implies the utilization of several equations whose involved variables (see Jeppsson (1996) for a detailed explanation) value must be provided to GPS-X as prior information for each simulation. As InfoWorks does not directly generate all the required quality parameters for the GPS-X procedure, the utilization of a conversion process becomes essential. This task is carried out by the fractionation module (Martin & Vanrolleghem 2014): by means of information about the entrance flow and TSS concentration to the treatment plant and the event date. This process produces almost all the necessary data required by the WWTP simulator.

Real-time controller (RTC)

The RTC module for this pilot is composed by a control algorithm dependent on the selected approach and an operational unit in charge of the WWTP integration. Both of them use input data from the simulators, as well as their previous results, to generate set-points for the involved variables, which are the gates position and pump activation mode for the InfoWorks sewer network, and the WWTP inflow capacity for the GPS-X model.

Control algorithm

The two implemented control approaches for this work, as previously mentioned, are MPC and RBC.

Model predictive control (MPC)

The MPC strategy entails the necessity of a simplified model of the considered sewer network. The validation of the behaviour of this model in comparison with the InfoWorks ICM high-fidelity simulations is presented in Romero et al. (2019). Figure 4 shows its graphical representation.

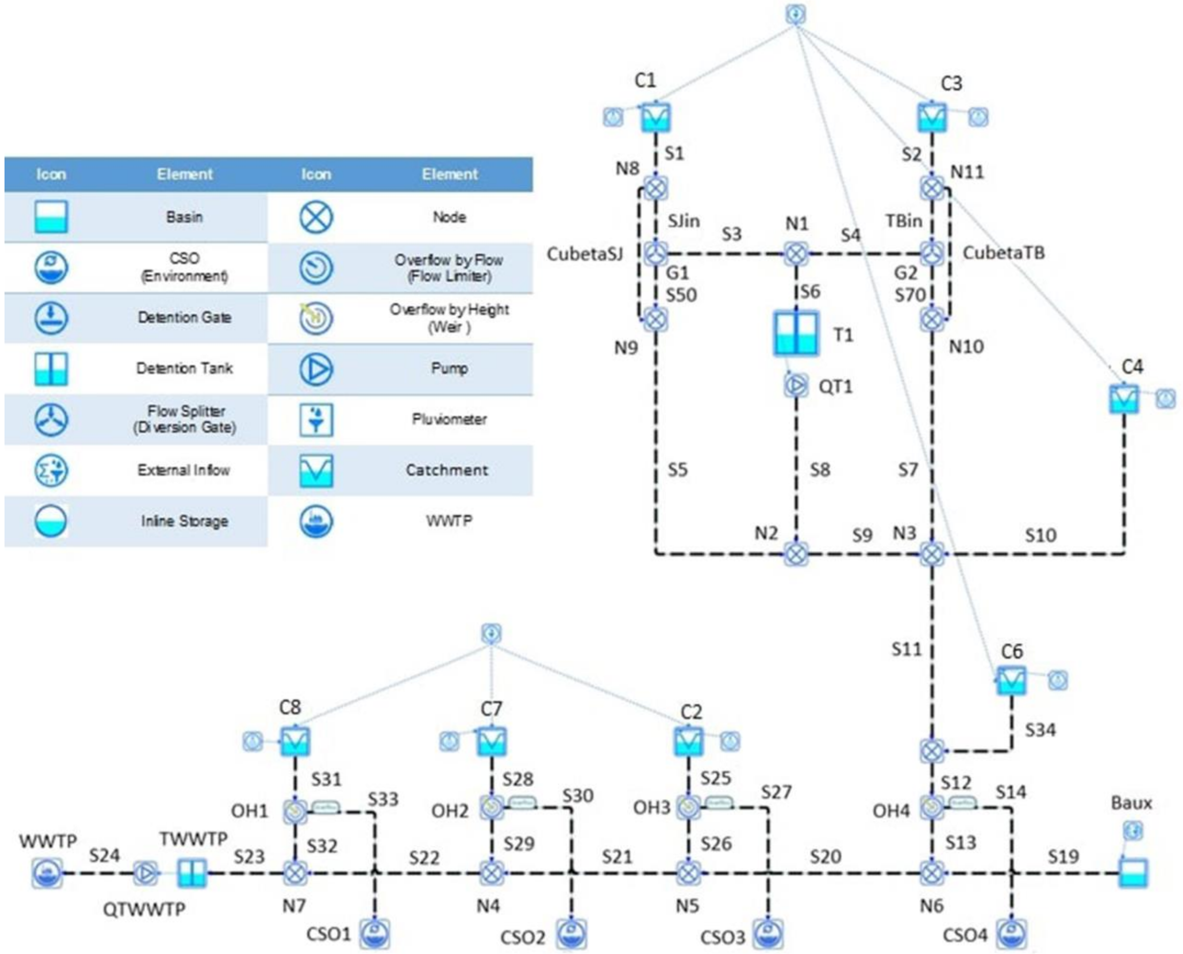

Figure 4: Schematic representation of the simplified model of the Badalona-based SN (Romero et al. (2019)).

To facilitate its comprehension, it is important to clarify some terms:

- The catchments (**Cx** and **Baux**) emulate the network basins from which the water enters the SN.
- Each **Cubeta** element corresponds to a small waterway located at the bottom part of the gates, so that there is always a minimum amount of water escaping to the downstream part. The detention tank corresponds to **T1**.
- The overflow-by-height elements divide the incoming flow into a part continuing to the downstream and the remaining flow (only if the water surpasses a certain level) is conveyed to the receiving body via CSO.
- The final part of the network is depicted as a tank (**TWWTP**) whose output utilizes a pump (**QTWWTP**) to send water to the treatment plant. However, this structure does not exist in the real UDN. It indeed approximates the behaviour of a pumping station used to convey water to the WWTP, and where water can be stored until it reaches the pumping level.

