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EXPLOITING HYDRAULIC MODEL TO ENHANCE WATER NETWORK OPERATION, PERFORMANCE MONITORING AND CONTROL WITH FDD ALGORITHMS*

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Abstract

The paper presents the Fault Detection and Diagnosis (FDD) approach for water networks developed within the Waternomics project. In particular, the FDD system developed is based on the hydraulic modeling of the water network (done using the EPANET software) that is used to the train a Anomaly Detection With fast Incremental ClustEring (ADWICE) algorithm which in turns is applied to real time data of water flow and pressure monitored in the network to infer performance and detect leaks and operation anomalies. The developed FDD system is particularly useful when more than one parameter needs to be considered at the same time to determine if an anomaly or fault is in place in a complex water network. For a first evaluation, simulated training scenarios have been developed and tested for Linate airport (Milan - Italy) water network and the results are presented in this paper. WATERNOMICS is an EU FP7 research project and the key problem addressed is the lack of water information, management and decision support tools that present meaningful and personalized information about usage, price, and availability of water in an intuitive and interactive way to end users. On average water networks in EU have leakages and inefficiencies that results in 20-30% water losses. As such, new technologies and leakages detection methods are needed to solve this issue, to make the EU more sustainable and in this context the FDD method presented can be helpful.

Keywords: ADWICE, leak detection, model based FDD, water saving

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1. Introduction

The need for an efficient Water Management System (WMS) is strongly felt by water utilities, municipalities and in general by corporates that have to face every day with problems dealing with water usage and supply. Therefore, the basic idea to develop an automated system to implement the fault detection in the water network at an early stage is essential to manage the water resource in a sustainable way by avoiding both the waste of the natural resource and the waste of money. Whichever water network we consider the leakages exist; and they have to be localized and measured and solved.

This problem is more severe when we have to face cases in which large water network are implied and where, due the many variables coming into play, it could be very difficult to detect anomalies or fault in the system. In these cases we need to adopt more sophisticated fault detection techniques that are designed to cope with a larger features set and a Model based FDD could be appropriate. This is the case study addressed in the WATERNOMICS project at the Linate airport (Milan – Italy) water network where for the first time we are working toward putting together a hydraulic model simulation with an FDD algorithm (ADWICE) to detect abnormality in the operational phase of the water network. The automated FDD method introduced in this paper is suitable for large water networks for this reason the approach serves as a first step toward its implementation at Linate when sensor data becomes available.

The fault detection method proposed is made up of 5 phases described in the following Fig. 1.

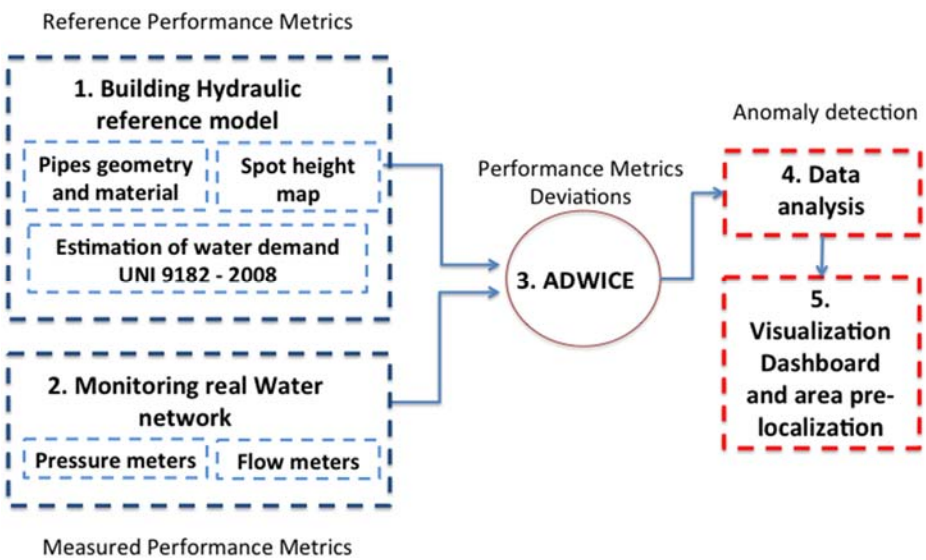

Fig. 1. Waternomics Model Based FDD Methodology

A short description of each phase is provided:

Phase 1 – Building Hydraulic reference model

In this phase, technical information is used to provide knowledge about the water network and for estimating the water demand. Information required to attain an accurate hydraulic model includes: pipe geometry, material types, age and an inventory of the buildings and their water equipment.

