# Assessment and Planning for the Application of Fault Detection and Diagnosis (FDD) to Building Water Networks, A WATERNOMICS Approach

N. CHAMBERS(1), D.COAKLEY(2), M. MCCAFFREY(3), E. CURRY(4), M.KEANE(5), A.COSTA(6), E.CLIFFORD(7)

*(1)Dept. of Civil Engineering, National University of Ireland, Galway, Ireland, n.chambers1@nuigalway.ie*
*(2)Dept. of Civil Engineering, National University of Ireland, Galway, Ireland, danielcoakley1@gmail.com*
*(3)Dept. of Civil Engineering, National University of Ireland, Galway, Ireland, mccaffrey.mark@gmail.com*
*(4)Digital Enterprise Research Institute and Insight, Galway, Ireland, ed.curry@deri.org*
*(5)Dept. of Civil Engineering, National University of Ireland, Galway, Ireland, marcus.keane@nuigalway.ie*
*(6)Research 2 Market Solutions © andrea.costa@r2msolution.com*
*(7)Dept. of Civil Engineering, National University of Ireland, Galway, Ireland, eoghan.clifford@nuigalway.ie*

**Abstract**

*Waternomics* is an EU-funded research project that addresses key challenges regarding the efficient management of, and decision support tools within, the water supply sector. A novel aspect of the *Waternomics* project is to apply Fault Detection and Diagnostics (FDD) to building water networks in order to identify faults (leaks, malfunctioning equipment, inefficient operation etc.). FDD is a measurement science which has traditionally been used in buildings for Heating Ventilation and Air-Conditioning (HVAC) systems to identify and rectify faults at the earliest possible stage and thus reduce maintenance costs, increase efficiency and result in energy savings of between 10 and 30%. To date, these FDD tools have not been applied systematically to building water infrastructure. This *Waternomics* project aims to develop and implement FDD systems, in a number of large scale pilots; (i) a municipal water based demonstration in the National University of Ireland, Galway engineering building and a school in Galway City (both in Ireland) (ii) a corporate operator in Linate airport, Milan, Italy and (iii) domestic users in Thermi, Greece. This paper specifically describes the standard based methodology to be used in applying FDD to a building, which has been developed thus far from the NUI Galway Engineering pilot site.

*Keywords:* water leak detection; water fault detection; building water networks; water metering

## 1. Introduction

### 1.1 Water Crisis, Energy Nexus, Waste in Buildings and the WATERNOMICS Solution

Climate change, increased urbanization and increased world population are several of the factors driving global challenges for water management. In fact, the World Economic Forum has cited "The Water Supply Crises" as a major risk to global economic growth and environmental policies in the next 10 years. During the 20th Century, water use increased by double the rate of population growth, and, if these rates continue, it is estimated that by 2030 demand for water globally could outstrip supply by over 40% (McKinsey, 2009). By 2025, 1.8 billion people will live in water scarce regions and two thirds subjected to water stress (Barker et al., 2007). Globally, 25 to 30% of drinking water is lost every year due to leakages in urban water distribution systems that significantly exacerbate water scarcity (EC, 2013). The interconnected nature of water and energy (Water, Energy Nexus) give further impetus to manage and conserve available water more effectively (DOE(U.S.), 2014). A simplified way of thinking about the nexus is that we need energy for water, energy from water and water for energy (EC, 2014). Energy is already the largest user of water, with water abstracted for cooling in energy production accounting for 44% of total water abstraction in Europe (Meade, 2013).

It is estimated that buildings use 21% of all water in the EU (E.C, 2012). With an estimated 25 to 30% of this wasted or leaked, there is considerable scope to improve the state of water consumption across the continent by improving methods of managing water in buildings alone. With regard to water prices, given the low tariffs applied to water consumption, price elasticity is too low. Thus demand has limited impact on cost, which leads to disinterest of the general public in conservation and water has not been adequately considered as a valuable resource yet. The result is that our water infrastructure, business models, and behaviours at all levels of the water value chain reflect this fact. Clearly, a platform, which empowers and informs corporate decision making, municipal managing and domestic usage in European buildings to conserve water, is required immediately.

### 1.2 Fault Detection and Diagnosis

Fault Detection and Diagnosis (FDD) is present in many systems where faults can compromise system operation and/or efficiency. Accordingly, FDD has grown simultaneously with the expansion and development of technology in the past half century. For example, FDD is applied in sectors such as the automotive industry (Lanigan, Kavulya, Narasimhan, Fuhrman, & Salman, 2011). Today's premium automobiles can include fifty or more individual electrical control units communicating over multiplexed data networks such as controller area network (CAN). With increased integration comes increased complexity and a higher possibility of faults. To date, on-board diagnostic systems have come into play to cope with faults (Suwatthikul, 2004) to ensure customer satisfaction. The alternative to this would be to observe the growth of cars and on-board electronics without recognising the need for backup algorithms to counteract defects. This alternative is akin to what has happened with water networks in buildings in recent decades.

Water systems in buildings have recently grown in complexity due to increased building size, the number of end users that they service and the additional systems that they now interact with. In the same way that cars now support additional applications (reversing cameras and on board phones) water networks now service additional systems such rainwater harvesting and thermal solar panel services, however, the FDD to ensure that building water systems work efficiently is absent.

The reasons for faults in water networks can include equipment over or under dimensioning, equipment malfunction, pipe blockages, leaks, contaminants, behavioural issues, procedural errors, etc. Detecting faults at the earliest possible stage can lead to more efficient maintenance and repair processes and savings well beyond those associated with only water savings by increasing awareness of the role of system faults in (i) increasing costs and (ii) causing meter problems at the consumer level and (iii) contributing to higher water consumption rates. For this to happen however, system characterisation of various buildings and collaboration between multiple institutions is required.

### 1.3 WATERNOMICS & FDD

*Waternomics* is a project co-financed within the 7th Framework Program to develop new Information and Communications Technology (ICT) solutions for water efficiency. It aims to provide personalized and actionable information on water consumption and water availability to individual households, companies and cities in an intuitive and effective manner at relevant time scales for decision making. The project will develop and introduce ICT as an enabling technology to manage water as a resource, increase end-user conservation awareness and affect behavioural changes, and to avoid waste through leak detection and diagnosis.

This paper deals specifically with the fault detection and diagnosis aspect of the project. As will be shown from the literature review there is a considerable void in development and deployment of a tool which identifies and rectifies water wastage in buildings at present. The *Waternomics* approach to FDD will allow for straightforward and effective deployment of FDD to different building types through a unique Standard based methodology.