The mathematical expressions relating all these elements, as well as the input information received from the integrated model simulator, allow the optimizer to compute the required reference values for the different actuators which give room to the objectives minimization. For the case study, the elements composing the optimization cost function are the following:

(1) CSO minimization (J_{cso}): it entails the maximum possible reduction of the water flow conveyed to the receiving body by means of the CSOs. To remark that, for the case study, and referring to Figure 4 scheme labelling, only **$\mathbf{CSO_4}$** and the overflow of **TWWTP**, known as **$\mathbf{CSO_{WWTP}}$**, are considered by this objective, because the rest of CSO points of the sewer network are passive and they can not be controlled.

(2) CSO pollutants mass minimization (J_{mass}): it pursues a similar aim to the previous term, but seeking the pollution mass (it is computed as the product between flow and TSS) spilling minimization. The same CSO points are considered.

(3) WWTP usage (J_{wwtp}): its purpose consists of the comparison between the value supplied by the WWTP inflow capacity calculator and the inflow to the treatment facility. Then, if this difference is bigger, the value of this objective will grow.

(4) SN elements safety (J_{safety}): it mainly involves the detention tank safe functioning, regarding the filling operation. Hence, it watches the tank volume and rapidly grows once a certain threshold is surpassed.

(5) Actuators operation smoothness (J_{smooth}): the reduction of this objective depends on the velocity and frequency of change in the set-point value of the different actuators. Therefore, the smoother their operation, the minimal this objective is.

The presented terms are unified in a cost function, where each objective is accompanied by an associated weight:

$$J = w_{cso}J_{cso} + w_{mass}J_{mass} + w_{wwtp}J_{wwtp} + w_{safety}J_{safety} + w_{smooth}J_{smooth} \quad (2)$$

The weights values must be established in accordance with the requirements of the UDN operators and the water utility. For this case study, after performing an analysis to study the effect of the weight values on the individual objectives, these weights are settled as: w_{cso}=240, w_{mass}=8000, w_{wwtp}=80000, w_{safety}=10000 and w_{smooth}=100 (some of these terms are composed by several subobjectives, and the given value corresponds to the weight of the highest of these subitems. For example, the smoothness term is composed by three elements: two for the tank gates and one for the pump. While the pump term is accompanied by a weight of 100, the remaining subitems are multiplied by 1.

Once the urban drainage system simplified model and the objective function are described, the operation of the MPC-based approach must be detailed. In the case study, the MPC-RTC problem is solved through the General Algebraic Modelling System or GAMS optimization engine and the CONOPT3 algorithm.