Phase 2 – Monitoring real water network

In this phase it is necessary to implement water meters installation in the network with the objective to get data to implement the training of the FDD algorithm ADWICE.

Phase 3 – ADWICE Algorithm

The FDD algorithm ADWICE (Anomaly Detection With fast Incremental ClustEring) is a clustering-based anomaly detector that has been developed in an earlier project targeting critical infrastructures protection. Originally designed to detect anomalies on network traffic sessions using features derived from TCP or UDP packets ADWICE has been adapted in this paper for the drinking water network and it is useful to determine if an anomaly or fault is in place in a complex water network. This class of algorithms is based on modeling the system selecting the best set of parameters that characterize the operational conditions (in our case the flow rate and the pressure) assuming normal operation, i.e. absence of problems (leaks, faults, etc.). This model is used as a comparison baseline with the operational values observed by the water sensors installed in the network in real time.

Phase 4 – Data analysis

If system under observation is not found to be operating in the modeled normal region and the deviation between the normality and the current situation exceeds a certain threshold, an anomaly is detected and an alarm is raised.

Phase 5 – Dashboard visualization

A notification event is raised through the Waternomics Platform to inform the users about the anomaly detected. The users will have the option to act immediately on the notification.

2. Water network modeling and ADWICE training

Water network information, as pipes geometry material and age, are necessary in this phase. This kind of information can be gathered both through design documents study and on site surveys. In Linate airport, 12 technical meetings have been held in order to get an accurate knowledge of the WDS (Water Distribution System) and its characteristics like the pumping stations system, the materials of the pipes, the spot height map of the pilot area and the depth of installation of pipelines. For estimating the water demand, an accurate survey of all the buildings within the pilot area was also conducted in order to develop, for each building, an inventory of the water equipment installed on each floor.

The UNI EN 9182/2008 was utilized in order to get, for each building, a corresponding water demand. The UNI EN 9182/2008 is an Italian law that defines design, installation, testing and management criteria for hot and cold water supply and it is generally used in the design and sizing of water pipes through the calculation of the estimated out flow rate. The water demand is estimated by conducting a *loading units* methodology. Loading Unit value is assumed conventionally according to the flow of a delivery point, taking into account its characteristics, its frequency of use and the simultaneous utilization of the other water appliances installed in the water distribution network inside the building. The method basically consists in assigning to each water equipment a load unit.

Figure 2 (extracted from UNI EN 9182/2008), has been used to assign the load units. The first column lists the appliances, the second is the typology of the water fixture, the third reports in order the Load unit for cold water, hot water and the total of hot plus cold water. As for example for the washbasin we have to consider the first line and assign the load unit corresponding to the total of hot plus cold water (2,00 U.L.).