*Waternomics* will develop a standard based methodology which will direct building managers, site engineer's etc. how to apply an FDD system to a building from direct experience of applying smart meters, engaging in leak detection and associated data analysis mechanisms in the pilot scale trials. The varied nature of the pilot buildings which the *Waternomics* project will interact with throughout the FDD development will create a versatile, robust and adaptable FDD system.

The *Waternomics* unique approach developed thus far will enlighten the user about the following:

- How to find and examine existing material and information relating to the building water network;
- Usage of graphics to better understand the flows of water in and out of a building;
- The development of Key Performance Indicators (KPI's) so as to prioritise the main concerns of of the project stakeholders;
- How to find and record water network faults;
- Making decisions on what type of FDD is most suitable for a particular building;
- What meters are best for a building and how to install smart meters.

## 2. Literature Review

### 2.1 Introduction

In section 2.2, the definition and principles of Fault Detection and Diagnosis will be introduced in their most elementary form and some desired characteristics of generic FDD systems will be outlined to give the reader an insight into what a universal FDD scheme entails. Following this, Heating, Ventilation and Air Conditioning (HVAC) installations will be introduced. HVAC is an application which has seen rapid development in its FDD in recent years due to increased energy efficiency concerns. It will be shown to be quite analogous to water networks in buildings and so its similarities will provide a basis from which underdeveloped water network FDD can draw examples and influence from. Finally, all of the current literature and services pertaining to faults in water networks will be reviewed. This analysis of the current state should illuminate the gaps in water network FDD at present and justify the approaches introduced in the methodology section herein.

### 2.2 Fault Detection and Diagnosis (FDD)

A fault is a malfunction of a system component, which ultimately leads to a decline in the system's intended performance and/or efficiency. Detection is the recognition of when and where there is a fault present in the system. Diagnosis is the act of isolating the location and nature of the fault to the extent that it can be rectified, so as to restore the effected system's performance to its intended level. To implement FDD to a system, at the very minimum, the full extent of a system's operational capacities must be understood and information from a system must be received so that its state/operation can be characterised at any one time.The desired attributes of an FDD system include (Sobhani-Tehrani & Khorasani, 2009):

- **Early Detection and Diagnosis:** The longer that a fault persists, the greater the accumulative effect of the associated inefficiency's. More importantly, the more time that it goes undetected and undiagnosed, the more likely it is to develop into a component failure which could lead to economic loss and potential human injury/fatality.

- **Fault Segregation:** This is the ability of an FDD system to zone in on the offending component and to distinguish the faulty component from others.
- **Fault Characterisation:** This is to estimate the severity, type or nature of a fault. To fix a fault, the exact problem with the component must be known. This is usually carried out by a person who was informed of the fault and its location, but can be done automatically.
- **Robustness:** There is an uncertainty relating to the extent of variability which does not indicate a fault in any given system. A fault detection algorithm able to handle uncertainty is called robust and its robustness is the degree of sensitivity to faults compared to the degree of sensitivity to uncertainty.
- **Adaptability:** A useful FDD system can be applied to multiple machines and systems of the same genre, without the need for a completely new set up and reprogramming.

FDD approaches to system faults can be broken down into 3 categories (i) rule based, (ii) data driven and (iii) law driven FDD models. The categories of FDD, described below, are listed relative to their increasing complexity (Bruton, Raftery, Kennedy, Keane, & O'Sullivan, 2013):

Table.1 Breakdown of Different FDD Methods

| Rule Based FDD | Data Driven FDD | Law Driven FDD |
|---|---|---|
| This method utilises elementary logic applied to a system to decide whether it is operating as designed or not. Basic on-off principles provide a simple example of an FDD rule. If a whole system (a water boiler) is turned on, but an integral component (the water pump) is turned off, then a fault is present and the systems operation is impaired. | Sensors are applied to the various components of a system to measure various operating properties e.g. temperature, air flow rate, humidity etc. Statistical models will be developed over time, while the system is running fault free, to develop a baseline for how the system should operate in various conditions. This model is then compared to the actual (real time) operation of the system and checked for abnormalities. Variances from its modelled optimal operation then indicate a fault. An example would be emissions from a car. From observing how the emissions change with different variables (car speed, acceleration, and load), the FDD platform can compare expected emissions with actual emissions and suggest a fault if the expected and actual emissions differ. Data driven FDD is also known as *backward modelling* as it uses historical data from the system to recall the intended operation. | This applies physical laws to the system to forecast its operation under a given set of conditions. A model of the system will be developed through computer programming. Limited operational data of the system is required, but extensive knowledge of the system and its laws is essential. In the example of an air-conditioning system, laws of thermodynamics and Newtonian equations are used to predict the optimal running of the system. Similarly to the Data Driven models, if the characteristics of the day to day running vary from its predicted operation then a malfunction is likely. Law driven FDD is also known as forward modelling as it uses laws to project the intended operation. |

A simplified way of considering their levels of detail is with the notion of black, grey and white box modelling. Black box modelling requires no knowledge of internal workings and should only be developed in terms of its inputs and outputs, which is analogous to the way that FDD rules are created. Grey box modelling is unaware of the detailed specifics of a system, but a certain model can be created with some insight and ascertained experimental data. This is the basis of how data driven FDD is developed. White box modelling is based on the first principles of a system, knowing its intricacies and the physical laws governing it. White box modelling is often too complex to apply to whole systems. Testament to this is that there are whole studies allocated to just valves in HVAC systems (S. Wang & Jiang, 2004).

2.3 Fault Detection and Diagnosis in HVAC

A Heating Ventilation and Air Conditioning (HVAC) system's purpose is to provide people in buildings with conditioned air so that they will be able to work and live comfortably within the building space. It will do this using a system or platform that controls components such as heating coils, cooling coils, humidifiers and dehumidifiers.

Due to technology advances and a higher emphasis on system performance HVAC performance measures, such as energy efficiency, indoor air quality, comfort, reliability, limiting peak demand on utilities, etc, are key performance indicators in many buildings. To facilitate this, the processes, systems, and equipment used in both commercial and residential buildings are becoming increasingly sophisticated (Schein & Bushby, 2006). This increased system complexity can in turn lead to an increase in faults, a degradation of performance and energy inefficiency of between 20-30% in some cases (IEA, 2002). To counteract potential malfunctions of the components in a HVAC, FDD is seen as a key tool to retrieve the lost efficiency and to reduce its unnecessarily high running costs.

