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Water conservation with novel application of fault detection diagnostics (FDD) applied to a rain water harvesting system in Ireland

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Abstract

Waternomics is an innovative project aimed at improving water management within municipalities, corporations and domestic users by providing water managers and consumers with timely and actionable information relating to water usage, water availability and the state of systems within a building's water network infrastructure. A novel aspect of *Waternomics* is to apply Fault Detection and Diagnostics (FDD) methods and techniques to building water networks in order to identify potential operational issues including leaks, malfunctioning equipment and inefficient operation. FDD is a measurement science which has traditionally been used to identify and rectify faults in Heating Ventilation and Air-Conditioning (HVAC) systems in buildings. The results have been reduced maintenance costs, increased efficiency and energy savings of between 10 and 30% in the HVAC industry. To date, these FDD methods and tools have not been applied systematically to water infrastructure in buildings and thus it could provide the basis for significant innovation in managing water infrastructure. This paper outlines how a water wasting fault was found in a Rainwater Harvesting System (RWHS) within an engineering building at the National University of Ireland, Galway (NUIG) and how a concept FDD methodology may be applied to the RWHS to prevent such faults and water waste occurring in the future.

Keywords: fault detection; building water networks; water metering; rain water harvesting; water conservation

1. Introduction

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

Climate change, increasing urbanization and populations are some of the factors driving global challenges for water management. 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 will be subjected to water stress (Barker et al., 2007). 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).

Water prices are often estimated to be too low compared to the actual value of water. As well as this, water is usually considered to have low price elasticity (E.C, 2012), thus demand has limited impact on cost. This has led to a fundamental ignorance by the general public as to the urgent need in water conservation. The result is that our water infrastructure, business models, and behaviours at all levels of the water value chain reflect this fact.

It is estimated that buildings use 21% of all water in the EU. With an estimated 20 to 30% of this wasted or leaked (E.C, 2012), there is considerable scope to improve the state of water consumption across Europe by improving methods of managing water in buildings alone. In this context *Waternomics* will develop new Information and Communications Technology (ICT) as enabling solutions for stakeholders to more efficiently manage water resources in buildings. 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.

1.2 Fault Detection and Diagnosis (FDD)

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 (Suwatthikul, 2004). With increased integration comes increased complexity and a higher possibility of faults. On-board diagnostic systems have been developed to cope with faults 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 embedded algorithms to identify and counteract defects/malfunctions. 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. FDD technology platforms needed to ensure that building water systems work efficiently are absent however.

The reasons behind faults in water networks can include: reliance on unsuitable equipment, equipment malfunction, pipe blockages, leaks, contaminants, behavioural issues, and procedural errors. Detecting faults at the earliest possible stage could thus lead to more efficient maintenance, repair processes and savings well beyond those associated with water savings alone 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.

1.3 FDD Rainwater Harvesting Case Study

Rainwater Harvesting is an additional service becoming increasingly available within buildings. These systems are gaining increased popularity in both the residential and commercial sector due to end-user desire to reduce water tariffs, their capacity to reduce water stress and an increasing onus on public and private bodies to enhance the sustainability and security of their water supplies. The basic and most common implementations of RWHS' are those which supply 'non-potable' water to a building. This is water which is not fit for human consumption or bathing, but can be used for toilet flushing and irrigation. Additional filtration systems can be incorporated in conjunction with a RWHS to upgrade the status of the water to 'potable' and thus allow it to be used for human consumption; however this technology is not commonly used due to its high cost.

RWHS' have significant potential in many countries; particularly those with relatively consistent rainfall. For example, in Ireland, RWHS' without additional filtration systems (supplying only non-potable water) have the potential to save 55% of publically supplied-water in buildings (Z. Li, Boyle, & Reynolds, 2010). This makes RWHS's a very attractive option for saving water and improving environmental conditions combined.

This paper presents a new concept FDD methodology which may serve to reduce the downtime of RWHS' if a fault manifests itself within the system. The decision to apply FDD to a RWHS instead of other water systems was because a significant fault, wasting 15% of the total buildings water usage, was found in a RWHS within an engineering building at the National University of Ireland, Galway (NUIG). This made for an excellent starting point in reducing the aforementioned 20-30% water waste in European buildings.

A thorough literature review has not revealed any previous implementation of FDD in this context. Therefore, this study demonstrates, for the first time as far as the authors are aware, the use of FDD concepts and tools in this context and thus opens the door to the development and deployment of FDD to water systems in buildings.

2 Literature Review

2.1 Introduction

FDD has seen rapid development in its deployment to Heating, Ventilation and Air Conditioning (HVAC) installations in recent years due to increased energy efficiency concerns. However, to date its application in the water sector has been extremely limited. HVAC systems however, can provide the basis of and key lessons for the development of FDD methodologies for the water sector.