Apparecchio	Alimentazione	Unità di carico		
		Acqua fredda	Acqua calda	Totale acqua calda + acqua fredda
Lavabo	Gruppo miscelatore	1,50	1,50	2,00
Bidet	Gruppo miscelatore	1,50	1,50	2,00
Vasca	Gruppo miscelatore	3,00	3,00	4,00
Doccia	Gruppo miscelatore	3,00	3,00	4,00
Vaso	Cassetta	5,00	-	5,00
Vaso	Passo rapido o flussometro	10,00	-	10,00
Orinatoio	Rubinetto a vela	0,75	-	0,75
Orinatoio	Passo rapido o flussometro	10,00	-	10,00
Lavello	Gruppo miscelatore	2,00	2,00	3,00
Lavatoio di cucina	Gruppo miscelatore	3,00	3,00	4,00
Pilozzo	Gruppo miscelatore	2,00	2,00	3,00
Vuotatoio	Cassetta	5,00	-	5,00
Vuotatoio	Passo rapido o flussometro	10,00	-	10,00
Lavabo a canale (per ogni posto)	Gruppo miscelatore	1,50	1,50	2,00
Lavapiedi	Gruppo miscelatore	1,50	1,50	2,00
Lavapadelle	Gruppo miscelatore	2,00	2,00	3,00
Lavabo clinico	Gruppo miscelatore	1,50	1,50	2,00
Beverino	Rubinetto a molla	0,75	-	0,75
Doccia di emergenza	Comando a pressione	3,00	-	3,00
Idrantino Ø 3/8"	Solo acqua fredda	2,00	-	2,00
Idrantino Ø 1/2"	Solo acqua fredda	4,00	-	4,00
Idrantino Ø 3/4"	Solo acqua fredda	6,00	-	6,00
Idrantino Ø 1"	Solo acqua fredda	10,00	-	10,00

Fig. 2. Unit Load methodology – image extracted from UNI EN 9182/2008

By knowing the loads units for each building, it is possible to obtain the estimated global water demand by applying the conversion presented in Figure 3 (extracted from UNI EN 9182/2008). These data are valid for public use buildings (offices, schools, hotels, restaurants).

Unità di carico UC	Portata l/s	Unità di carico UC	Portata l/s	Unità di carico UC	Portata l/s
6	0,30	120	3,65	1 250	15,50
8	0,40	140	3,90	1 500	17,50
10	0,50	160	4,25	1 750	18,80
12	0,60	180	4,60	2 000	20,50
14	0,68	200	4,95	2 250	22,00
16	0,78	225	5,35	2 500	23,50
18	0,85	250	5,75	2 750	24,50
20	0,93	275	6,10	3 000	26,00
25	1,13	300	6,45	3 500	28,00
30	1,30	400	7,80	4 000	30,50
35	1,46	500	9,00	4 500	32,50
40	1,62	600	10,00	5 000	34,50
50	1,90	700	11,00	6 000	38,00
60	2,20	800	11,90	7 000	41,00
70	2,40	900	12,90	8 000	44,00
80	2,65	1 000	13,80	9 000	47,00
90	2,90			10 000	50,00
100	3,15				

Fig. 3. Unit Load conversion – image extracted from UNI EN 9182/2008

The geometry of the pipes in the water network, the materials, the depth of installation, and the water demand calculated in accordance to UNI EN 9182/2008 are all input data for the EPANET software and for the development of the hydraulics model of the WDS. The outputs of the EPANET model that are helpful to implement the reference performance metrics are: pressure in the junctions (nodes) and flow in the pipes. Figure 4 shows the hydraulic model of the Linate Airport WDS.

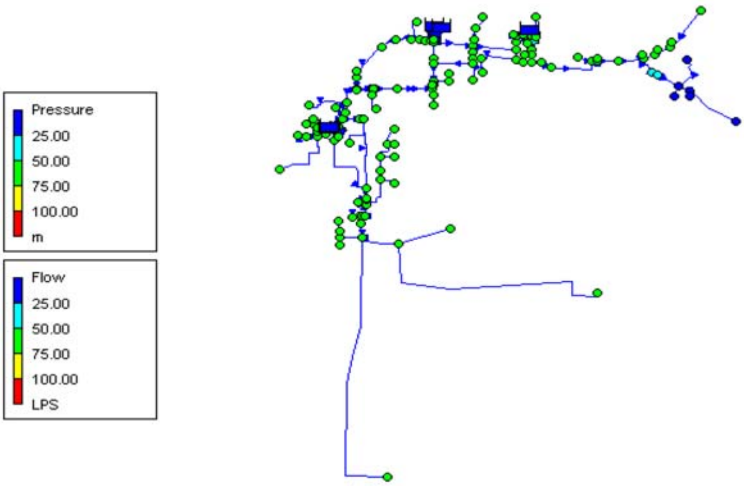

Fig. 4. Linate Airport water network model simulation with EPANET tool

The model is composed of 149 nodes and 159 links and simulates the entire water network of the Linate airport for a total length of about 10 km of water network. For the development of this hydraulic model a lot of information have been collected both with the documents made available by SEA (the airport operator) and also through physical surveys. To implement the simulation the Hazen-Williams formula has been used, while minor losses have been neglected.