The techniques used in implementing FDD have grown to be complex and varied. Rule based FDD has been enhanced with the computing technique of Fuzzy Logic (Lo, Chan, Wong, Rad, & Cheung, 2007). Examples of Data Driven FDD include Artificial Neural Networks (Zhu, Jin, & Du, 2012), Principal Component Analysis (Li & Wen, 2014) and Wavelet Analysis (H. Wang, Chen, Chan, & Qin, 2012), while a common method of producing Law Driven FDD is with reduced order models (Berton & Hodouin, 2003). The field of FDD in HVAC applications is considered well developed and up to date. This has led to improvements in efficiency and in turn financial savings for buildings utilizing HVAC coupled with specifically developed FDD. To date there have been limited attempts to apply these techniques to water systems in buildings.

2.4 FDD in Water distribution Systems and Building Water Networks

There has been a focus on the avoidance of leaks in water networks upstream of buildings i.e. in larger distribution networks that do not interact with the industrial, domestic or public end users of water. Water scarcity in southern Europe due their limited rainfall and dependence on irrigation for agriculture has led to the investigation of how best to detect and isolate faults in water distribution systems using similar statistical techniques and other methods such as those applied to HVAC. Law based or forward based, Linear Parameter Varying (LPV) models are used on non-linear systems such as irrigation canals and pressurized water pipes so as to detect faults (Blesa, Puig, & Bolea, 2010; Blesa, Puig, Saludes, & Vento, 2010). A method for placing and utilizing pressure sensors so as to develop data based models (Pérez et al., 2011) as well as a combination method of using rule and data model based FDD have been tested on the Barcelona water distribution network (Quevedo et al., 2014). Similar to the combination study, a dual approach of using deterministic modelling in conjunction with machine learning techniques such as fuzzy theory and neural networks was developed in a Valencian university (Izquierdo, 2007). A purely artificial intelligence approach through the medium of fuzzy logic is used to develop models and acquire FDD capabilities in (Ragot & Maquin, 2006). In the United States recent work proposed the use of fault diagnosis and security framework due to the threats and consequences of water supply terrorism (Eliades, & Polycarpou, 2010).

In buildings and industrial facilities there is some use of once off services to detect and rectify leaks. Remote wave detection, acoustics, tracer gas and thermography are all common techniques used to identify suspected leaks on private properties or businesses. An insightful study into the various types of remote wave detection methods compared time domain reflectometry (TDR), ground penetrating radar (GPR) and electrical resistivity tomography (ERT) and found GPR to be the suggested industry standard among these techniques (Cataldo et al., 2014). Acoustic listening devices include listening rod and ground microphones and can be used to sense leak-induced sound or vibration (Hunaidi & Wang, 2006). Listening methods are the most widely used in the field of local, one-off leak detection. Tracer gas is a method which uses small molecule gases such as hydrogen and nitrogen in conjunction with gas detectors to locate where the gas, as well as water is seeping through a pipe, an example product in this market would be the (Variotec, 2014). "A Thermography (IR) camera measures and images the emitted infrared radiation from an object. It can detect thermal contrasts on pavement surface due to water leaks. In addition, it enables relatively large areas to be investigated effectively in less time and consequently less cost comparing to current leak detection methods" (Fahmy, Asce, Moselhi, Eng, & Asce, 2009). Thermography is not applicable in locations which experience harsh weather conditions however, as high pavement temperatures and snow coverage will compromise its effectiveness.

Water networks, similarly to HVAC systems, are increasingly linked with a Building Management Systems (BMS) and contain sensors to observe and manage their operation. In many case however, such monitoring is passive and the data is not actionable (i.e. building managers are not able to usefully or efficiently use data to limit inefficiencies).

Thus the development of a continuously operating platform, capable of detecting faults at the earliest possible stage to counteract the 25-30% water loss in European buildings is timely. Furthermore, unlike in other sectors, there are no methodologies available to describe best-practice when applying FDD to the water infrastructure in buildings. . This study presents a standard based methodology, developed through the use of large pilot buildings that inform the effective deployment of FDD systems and platforms in building water networks.

## 3. Methodology

Given the lack of standard based methodologies in this area, *Waternomics* focused on adapting existing standards (namely ISO 50001, 50002 and 14046) to inform the methodology development (Figure 1). The reason for adapting this standard based methodology is because of the need to create as much literature and procedures as there are in the energy sector. The energy sector is fully developed with methodologies relating to energy efficiency and so this project draws from its success to achieve the same level of conservation with water in buildings.

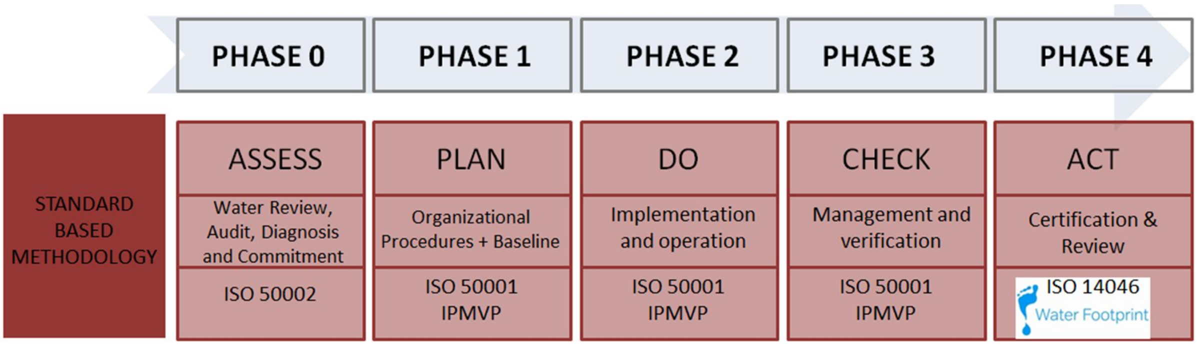


Figure 1. Standards based approach adopted by the *Waternomics* project.

### 3.1 Assessment of Building Water Network

The foremost objective of the assessment stage of the FDD methodology is to become familiar with the water network and associated systems. This stage requires that engineering drawings and models are studied, existing sensors and data located and identified and gaps in knowledge recognised. With the advent of building information modelling this stage could be mostly completed at a desk, however, for most buildings much of this work may require extensive surveying of the building and the building managers (where they are present). Five key areas of assessment are described below.

*3.1.1 Create a "Body of Knowledge" Relating to the Water Network*

This initial part of the assessment involves meeting and surveying relevant building stakeholders. These can include the building manager, a design engineer, end-users etc.