The process starts extracting the required input information, associating it to the corresponding GAMS variables:

- The optimizer requires data about the water and mass inputs to the model at the whole horizon H (30 minutes) with a time step of 5 minutes. For the case study, this knowledge about the basins that provide water to the network (Catchment in the legend of the simplified model at Figure 4) is supplied by a historical dataset of hydraulic and quality information, adapted to the simulated scenario, and obtained from InfoWorks ICM. Therefore, the optimizer is considered to be receiving a "perfect" dataset about the water input to the network. For further implementations, this knowledge may be furnished as the output of a module which employs the rain prediction.
- Information about the volume and mass of the tanks at the initial time step of the optimization horizon must be provided: the first is obtained from InfoWorks ICM, whereas the latter is provided by the previous optimization results.
- Besides, a forecast about the flow values at every pipe in the network is utilized as input information for the quality computations during the optimization process, so that the product between flow and TSS

becomes simpler. This information is obtained from the results achieved at the previous simulation (and default values for the first iteration).

- The WWTP inflow capacity must be supplied to the optimizer in order to compute the J_{wwtp} objective, importing this knowledge from the WWTP inflow capacity calculator. However, as the optimizer needs a forecast of this value over the horizon, this capacity calculator must be able to produce as many output values as inputs it receives.

Then, GAMS is prepared to be utilized, carrying out the optimization with the objective of minimizing the cost function described in Equation 2.

Finally, the actuators reference values are achieved from certain flows at the simplified model (after the optimization) through a flow-to-setpoint function (concretely, a conversion table). For the Badalona-based pilot, and considering the terminology applied in Figure 4, the measured flows would correspond to pipes **S3** (G11/Gate 1 to tank), **S4** (G21/Gate 2 to tank), **S50** (G12/Gate 1 downstream), **S70** (G22/Gate 2 downstream) and **S8** (P1/Pump).

The output result is provided to the InfoWorks ICM regulator for the control of the actuators during the next iteration of the closed-loop. Therefore, the employed flow values must come from the first step of the optimization horizon, as it represents the next simulation time instant.

Rule-based control (RBC)

The knowledge-based strategy proposed in this work entails the generation of a set of rules based on conditions regarding the SN and wastewater treatment plant states. Their evaluation allows to achieve values for the actuators set-points. For this case study, they are the position of the four gates and the pump functioning mode. The designed decision-tree has been continuously refined by means of the knowledge gained from the pilot performance and the MPC-based approach results.

The first step consists of extracting the necessary information from the available data: the water level at the critical point of the network (the least prepared location to endure a flooding), the level of the detention tank, the flows and TSSs coming from the basins represented by **C1** and **C3** (they directly affect the tank gates), as well as the flow conveyed to the WWTP and the treatment plant inflow capacity (coming from the inflow capacity calculator).

Depending on the comparison between the previous variables and a set of thresholds, which were derived from the knowledge of the system, different actions are triggered with respect to the tank emptying and filling operations. The former checks the tank level to evaluate the necessity of activating (or deactivating) a certain number of pumps, which depends on the WWTP inflow capacity, the actual flow entering the wastewater treatment plant and the current mode of the pumping operation. The latter assesses the difference in pollution concentration arriving the tank from the basins **C1** and **C3**, so that the most polluted water enters the tank with a higher priority. Consequently, the set-point values are derived depending on the desired tank operation mode, as well as the values of the previously mentioned variables.

The RBC approach has been directly programmed in Ruby, without needing extra software, designing and implementing the set of required functions at the control module of the coordination environment.

Wastewater treatment plant (WWTP) inflow capacity calculator

The importance of the WWTP inflow capacity calculator as part of an integrated closed-loop architecture has been remarked through the document at various sections. It provides the WWTP inflow capacity to the controller and GPS-X, allowing to consider the treatment facility state during the decision making process carried out by the control approach.

In the Badalona-based pilot, the capacity calculator has been derived from a criteria based on the State Point Analysis (SPA) or Operating Point Analysis method (Wahlberg 2001). It is applied to the secondary clarifier with a double objective: to detect faults in its operation and to tune the return activated sludge or RAS, which is the part of the outcome obtained from the secondary clarifier that is conveyed back to the aerated bio-reactor to maximize the plant inflow capacity.