The proposed model based FDD requires data from the meters installed in place in order to create a baseline through which to get the ADWICE algorithm trained and/or tested. Due the fact that in Linate airport the installation of the meters necessary to implement the algorithm trainer is on going, the problem has been solved by getting data from virtual scenarios created ad hoc to implement the algorithm trainer. With the objective to create realistic scenarios, a categorization of the Linate airport building was carried out. The categorization was implemented by considering the typical working time of each building. The homogeneous categories individuated for this are the following:

A. buildings with operation time from 6:00 am to 23:00 pm;
B. buildings with operation time from 8:00 am to 18:00 pm;
C. buildings with operation time 24/24 h.

For each category, a different water demand has been considered:

1) full water demand (100% demand pattern as identified before with UNI EN 9182/2008);
2) water demand corresponding to the 50% of the demand pattern identified with UNI EN 9182/2008);
3) water demand corresponding to the 0% of the demand pattern identified with UNI EN 9182/2008).

The combination of the above-mentioned categories and of the demand pattern has allowed us to consider 45 different scenarios summarized in Table 1.

In the second step, a list of buildings served from the water supply has been identified. The number of buildings served by the water network in Linate airport is 36 and they have been named utilizing a codification number. For each scenario, more instances starting from of it have been generated by scaling down the water demand of a building at a time with a factor ranging from 60% to 100% in steps of 10% of its estimated water demand, while keeping all the other buildings with the demand specified in the scenario.

Table 1. Categorization of the Linate Airport buildings and first 45 scenarios

	A	B	C		A	B	C		A	B	C
scenario 1	1	1	1	scenario 16	1	1	1	scenario 31	1	1	1
scenario 2	1	0,5	1	scenario 17	0,5	1	1	scenario 32	0,5	1	1
scenario 3	1	0,5	0,5	scenario 18	0,5	1	0,5	scenario 33	0,5	0,5	1
scenario 4	1	0	0,5	scenario 19	0	1	0,5	scenario 34	0	0,5	1
scenario 5	1	0,5	0	scenario 20	0,5	1	0	scenario 35	0,5	0	1
scenario 6	0,5	1	1	scenario 21	1	0,5	1	scenario 36	1	1	0,5
scenario 7	0,5	0,5	1	scenario 22	0,5	0,5	1	scenario 37	0,5	1	0,5
scenario 8	0,5	0,5	0,5	scenario 23	0,5	0,5	0,5	scenario 38	0,5	0,5	0,5
scenario 9	0,5	0	0,5	scenario 24	0	0,5	0,5	scenario 39	0	0,5	0,5
scenario 10	0,5	0,5	0	scenario 25	0,5	0,5	0	scenario 40	0,5	0	0,5
scenario 11	0	1	1	scenario 26	1	0	1	scenario 41	1	1	0
scenario 12	0	0,5	1	scenario 27	0,5	0	1	scenario 42	0,5	1	0
scenario 13	0	0,5	0,5	scenario 28	0,5	0	0,5	scenario 43	0,5	0,5	0
scenario 14	0	0	0,5	scenario 29	0	0	0,5	scenario 44	0	0,5	0
scenario 15	0	0,5	0	scenario 30	0,5	0	0	scenario 45	0,5	0	0

LEGEND	
1	100% Base demand
0,5	50% Base demand
0	0% Base demand

As results from this two steps categorization methodology we have obtained 8.100 scenarios (45 scenarios * 36 buildings * 5 scale factors) that are likely to be able to simulate, although not in-exhaustive way, a reasonable subset of the possible operating conditions that may occur in the water network and obtain an early feedback whether anomaly detection is feasible or not.