- Who is responsible and knows most about the water network?
- How old is the building and water network?
- Have there been any previous studies carried out on the network?
- Was any part of the water system retrofitted or changed from its original installation?
- Are there as-built drawings for the water network?
- Are there any common problems with the network? i.e. recurring leaks, increased water bills at certain times of year.

The questions that can be asked are not limited to those stated above as each building differs considerably in its management, usage, age etc. The main paradigm to be adopted at this stage is that the body of knowledge relating to the water network must be uncovered and gathered and developers should use all resources and contacts available to achieve this.

*3.1.2 Examine existing material relating to the Water Network*

Following the creation of a body of knowledge, any previous material should be studied, cross checked and updated with the existing water network. In the example of an as-built mechanical drawing, a selection of pipes that are shown in a drawing should be found physically and followed from source to end use while comparing them to the drawing. This will clarify if the drawing is an exact replica of the existing network or not. The developer will realise very quickly whether the drawing should be disregarded because of inaccuracy or used as a tool to understand the network better. A useful exercise with the existing material is to summarise it and present it to key stakeholders. Summarising the material will ensure that the developer is very familiar with the network and the material relating to it, it will also allow for the stakeholders to better understand the existing system and to provide their informed judgement.

*3.1.3 Create a Building Water Balance Graphic*

A water balance graphic will convey all of the inputs and outputs of water in a building, as well as highlight the paths that water takes from source to end use and the services that they interact with. The highly recommended type of graphic that should be used is a "Sankey Diagram". They were originally used for visualising flows of energy in mechanical systems whereby the width of the arrows is shown proportionally to the flow quantity. E-Sankey software for developers can be downloaded from (ifu Hamburg GmbH, 2015). An example of a Sankey diagram can be seen in figure X.

The development of a Sankey water balance graphic is useful for a number of reasons. It forces the developer to become familiar with all of the inputs and outputs in the water network, this in turn leads to more investigation of the network and more faults found. It highlights the quantities of water that are not metered and informs better decision making where additional extra meters are required (and indeed can identify existing leakages). Finally, it is a novel way of communicating water information to which could induce a different understanding of how much water they are responsible for and cause them to and actively engage users in conserving water to a greater degree.

*3.1.4 Engage Stakeholders and develop FDD KPI's*

A project stakeholder is anyone who can affect or be affected by a project and who has a particular interest in the outcome of the activity. It is fundamental then that the development of an FDD platform in a building should be tailored to the specific concerns of the stakeholders. To do this, a meeting should be called with the stakeholders (either individually or together) and the project, its objectives and progress should be explained in detail. The stakeholders should then be asked the vital question; "What determines the success of this project from your point of view?"

Stakeholders will invariably have varied priorities and conflicting interests with regard to the success of the project. After understanding the concerns of the stakeholders, their definition of success should be abbreviated into key performance indicators (KPI's). KPI's are quantifiable measurements that reflect the critical success factors of the different points of view. An example of a KPI would be "Litre's/person consumed" or "Flushes/Person" and can be used to guide the direction of the FDD that is developed and implemented.

*3.1.5 Record all Faults Encountered.*

In completing the above steps faults and/or leaks may be found, particularly as faults which would not be obvious to stakeholders in the building may not have been previously identified. An example of this is uncovering a broken meter that does not have a commissioning schedule attached to it. These faults should be recorded and presented to relevant stakeholders. The faults found should be considered when the first sets of FDD rules are implemented to the building so that at the very least, the potential for recurring faults will be eliminated. Key information should be recorded for each fault, (e.g. Figure 2) which in turn informs data to be recorded by the FDD platform.

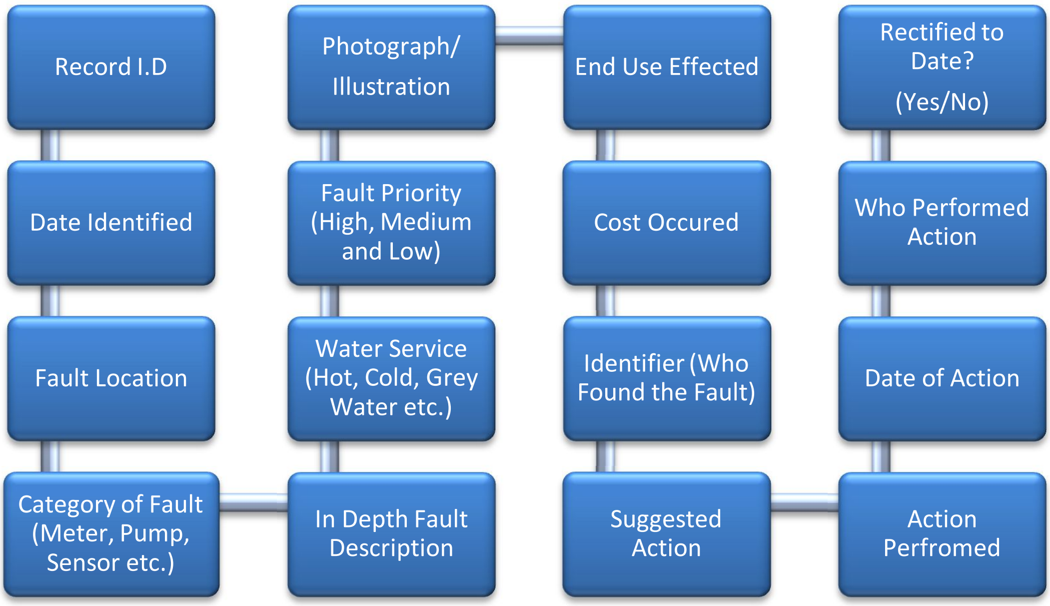


Figure 2. Suggested columns to be used when defining faults found in a building's water network.

3.2 Planning of FDD development

Once the above assessment is completed, the type of and extent to which FDD should be applied to the system can be decided. The assessment will also reveal to what extent new sensor or metering equipment is required.

*3.2.1 Factors effecting type and level of FDD to be chosen*

The factors influencing the type of FDD to be implemented are;

1. Priority of improving water system
2. Resources

Rule based is the simplest form of FDD available and the most straightforward to implement following the assessment stage. At the very minimum, the faults that were found in the assessment stage should be rectified and rules should be put in place so that these same faults do not reoccur. As an added venture, which will take more time, the systems which interact with and which are affected by the water network should be analysed and rules should be developed. These additional developed rules will impede the chance of certain faults in the future. Solar panel system, calorifiers, rain water harvesting systems, pumps header tanks etc. should be investigated in terms of their inputs and outputs and rules should be created. In light of this, rule based FDD should be implemented if the priority of improving the water system is only to ensure that its associated systems are operating effectively so that their potential/payback period can be achieved. Depending on resources, from limited to extensive, rules relating to only the faults found or potential future faults in the systems should be developed respectively.