The calculator receives the entrance flow to the treatment facility and the mixed liquor settleable solids concentration or XMLSS (obtained from the previous GPS-X simulation), as well as it employs several parameters, highlighting WWTP design values or the Sludge Volume Index (SVI).

The implementation of this module has also been developed in Ruby, hence avoiding the necessity of incorporating new external components.

Closed-loop coordination environment

Once the integrated framework ingredients have been individually explained for the case study, the closed-loop coordination environment must be presented to completely define the proposed architecture.

As mentioned at the case study introduction, a Ruby module has been selected to play this role, as it is presented in Figure 5.

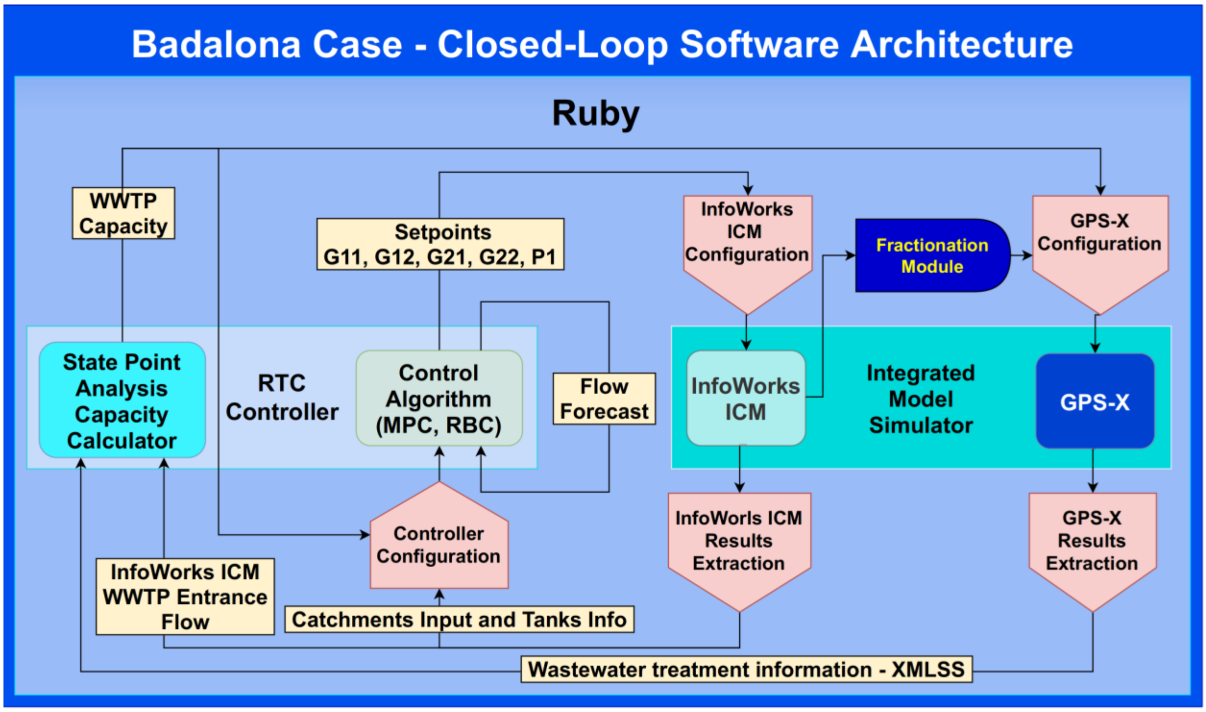

Figure 5: Detailed scheme of the CLSA framework applied to the Badalona-based case study.

The similarities between this diagram and the scheme depicted in Figure 2 are evident, as the different components used in the case study have substituted their general counterparts. The main difference lies in the inclusion of the flow forecast input to the control algorithm, necessary for the MPC approach.

The implementation is based on the instantiation and sequential usage of several classes defined in Ruby, involving each one of the necessary elements:

- InfoWorks ICM Exchange is an Application Programming Interface (API) developed by Innovyze to manage InfoWorks ICM resources from a Ruby program or module. It has been exploited to develop a new class for the management of InfoWorks ICM. It is capable of, by means of the API methods, carrying out the configurations to the slightest detail, proceeding to simulate and saving the achieved results in the desired format.
- A class has been designed and programmed from scratch to manage the WWTP simulator operation. It implements GPS-X related tasks like input information gathering from InfoWorks ICM, simulation configuration and launching, and results storage. Additionally, the fractionation module and the WWTP inflow capacity calculator are included in this class. There are two different functioning modes for this

calculator: one provides a single capacity value and another supplies a complete forecast (necessary for the MPC approach) depending on the size of the input values array.