The simulation of the full set of possible operating conditions would be too complex from the computational point of view and would include too many unrealistic conditions (e.g. if we want all the possible combinations by varying the demand of each building from 0 to 100% in steps of 10% we should generate 11^36 scenarios, a huge number). Each of the 8.100 instances simulated with the EPANET model of the Linate Water network provided us with data, in terms of pressure at nodes and flow at links, that we used to train the ADWICE algorithm. The above procedure allowed to have available data for the water network prior to the installation of the meters and the real time measurements. Again, this dataset is not exhaustive and may not capture all the real operating conditions but it is valid for the purpose of evaluating the effectiveness of the anomaly detection algorithm. As described in the following section, a script that performs the 8.100 simulations in one single batch has been developed. The output is a CSV file where each line is the output of the simulation of an instance of a scenario and the columns are pressures and flows.

This file is given as input to ADWICE to build the normality model. ADWICE needed to be configured to work properly with this dataset: first, a feature selection procedure was performed, selecting only the most significant nodes and links that show more variation; the order of the features is also important and we gave more priority to one that shows the highest variance, than the second and so on. Finally, as any clustering algorithm, the dataset needs to be studied to get an idea of the proper amount of clusters to be set. If the number is too low we get a more general model, with big clusters trying to cover scattered points that are quite far away from each other. This model would generalize too much and fail considering as normal anomalous points that fall in areas that should not be covered by any clusters.

The other way round is not good either; if we let the algorithm create and use too many clusters we would over-fit the model to the training dataset creating little clusters around the given points. The algorithm would then correctly raise alarms with anomalous points falling outside those clusters, but would then raise also too many false alarms when normal behaviour generates points that are just away from the closest cluster.

ADWICE has a parameter that specifies the maximum amount of clusters it can use. This parameter is called **M**. Another important parameter is the threshold **E** it uses to accept new points outside the clusters. If E=1 it means no threshold, E=2 it means two times the size of the cluster etc. During training **E** is important to set how much a cluster can be stretched to embed the new point. During evaluation instead **E** is used to determine whether the algorithm should accept as normal or launch an alarm if the point is close (with a certain distance) to a cluster. To find a suitable range of values for M and E, we performed the following heuristic procedure:

- set a value of M and E and launch the training of the algorithm to create the normality model;
- check how many clusters it has use;
- Test the anomaly detection using the same (fault-free) dataset.

If the anomaly detector raises too many false alarms (we check the false positive rate FPR, which represents the percentage of good points wrongly classified as anomalies), we raise M and/or E. Once we stabilize the FPR, we check whether by increasing M the number of clusters used increases as well. If not, the model is over-fitted and we need to scale down M. This procedure gives an idea of possible values for M and E. Usually these are further tuned during the validation phase trying the algorithm with known faults to see how it performs in terms of alarm detection (measured as detection rate DR – the percentage of anomalies correctly classified as such). The final values of M and E are selected in order to get a good trade-off between false positive rate and detection rate.

3. Leakages scenarios development and ADWICE testing

In the same way, we generated "clean" scenarios that capture normal operating conditions for the WDS, to be able to test the effectiveness of the ADWICE as fault detector we need to develop some scenarios that contain leakages in the water network. In doing this, a methodology to simulate a leakage in the water network has been found and generally we can assume that the phenomenon of water leaks is governed by the relationship between the leakage rate (qi **) and pressure (pi):

$$q_i^{**} = c \cdot p_i^{\beta} \tag{1}$$

where: C is the coefficient of loss, β is the loss exponent.

It is evident that reducing pressures allows to decrease, exponentially, lost volumes.

a) **b)**

Fig.5. Water loss at high pressure a) and at low pressure b)

In the EPANET model, the leakages have been simulated by introducing a leakage through the emitter coefficient in some junctions. The introduction of the emitter allow to simulate the outflow rate depend on the pressure (Figure 5). In this way, 10 leakage scenarios have been implemented by introducing the emitter coefficient in some junctions as shown in Table 2.