Data driven FDD is incrementally more complex than rule based FDD. Statistical models of the water network's operation need to be developed with the aid of metering and data acquisition. As many buildings do not have extensive (or any) metering retrofitting of meters in strategic places of the water network will likely be necessary. Incorporating data driven FDD ensures that the quantities of water used in different locations of the network can be *measured* and therefore *managed*. If the priority of the project is to lower water use to achieve lower water costs or to work towards low water usage accreditation then model based FDD may be preferred. The amount of meters depends on the project's budget, while the priority and placement of the meters should be influenced by the stakeholder's KPI's. For example, if a stakeholder makes it clear that a reduction of water used in a canteen cleaning area is an essential deliverable from the project, then an associated KPI of (e.g. Litres/unit cleaned or floor area cleaned) should be created and the water supply into the canteen cleaning area should be metered. With the area metered, statistics relating to the KPI can be developed and measures can be taken to reduce the water use in this area. It should be noted that implementing, for example, rule based FDD on a particular system in the building does not preclude the use of data based FDD elsewhere within the building.

*3.2.2 Metering Implementation planning*

If additional metering is planned a decision on meter type is required. The common trade-off between intrusive turbine and non-intrusive ultrasonic water meters is that the intrusive type tends to be cheaper to buy but more expensive and disruptive to install, while non-intrusive meters are more expensive but much easier to install as a retrofit. A building with low funds but periods of dormancy throughout the year may opt for the intrusive type, while a building with ample funding but a need for water supply all year round would be more likely to choose the non-intrusive ultrasonic type. Communication then needs to be resolved. Where and how the water meter reports to an accessible database, is a crucial part of installing meters. Data acquisition should be uninterrupted so that the best data can be ascertained for the generation of best models. Specific building procedure for the installation of meters and additional hard ware needs to be adhered to. Building managers may require Risk assessments and operating procedures relating to the installation and operation of the flow metering device. Finally, the meters must be installed by trained professionals to ensure satisfactory readings from the devices.

*3.2.3 Smart metering*

Retrofitting meters, whether intrusive or non-intrusive has an associated cost and/or disruption factor. For this reason, the least amount of meters that allow access to most amount of information is desirable. A way of achieving this is through strategically placed "Smart Meters". The basic premise of a Smart Meter is that it can identify and measure specific water users downstream, in different pipes, based on its flow signature

In this theoretical set-up one pipe off a main water pipe supplies water to shower, a hand wash basin and a laboratory in the next room. Usually, to monitor the flow of different end users, separate meters would need to be installed. With a Smart Meter however, one meter can be placed before different end users diverge and can be used to replace the meters that would have needed to be installed otherwise (marked with an x).

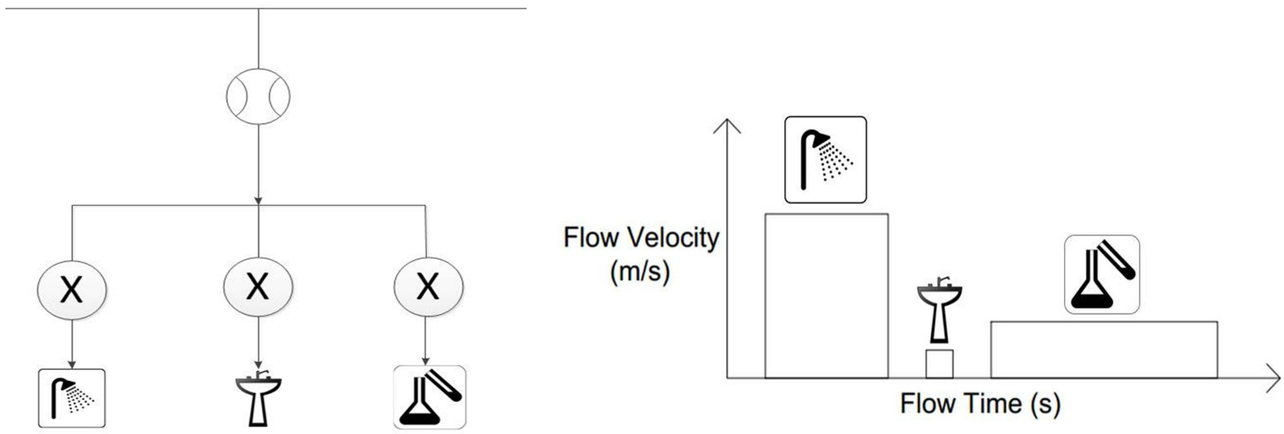


Figure 3. Theoretical set up and data retrieved from a Smart Meter

The smart meter can differentiate the end users based on their characteristic flow velocity and flow time. It is intuitive that a shower will have a higher flow rate and will be used for much longer than hand wash basin for example. In this way, they can be identified from the same meter data set. Other uses such as lab experiments can be characterised by low velocity but long flow time as also shown in figure 3.

**4. Case Studies**

4.1 Public and Mixed Use Buildings

The *Waternomics* project comprises two pilot buildings in Ireland, both located in Galway (a city with a population of about 70,000 on the west coast of Ireland). The buildings are (i) the New Engineering Building at the National University of Ireland, Galway (NUI Galway) and (ii) an Irish speaking secondary school (students range in age from 12 – 18) Coláiste na Coiribe which is currently under construction and is due to open in September 2015.

The NUI Galway engineering building houses about 1,100 undergraduate and postgraduate students and about 100 staff during teaching term and about 100 staff and 100 postgraduates during the rest of the year. The building includes lecture halls, classrooms, offices, laboratory facilities, a café, and shower and toilet facilities spread across 14,000 $m^2$ of floor space on four storeys. Thus it has a variety of end-uses for water and significant variation in how water is used. The building is managed through a Building Management System (BMS) that collects data on building performance and operational efficiency – including 11 water meters. Some of the key water users include showers and hand wash basins, grey water from a rainwater harvesting system for toilets and urinals and potable water for the water fountains and café. Currently, NUI Galway is subject to a flat water tariff of €2.45/$m^3$; € 1.19/$m^3$ for water supply and €1.26/$m^3$ wastewater charge. Given its primary function as an educational and research building there are significant opportunities to engage educators, students and researchers in this project. The pilot offers significant challenges in terms of fault detection and an underlying need to reduce operating costs. Figure 4 shows the NUI Galway Engineering Building

Figure 4. National University of Ireland (Galway) Engineering Building, Ireland.