- About the control approaches, on the one hand, another class has been generated to operate the MPC strategy at GAMS from the Ruby environment. The optimization can be configured using the necessary information obtained from InfoWorks ICM results files, previous optimizations and the WWTP inflow capacity supplied by the calculator. Besides, the optimization can be launched and its results gathered for further analysis or utilization during next iterations.
- On the other hand, a different class has been defined for the RBC operation, implementing the explained functionalities, as well as the results files generation for posterior analysis.
- Finally, two more classes have been created for general purpose: one deals with the creation and management of Excel files from Ruby, and the other allows to generate a complete simulation results file from the ones that InfoWorks ICM creates each iteration, that is, the separated information regarding each individual iteration is encompassed into a general results record.

To manage the usage of all these classes, a main Ruby program serves as binding element. It controls the proper execution of the scheme depicted in Figure 5: receiving simulation settings from an external source, configuring the control approach (the employed classes and the input information that these same classes receive changes among different strategies: Volume-Based MPC, Pollution-Based MPC or RBC), managing the coordination of the different objects created from the previously presented classes inside the loop, and saving the final results of the employed platforms; or even gathering data for subsequent analysis like the consumed time by each software.

RESULTS AND DISCUSSION

Once the proposed integrated closed-loop approach and the case study implementation have been presented, a set of simulation scenarios are employed to show the correct operation of the CLSA and the enhanced performance of the pollution-based approach.

As introduced in Section ‘Case study’, Subsection ‘Sewer network simulator’, there exists an alert criterion to classify the different rainfall episodes, based on the relation between the precipitations intensity considering a 20-minutes time step and a 60-minutes time step (I_{20} and I_{60} respectively). Badalona City Hall defines it as follows:

(a) Alert Level 0: there is no rain.

(b) Alert Level 1: the rain is considered as very small ($I_{20} < 0$ mm/h or $I_{60} > 0$ mm/h).

(c) Alert Level 2: the rain is small ($I_{20} < 10$ mm/h or $I_{60} > 5$ mm/h).

(d) Alert Level 3: it is a medium-sized rain ($I_{20} < 20$ mm/h or $I_{60} > 10$ mm/h).

(e) Alert Level 4: the rain is considered as big ($I_{20} < 40$ mm/h or $I_{60} > 20$ mm/h).

(f) Alert Level 5: the rain is very big ($I_{20} < 60$ mm/h or $I_{60} > 30$ mm/h).

Therefore, regarding the necessity of considering high-intensity episodes, which demand a suitable tank management from the control approach, the following rain events have been selected:

- **22/08/2014**: this episode presents an alert level of 3, due to a $I_{20} = 42.6$ mm/h and a $I_{60} = 17.8$ mm/h. About the quality information, the previous rainfall occurred 20 days before this one. The associated return period is 0.44 years.
- **18/06/2016**: it is classified as an event with alert level of 4, due to a $I_{20} = 60.3$ mm/h and a $I_{60} = 24.40$ mm/h. Regarding the quality data, the preceding rain happened 20 days before this event, and the return period is 0.92.
- **24/03/2017**: it presents an alert level of 3 because of a $I_{20} = 39.6$ mm/h and a $I_{60} = 24.6$ mm/h. In terms of quality, the period between this event and the previous precipitation is 20 days, as well as the return period is 0.38 years.
- **T10**: this event was artificially designed as an episode with alert level of 5 ($I_{20} = 110.5$ mm/h and a $I_{60} = 52.9$ mm/h), in order to challenge the control approach capabilities due to the occurrence of the tank complete filling. It is assumed a period of 10 days of dry weather flow between the preceding event and this one. It also presents a return period of 10 years.

The performance at these scenarios is evaluated by means of the following key performance indicators (KPIs):

(1) CSO_{volume}: total volume spilled through all the considered CSO points (from both sewer network and WWTP).