Table 2. Leakages scenarios for Linate water network simulation

LEAKAGE SCENARIOS			Emitter coef.= 1					
SCENARIOS	**NODE ID**							
SP1	136							
SP2	136	126						
SP3	126	115	103					
SP4	126	115	103	111				
SP5	17	19	25	35	29	54	49	46
SP6	55	56	60	85	91	59	62	
SP7	75	73	100	93	63	74		
SP8	38	76	108	74	125	97		
SP9	1	4						
SP10	46	47	52	53				

With the same approach used to generate the normal dataset, we simulated a leakage at a time applying the emitter coefficient to the specified nodes. Each leakage is then produced in all the 8.100 scenarios as above. This gives us ten more files, one for each leakage scenarios, with 8.100 cases. To test the efficiency of the anomaly detection algorithm, we modified these files adding the 8.100 normal fault-free scenarios at the beginning of the files, letting the 8100 with the leakage be after these. This gives us the possibility to compute the accuracy of the algorithm (percentage of instances correctly classified either as alarms or not). EPANET is a Windows-based application and it allows modelling a water network and running a simulation from the graphical user interface (GUI). However, we need to simulate a high number of scenarios changing some input parameters (the demands at nodes) from one simulation to the other. To perform this task we created a C program that uses the libraries provided by the EPANET programmer's Toolkit. These libraries allow programmers to open network models, run simulations a retrieve the results from custom programs without the need of the EPANET GUI. Our script is structured as following:

- open the network input file which is exported from the model built using the GUI;
- read the scenarios configurations (scenario number, value of A, B, C) from a file. For each of them
  - for each building at a time;
  - for each scale factor between 60% and 100%;
- scale down the demands assigned to nodes according to their category (A, B, C);
- scale further down the demand assigned to the current building according to the current scale factor;
- add the leakage (if generating the validation dataset);
- run the simulation;
- write resulting pressures and nodes in a line in the input file.

4. Results and discussion

The Linate airport, given its large water network (about 10 Km), represents a good test site for the model based FDD. However, the lack of real measurement data represents an issue and it has been solved, as mentioned above, through the implementation of 8.100 virtual scenarios to simulate the WDS in a large variety of operational environments. The study will be much more detailed in future where, after to have installed the meters in Linate airport, real time measurements and data will be available. However, the results obtained with the virtual simulation of 8.100 operational scenarios give to us the hope for a good functioning of the Model based FDD methodology applied to the real case.

As an example, Table 3 reports the results of the validation of ADWICE with the leakage scenarios described above. As explained earlier, we had to tune the parameters M and E in order to get a trade-off between detection rate and false positive rate. In general, we want to have the minimum FPR and the maximum DR at the same time. In the test performed, we found that the lowest false positive rate we could obtain was as little as 0.01 (1%), but the detection rate was very low as well, being 30% on average. On the contrary, an 80% detection rate was achieved at the cost of a 10% false positive rate. Overall, we need to look at the accuracy, and the results presented in Table 3 provide the best average achieved. On average, the false positive rate is around 5%, the detection rate around 60% and the accuracy 80%. The results were obtained setting M=200 and E=3 for the training phase and E=1 for the validation phase.

Table 3. Results of the Model Based FDD Methodology

Scenario	False Positive Rate	Detection Rate	Accuracy
SP1	0.049	0.84	0.89
SP2	0.049	0.60	0.77
SP3	0.049	0.33	0.66
SP4	0.049	0.68	0.82
SP5	0.049	0.43	0.68
SP6	0.049	0.38	0.66
SP7	0.049	0.42	0.68
SP8	0.049	0.42	0.68
SP9	0.049	0.93	0.94
SP10	0.049	0.58	0.77

4. Concluding remarks

This paper aim is to introduce a model based FDD method helpful in leakages and faults detection in water networks. The method is based on the analysis of both pressure and flow variation produced by leakage in the WDS, for this reason this technique differs from the others we can find in the literature because it is not based on the transient analysis of the pressure waves but on the comparison of real pressure and flow data with their estimation using the simulation of the mathematical network model. For a first evaluation, simulated training scenarios have been developed and tested.