Coláiste na Coiribe is an Irish language secondary school and currently has about 350 students and 25 teaching and administrative staff. Due to expansion, space pressures and the need for updated facilities a new 7400 $m^2$ school is currently under construction. This new building will comprise classrooms, offices, sports halls and associated toilet and shower facilities. As the school is in the early stages of construction it presents a unique opportunity for *Waternomics* to engage with the designers and contractors at an early stage and monitor this new building from commissioning stage. It is proposed this pilot will engage students at an early age in the importance of water conservation. Furthermore these students can test and give feedback to the project on how the *Waternomics* platform functions in communicating complex water-related data (e.g. FDD) to a wider audience. The school management also face key budgetary and conservation targets and the pilot inform future design of similar buildings with particular focus on water conservation measures and rainwater harvesting systems.

4.2 Corporate Operator

The large scale commercial pilot site is Milan Linate Airport. It is the oldest of the three experimental building groups, with the original airport constructed in the 1930's before it was completely rebuilt in the 1950s and then again in the 1980s. The airport provides a unique opportunity given the varied nature of water use on site (from washing activities, toilets, restaurants, irrigation etc.) and its role as a large-scale consumer. As well as this, it is also an older building with varying stages of construction and retrofitting which is much like the rest of the airports and some buildings in Europe today. 38% of residential buildings in Europe were built before 1960 (Nolte & Strong, 2011), and so the techniques develop to deal with older pipes and systems will be invalid to creating a *Waternomics* platform which is applicable to as many buildings as possible across the continent.

4.3 Domestic Users

Thermi Municipality is located in the south-eastern part of the prefecture of Thessaloniki in Greece. The domestic site is important for the project as it provides an opportunity to ascertain a baseline for residential water use in a country which does not require residential water metering and to realise remote data collection for households.

**5. NUIG Pilot Progress**

5.1 Assessment of Building Water Network

5.1.1 *Examination of existing material relating to the water network*

To commence the investigation of the NUIG pilot, previous studies/work carried out to the building's water network were searched for and studied. There was one previous study carried out on the building's water network, which related predominantly to the rainwater harvesting system (Bunau & Clancy, 2012). The study gave vital information on the rainwater harvesting system, a very general layout of the water network and macroscopic estimates of how the water is used in its constituent elements i.e. Cold Water supply (CWS), Mains Water Supply MWS and Rain Water Supply (RWS). Other information such as the location of a meter proved to be false however, and so previous studies should be treated sceptically.

The as built mechanical drawings of the building were then examined and cross checked by locating the physical pipes in their respective locations. This allowed for a thorough understanding of the water system, how services such as the rainwater harvesting system and the boiler worked and where pipes diverged, converged and terminated. Similarly to the case study, the as built drawings did contain errors and so all drawings should be taken as a tool to comprehend systems and are not necessarily a replica of the building. A useful product of studying the as built drawings was a simplified schematic of the water system. The as built drawings are too detailed to present to every stakeholder in the project and so a simplified schematic is useful when describing plans and difficulties to someone not familiar with the water network in the building. A schematic produced can be seen in figure 5. This contains information such as where existing meters are located, potential locations for new meters, the different water pipes and what percentage of water relative to the global use in the building, is used in selected pipes.

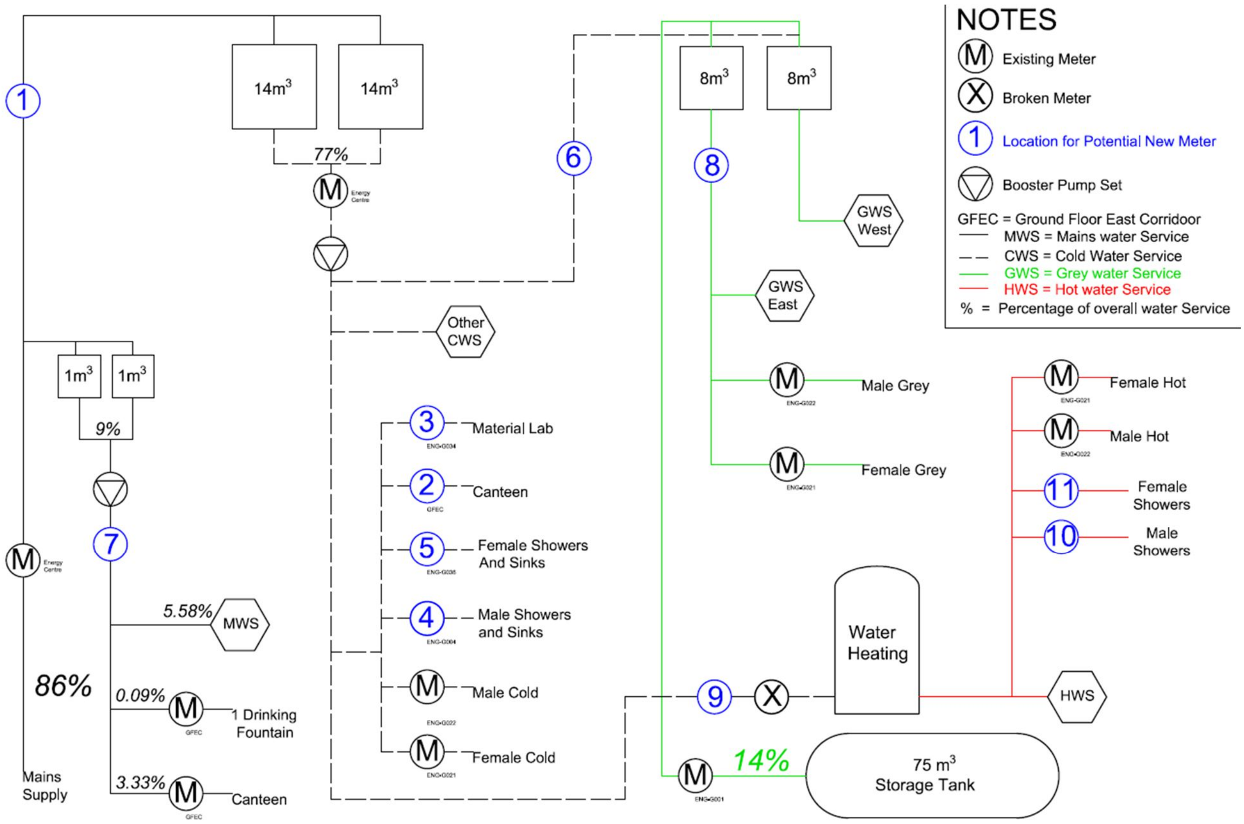


Figure 5. Example of a simplified water network schematic.