(2) CSO_{mass}: total mass emitted by the previously mentioned CSO points.

(3) Vol_{WWTP}: water volume reaching the WWTP.

(4) $Vol_{pretreat}$: treated water volume at the pretreatment.

(5) $Vol_{primtreat}$: water volume that passes through the primary treatment.

(6) $Vol_{sectreat}$: treated water volume by the secondary treatment.

In order to compare the different explained strategies, i.e., Local Control, Volume-Based MPC, Pollution-Based MPC and Rule-Based Control; the evaluation of the previous KPIs are presented in Table 1.

22/08/2014				
Control strategy	Local Control	Volume-Based MPC	Pollution-Based MPC	Rule-Based Control
CSO_{volume} (m^3)	83725	79805	79037	80475
CSO_{mass} (kg)	47214	43731	43696	44822
Vol_{WWTP} (m^3)	133660	137514	137599	133108
$Vol_{pretreat}$ (m^3)	119500	125577	125665	122901
$Vol_{primtreat}$ (m^3)	97523	102889	103027	100423
$Vol_{sectreat}$ (m^3)	91037	95584	96358	94118
18/06/2016				
Control strategy	Local Control	Volume-Based MPC	Pollution-Based MPC	Rule-Based Control
CSO_{volume} (m^3)	83207	78443	71820	72763
CSO_{mass} (kg)	56387	54375	53312	53950
Vol_{WWTP} (m^3)	114314	119364	117284	117161
$Vol_{pretreat}$ (m^3)	104509	114029	113796	112485
$Vol_{primtreat}$ (m^3)	88965	94587	101172	99625
$Vol_{sectreat}$ (m^3)	86560	92180	98733	97218
24/03/2017				
Control strategy	Local Control	Volume-Based MPC	Pollution-Based MPC	Rule-Based Control
CSO_{volume} (m^3)	406482	399975	390354	386144
CSO_{mass} (kg)	88863	88778	87402	87660
Vol_{WWTP} (m^3)	235505	260507	260664	262011
$Vol_{pretreat}$ (m^3)	208505	236791	236948	236902
$Vol_{primtreat}$ (m^3)	144097	154757	164122	167844
$Vol_{sectreat}$ (m^3)	134295	144035	153676	157791
T10				
Control strategy	Local Control	Volume-Based MPC	Pollution-Based MPC	Rule-Based Control
CSO_{volume} (m^3)	250399	247216	246968	233037
CSO_{mass} (kg)	56677	52965	49596	55196
Vol_{WWTP} (m^3)	112893	117360	118913	117331
$Vol_{pretreat}$ (m^3)	107563	113992	114227	113649
$Vol_{primtreat}$ (m^3)	98729	105782	105425	105692
$Vol_{sectreat}$ (m^3)	78523	81583	82242	95758

Table 1: Performance results for the presented rain scenarios

The presented results demonstrate the benefits and potential of the detailed software architecture and demonstrate the effectiveness of the proposed solution. The proposed methodology achieved explainable and expectable performance indicators for the different tested rain events and control strategies:

- The Local Control approach turns out to be the worst for all the considered indicators. Two upshots may be extracted from this fact: the implementation of the proposed control frameworks seems to be suitable and desirable, and the functioning of the communication between the RTC module and the virtual reality software environments works in the desired way, correctly applying setpoints coming from an external source to the SN virtual actuators.

- Regarding the pollutants emission to the receiving body, the PBMPC strategy presents the best performance, especially at intense and long rain events like T10. This not only demonstrates the effectiveness of the pollution-based strategy, but also the proper operation of the several elements composing the software architecture: the quality terms of the simplified model, the proper configuration of the RTC module depending on the selected control strategy, etc.
- The usefulness of the wastewater treatment plant integration is demonstrated at the PBMPC and RBC strategies by two facts: the lower CSO spilled volume at these integrated approaches (due to a better management of the treatment facility, so that its internal CSOs are smaller) with respect to the VBMPC, as well as a higher treated volume (this difference gets higher in the further treatment steps) despite the sent volume to the treatment plant is similar. Besides, the achieved results indicate the correct functioning of the integration scheme regarding its implementation, including the configuration of the WWTP simulator, the programming of the inflow capacity calculator, etc.
- Furthermore, the comparison among the different rain scenarios shows that the selection of the proper execution of different operations, like the SN simulation configuration and the results extraction.