The results obtained in terms of False Positive Rate, Detection Rate and Accuracy, with the virtual simulation of 8.100 operational scenarios give to us the hope for a good functioning of the Model based FDD methodology applied to the real case. Next step is to test the method in a real case studio (Linate water network) by using the real time data gathered from the flow and pressure meters installed in the water network.

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References

Brunone B., Ferrante M., Meniconi S., (2008), *Research and Monitoring of Leaks in Pipe Networks,* (in Italian: *Ricerca e controllo delle perdite nelle reti di condotte*), On line at: http://www.cittastudi.it/catalogo/ingegneria/ricerca-e-controllo-delle-perdite-nelle-reti-di-condotte-3274.

Bruton K., Raftery P., Kennedy B., Keane M.M., O'Sullivan D.T.J., (2013), Review of automated fault detection and diagnostic tools in air handling units, *Energy Efficiency*, **7**, 335–51.

Burbeck K., Nadjm-Tehrani S., (2007), Adaptive real-time anomaly detection with incremental clustering, *Journal Information Security Technical Report*, **12**, 56-67.

Chambers N., Coakley D., McCaffrey M., Curry E., Keane M., Costa A., Clifford E., (2015a), *Assessment and planning for the application of Fault Detection and Diagnosis (FDD) to Building Water Networks, A WATERNOMICS Approach*, In: *E-proceedings of the 36th IAHR World Congress* (IAHR 2015), The Hague, the Netherlands.

Chambers N., Coakley D., Keane M., Clifford E., (2015b), *Water Conservation with Novel Application of Fault Detection Diagnostics (FDD) Applied to a Rain Water Harvesting System in Ireland*, In: *World Water Congress XVth (IWRA 2015)*, Edinburgh, Scotland, 2015.

Colombo P., Lee, A.F Karney B.W., (2009), A selective literature review of transient based leak detection methods, *Journal of Hydroenvironment Research*, **2**, 212-227.

Katipamula S, Brambley M., (2005), Methods for fault detection, diagnostics, and prognostics for building systems—a review, Part I., International *Journal of Heating, Ventilating, Air Conditioning and Refrigerating Research*, **11**, 3-25.

Perfido D., Messervey T., Noris F., Puglisi R., Smit S., Costa A., (2015), *Waternomics (ICT for water resource management) Methodology for Deployment of a Water Management System*, In: *The 11th IFIP WG International Conference on Artificial Intelligence Application and Innovation*, Bayonne Château-Neuf 2015, France.

Perfido D., Raciti M., Zanotti C., Chambers N., Hannon L., Keane M., Clifford E., Costa A., (2016), *Sustainable Water Networks, an Automated Fault Detection and Diagnosis of Water Network Systems*, ESI - ISSN 2345-0282, In: Sustainable Places 2016 International Conference, Anglet – France.

Raciti M., Cucurull J., Nadjm-Tehrani S., (2012), *Anomaly Detection in Water Management Systems*, In: *Critical Infrastructure Protection*, Lopez J., Setola R., Wolthusen S.D. (Eds), Springer Heidelberg Dordrecht London New York, 98-119.

Raciti M., (2013), *Anomaly Detection and its Adaptation: Studies on Cyber-Physical Systems*, Linkoping Studies in Science and Technology Licentiate Thesis No. 1586, Linköping University.

Stafford R.S., Singer D.E., (1996), National patterns of warfarin use in atrial fibrillation, *Archives of Internal Medicine*, **156**, 2537-2541.

Venkatasubramanian V., Raghunathan R., Kewen Y., Kavuri S.N., (2003), A review of process fault detection and diagnosis. Part I : Quantitative Model-Based Methods, *Computers and Chemical Engineering*, **27**, 293–311.