5.1.2 *Creating a Building Water Balance Graphic*

Comprehending the quantities of water used for each end user for a large building such as the NUIG pilot is overwhelming. An effective visual which shows the main water services in the building and their end users is a Sankey flow diagram, whereby the width of an arrow is proportional to the flow quantity. An example of a Sankey diagram developed to date can be seen in figure 6. The inputs i.e. MWS, CWS and GWS are known from existing metering, while many of the end users are estimated.

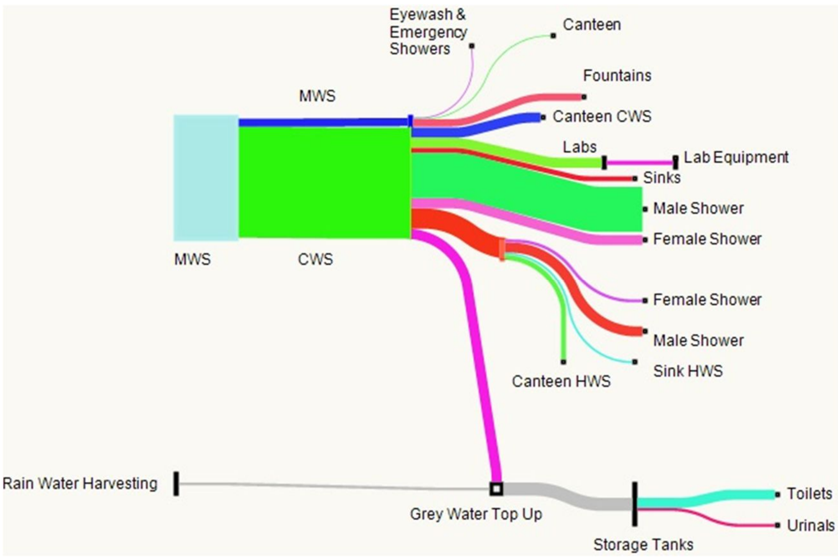


Figure 6. Example of a Sankey Diagram developed.

5.1.3 *Stakeholder Engagement*

There were two stakeholders formally interviewed for the development of FDD in the University Building pilot. These were the Building Services Manager (BSM) and the Chief Technical Officer (CTO). The overriding question that each of the stakeholders were asked was "What determines success for you in this pilot for you?" Both had quite distinct priorities relating to the management of water within the building, with the BSM being more focused on conservation and meeting budgetary requirements and the CTO having more of an interest in the water quality from the building network. Going forward, with the priorities of the stakeholders understood both conservation and quality of water will be emphasised.

5.1.4 *Recording all Faults Encountered*
There have been 8 faults detected in the building to date. They have been recorded in a table with the columns of figure 2, which has allowed for straightforward characterisation of each fault. They have been reported to the University buildings office for rectification and FDD codes will be developed in the DO phase of the project so as to ensure that they do not occur in the future.

5.2 Planning of FDD development

5.2.1 *FDD type and level chosen*

With this being a research project, it has been decided that all types of FDD will be applied to the Engineering building pilot. This is so that the most amount of faults can be found and the most insight can be gained into the building water network. With the experience of developing an FDD platform with all of the FDD types, *Waternomics* will be able to suggest the best types of FDD for different circumstances and cases.

5.2.2 *Meter implementation planning*

Traditional intrusive turbine meters were rejected for consideration in the project as they would involve considerable work and inconvenience to install. The “UFM-TM/TS VTEC Ultrasonic Flow Meter” which uses ultrasonic transducers to gauge the flow in a pipe was chosen instead. Although this is much easier to install on to a pipe, it requires a power source and a way of connecting to the internet so as to transmit data to a database, which are already in place in certain locations but need to be installed in others. Another potential difficulty in installing non-intrusive ultrasonic flow meters is that they require a certain length of pipe upstream and downstream of the location where the transducers are to be placed. Unlike the power and network connection nuisance, sometimes the pipe length problem cannot be overcome.

5.2.3 *Smart Metering*

To date, one additional meter has been installed which is in its infancy of data production as of this writing. It is placed on a CWS pipe and is expected to identify different flow signatures, such as when showers, hand basins and leaks are in flow, based on what the velocity is and for how long it flows for.

## 6. Conclusion and Discussion

There are considerable efforts underway in many sectors to ensure water consumption is minimised. In the building sector which accounts for 21% of all water consumed in the EU, there is considerable scope to improve the state of water consumption across the continent by improving methods of managing water in buildings alone. In this context significant attention is being focused on the use of ICT to facilitate water efficiency and behavioural change. *Waternomics* aims to provide personalized and actionable information on water consumption and water availability to individual households, companies and cities in an intuitive and effective manner at relevant time scales for decision making. A novel aspect of *Waternomics* is to apply fault detection and diagnostics to building water networks to identify and rectify leaks, malfunctioning equipment, inefficient operation and other water related problems. A notable and successful application of fault detection and diagnosis is in heating ventilation and air conditioning (HVAC) systems. HVAC’s and building water networks are analogous in many ways and thus can provide the basis for the application of FDD in the water sector. However, there has been limited, if any literature to date on the development and application of FDD in water networks in buildings.

This paper presents a methodology that informs the development of automated FDD platforms for buildings. The methodology described utilises concepts from the energy sector to systematically create a standard based methodology so that an FDD system can be implemented in a wide range of buildings to aid in the conservation of water. Using the basic steps of IS0 50001 and 50002 the methodology facilitates the crucial first step of developing a FDD platform; notably “Assess”, “Plan” and “Do”. The methodology was piloted and refined using a pilot building (the Engineering Building at the National University of Ireland, Galway). It was found that while it may be necessary to spend considerable time on the “Assess” and “Plan” steps (notably to identify existing pipework and installed meters, sensors and equipment) the application of the methodology can significantly reduce effort at a later stage and optimise the performance of FDD when applied to a building.
The resulting automated FDD platform, developed as a result of the above methodology, will initially be applied to the NUI Galway pilot site. This pilot will form the basis for the application of FDD to a number of other pilot sites in Europe to create a versatile, robust and adaptable FDD system to mitigate the effects of malfunctions and leaks within building water networks.