Therefore, the presented methodology consists of an effective framework for the deployment of real-time control strategies for urban drainage systems. The software architecture gathers the most important features of previous state-of-the-art approaches: the exploitation of an efficient inter-application communication between modules as in Riaño-Briceño et al. (2016), the possibility of implementing pollution-based control strategies, as in Joseph-Duran et al. (2015), which have been demonstrated to be more effective by the results in Table 1; and the integration of the WWTP state during the control operation, as explained in Butler & Schütze (2005).

For an extended presentation of control strategies and results of additional scenarios, see Sun et al. (2020).

CONCLUSIONS

This work presents a complete methodology for the development of an integrated closed-loop framework to implement pollution-based control approaches for urban drainage systems.

The structure has been composed by an integrated model simulator, combining the sewer network and WWTP functionalities to operate as virtual reality; and the RTC module, composed by the control algorithm and the

WWTP inflow capacity calculator. The communication among the different software components, as well as the organization of the involved tasks, has been implemented inside a coordination environment.

A pilot based on the Badalona UDS has been presented to exemplify the usage of the proposed methodology in several scenarios, as well as demonstrating the capabilities of the advanced framework to generate effective control commands for the SN management. Results involving various rainfall events are exposed to highlight the appropriateness, efficiency and superiority of the presented methodology.

Therefore, new control strategies can be designed and initially tested implementing a sufficiently representative pilot of a urban drainage system by means of the proposed methodology, achieving different conclusions via the employment of a virtual reality application.

The generated closed-loop architecture deals with standalone and/or proprietary software components whose operation was not conceived to be coordinated by an external element. The election of the programs and applications composing the architecture of this case study arises from different reasons. The high-fidelity simulators correspond to proprietary software selected by the network and plant operators involved in the project. The optimization software was chosen due to the wide previous experience at its usage. Finally, the coordination platform was designed in Ruby because of the existence of an API to manage one of the simulators, facilitating its operation. These constraints in the software selection lay bare the difficulty of developing a proper coordination algorithm. However, the proposed solution entails a successful solution to the inclusion of these commercial tools, making the most of their outstanding capabilities while efficiently and effectively coordinating their tasks.

These achievements entail a further step in the urban drainage systems control field, due to the wide range of possible software solutions that can be incorporated to the presented methodology, as well as the several features that it allows to exploit, like pollution-based approaches, WWTP integration, etc.

Several future lines of work remain open. Regarding the software development, the design of a closed application would be of interest, including an application layer in order to improve the operator experience. Moreover, the efficiency of the methodology might be tested and compared with other approaches. About the water system operation, numerous control strategies can be implemented and evaluated, as well as new case studies may be considered. Finally, the implementation of the methodology into a real network would be the definitive step to assess the effectiveness of the solution.

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DATA CONFIDENTIALITY STATEMENT

Data, tools and models employed in this work are confidential or commercial, and hence we refer other researchers to contact SUEZ Spain Group (for access to detailed, simplified models; the Closed-loop Simulation Framework software; and the rain data) and Innovyze (for licenses to InfoWorks ICM).

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LIST OF ABBREVIATIONS

The following abbreviations are used along the article.

API: Application Programming Interface

ASM: Activated Sludge Model

CLSA: Close-Loop Software Architecture

CSO: Combined Sewer Overflow

GAMS: General Algebraic Modelling System

GUI: Graphical User Interface

ICM: Integrated Catchment Modelling

ICT: Information and Communication Techniques

LQR: Linear-Quadratic Regulator

MLSS: Mixed Liquor Suspended Solids

MPC: Model Predictive Control

PBMPC: Pollution-Based Model Predictive Control

RAS: Return Activated Sludge

RBC: Rule-Based Control

RTC: Real-Time Control

SCADA: Supervisory Control And Data Acquisition

SN: Sewer Network

SPA: State Point Analysis

SVI: Sludge Volume Index

TSS: Total Suspended Solids

UDN: Urban Drainage Network

UDS: Urban Drainage System

VBMPC: Volume-Based Model Predictive Control

WWTP: WasteWater Treatment Plant