## REFERENCES

Barker, S., Rast, W., Huber, M., Alder, J., Chilton, J., Gaddis, E., … Wagner, G. (2007). *Water Main messages*.
Berton, A., & Hodouin, D. (2003). Linear and bilinear fault detection and diagnosis based on mass and energy balance equations. *Control Engineering Practice*, *11*(1), 103–113. doi:10.1016/S0967-0661(02)00116-8
Blesa, J., Puig, V., & Bolea, Y. (2010). Fault detection using interval LPV models in an open-flow canal. *Control Engineering Practice*, *18*(5), 460–470. doi:10.1016/j.conengprac.2010.01.002

Blesa, J., Puig, V., Saludes, J., & Vento, J. (2010). Leak Detection , Isolation and Estimation in Pressurized Water Pipe Networks using LPV Models and Zonotopes, (1999), 36–41.
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*(2), 335–351. doi:10.1007/s12053-013-9238-2
Bunau, R. Von, & Clancy, N. (2012). *Bachelor of Science ( Project & Construction Management ) Final Year Project Water use and re-use in the New Engineering Building By : Kevin Carney Supervisor : Dr . Eoghan Clifford*. NUI Galway.
Cataldo, a., Persico, R., Leucci, G., De Benedetto, E., Cannazza, G., Matera, L., & De Giorgi, L. (2014). Time domain reflectometry, ground penetrating radar and electrical resistivity tomography: A comparative analysis of alternative approaches for leak detection in underground pipes. *NDT & E International*, *62*, 14–28. doi:10.1016/j.ndteint.2013.10.007
DOE(U.S.). (2014). *The Water-Energy Nexus: Challenges and Opportunities*.
E.C. (2012). *Water Performance of Buildings*. Retrieved from http://ec.europa.eu/environment/water/quantity/pdf/BIO_WaterPerformanceBuildings.pdf
EC. (2013). Focus on reducing urban water leakage. Retrieved from http://cordis.europa.eu/news/rcn/36134_en.html
EC. (2014). European Innovation Partnership on Water - Environment - European Commission. Retrieved January 15, 2015, from http://ec.europa.eu/environment/water/innovationpartnership/nexus.htm
Eliades, D. G., Member, S., & Polycarpou, M. M. (2010). A Fault Diagnosis and Security Framework for Water Systems. *IEEE Transactions on Control Systems Technology*, *18*(6), 1254–1265.
Fahmy, M., Asce, M., Moselhi, O., Eng, P., & Asce, F. (2009). Detecting and locating leaks in Underground Water Mains Using Thermography. *26th International Symposium on Automation and Robotics in Construction*, (Isarc), 61–67.
Hunaidi, O., & Wang, A. (2006). A New system for locating leaks in urban water distribution pipes. *International Journal of Management of Environmental Quality*, *17*(January), 450–466.
IEA. (2002). *Computer Aided Evaluation of HVAC System Performance*.
ifu Hamburg GmbH. (2015). E-Sankey Software. Retrieved January 31, 2015, from http://www.e-sankey.com/en/
Izquierdo, J. (2007). Fault detection in water supply systems using hybrid ( theory and data-driven ) modelling, *46*, 341–350. doi:10.1016/j.mcm.2006.11.013
Lanigan, P. E., Kavulya, S., Narasimhan, P., Fuhrman, T. E., & Salman, M. a. (2011). Diagnosis in Automotive Systems: A Survey. *Current*. Retrieved from http://www.pdl.cs.cmu.edu/PDL-FTP/ProblemDiagnosis/CMU-PDL-11-110.pdf
Li, S., & Wen, J. (2014). A model-based fault detection and diagnostic methodology based on PCA method and wavelet transform. *Energy and Buildings*, *68*, 63–71. doi:10.1016/j.enbuild.2013.08.044
Lo, C. H., Chan, P. T., Wong, Y. K., Rad, a. B., & Cheung, K. L. (2007). Fuzzy-genetic algorithm for automatic fault detection in HVAC systems. *Applied Soft Computing*, *7*(2), 554–560. doi:10.1016/j.asoc.2006.06.003
McKinsey. (2009). *Charting Our Water Future*.
Meade, R. (2013). *Living Within Our Means, Water And Resource Efficiency In The EU*.
Nolte, I., & Strong, D. (2011). *Europes Buildings Under The Microscope*.
Pérez, R., Puig, V., Pascual, J., Quevedo, J., Landeros, E., & Peralta, A. (2011). Methodology for leakage isolation using pressure sensitivity analysis in water distribution networks. *Control Engineering Practice*, *19*(10), 1157–1167. doi:10.1016/j.conengprac.2011.06.004
Quevedo, J., Chen, H., Cugueró, M. À., Tino, P., Puig, V., García, D., … Yao, X. (2014). Combining learning in model space fault diagnosis with data validation/reconstruction: Application to the Barcelona water network. *Engineering Applications of Artificial Intelligence*, *30*, 18–29. doi:10.1016/j.engappai.2014.01.008
Ragot, J., & Maquin, D. (2006). Fault measurement detection in an urban water supply network. *Journal of Process Control*, *16*(9), 887–902. doi:10.1016/j.jprocont.2006.06.005
Schein, J., & Bushby, S. T. (2006). A Hierarchical Rule-Based Fault Detection and Diagnostic Method for HVAC Systems, *12*(1), 111–126.
Sobhani-Tehrani, E., & Khorasani, K. (2009). Fault diagnosis of nonlinear systems using a hybrid approach. *Lecture Notes in Control and Information Sciences*, *383*, 1–266. doi:10.1007/978-0-387-92907-1_1
Suwatthikul, J. (2004). Fault detection and diagnosis for in-vehicle networks, 283–307.
Variotec. (2014). VARIOTEC ® 460 Tracergas. Retrieved from http://www.sewerin.com/cms/fileadmin/redakteure/Prospekte/pro_vt460_tracergas_en.pdf
Wang, H., Chen, Y., Chan, C. W. H., & Qin, J. (2012). An online fault diagnosis tool of VAV terminals for building management and control systems. *Automation in Construction*, *22*, 203–211. doi:10.1016/j.autcon.2011.06.018
Wang, S., & Jiang, Z. (2004). Valve fault detection and diagnosis based on CMAC neural networks. *Energy and Buildings*, *36*(December 2003), 599–610. doi:10.1016/j.enbuild.2004.01.037
Zhu, Y., Jin, X., & Du, Z. (2012). Fault diagnosis for sensors in air handling unit based on neural network pre-processed by wavelet and fractal. *Energy and Buildings*, *44*, 7–16. doi:10.1016/j.enbuild.2011.09.043