2.2 Fault Detection and Diagnosis (FDD)

A fault is a malfunction of a system component, which ultimately leads to a failure or degradation 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 point in time. The desired attributes of an FDD system include the following (Sobhani-Tehrani & Khorasani, 2009):

- <u>Early Detection and Diagnosis:</u> The longer that a fault persists, the greater the accumulative effect of the associated inefficiency's. More importantly, the more time that a systems fault 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. Timely identification and rectification is necessary.

- Fault Segregation: This is the ability of an FDD system to zone in on the offending component and to distinguish the faulty part from others. Ambiguous fault reports lead to chaotic maintenance procedures.
- 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 in Table 1, are listed relative to their increasing complexity (Bruton, Raftery, Kennedy, Keane, & O'Sullivan, 2013):

Table 1: Commonly implemented FDD methodologies

FDD Classification	Description	HVAC Examples
Rule Based FDD	• This method utilises elementary logic applied to a system to decide whether it is operating as designed or not. • Basic, binary on-off principles provide an 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. • It is the most basic form of FDD and will be utilized first in most systems due to the high savings/resource investment ratio.	Fuzzy Logic (Lo, Chan, Wong, Rad, & Cheung, 2007) APAR Rules (Bruton et al., 2014)
Data Driven FDD	• 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.	Artificial Neural Networks (Zhu, Jin, & Du, 2012) Principal Component Analysis (S. Li & Wen, 2014) Wavelet Analysis (Wang, Chen, Chan, & Qin, 2012)
Law Driven FDD	• 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.	Reduced Order Models (Berton & Hodouin, 2003) Feedforward (Salsbury & Diamond, 2001)

2.3 FDD in HVAC systems

Due to technology advances and a higher emphasis on system capabilities, HVAC metrics, 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 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. (Bruton, Coakley, Donovan, & Keane, 2013)

Water systems buildings (similarly to HVAC systems) 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. HVAC and water network systems are also similar due to the fact that they both service people in buildings, can be measured and managed from Building Management Systems (BMS'), have high operational performance requirements and can be prone to faults (which may go unnoticed for extended periods of time) which impair their efficiency. To date however, there have been limited attempts to apply FDD techniques to water network systems in buildings.

2.4 FDD in Water distribution Systems and Building Water Networks

To date the main focus of FDD in water systems has been on the detection and avoidance of leaks in water networks upstream of buildings i.e. in larger distribution networks that do not interact with the industrial, domestic and public end users of water. These industrial, domestic or public end users of water are exactly what the *Waternomics* project is concerned with.

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 both 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 frameworks due to the threats and consequences of water supply terrorism (Eliades, & Polycarpou, 2010). In summary, considerable attempts have been made to incorporate FDD in larger water distribution systems. This is in contrast to how FDD has been utilised in end user buildings.

In buildings and industrial facilities there is some use of once off services to detect and rectify leaks, but no established FDD protocols similar to those in HVAC or bigger water distribution systems as discussed above. Remote wave detection, acoustics, tracer gas and thermography are all aforementioned once off 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 methods use small molecule gases such as hydrogen and nitrogen in conjunction with gas detectors to locate where the gas and water is seeping through a pipe. Thermography (IR) camera methods measure and image the emitted infrared radiation from an object and thus detect thermal contrasts on surfaces due to water leaks. It can enable relatively large areas to be investigated efficiently but is not applicable in locations that experience harsh weather conditions as high pavement temperatures and snow coverage can compromise its effectiveness (Fahmy, Asce, Moselhi, Eng, & Asce, 2009).

Such techniques however are *reactive* and not *pro-active* in identifying and rectifying water leaks. These systems will only be called into action once an increase in water bills is noticed or if unusual vegetation starts to grow above water pipes. This results in a 'too little, too late' solution to faults and leaks in building water networks. Thus the development of methodologies that support platforms capable of detecting faults at the earliest possible stage to counteract the 25-30% water loss in buildings is both novel and timely.

2.5 Rainwater Harvesting systems and potential FDD

With RWHS being heavily dependent on the rainfall available to a region, the first concern is whether a RWHS is possible in an area or not. It has shown to be a viable solution in offsetting the cost and usage of treated mains water for non-potable services such as toilet flushing and clothes washing in most regions of the world including Europe, America, South America, Australia and Asia (Cheng, 2003; Eroksuz & Rahman, 2010; Ghisi, Bressan, & Martini, 2007; Z. Li et al., 2010; Thomas, Kirisits, Lye, & Kinney, 2014) with Africa being the only continent which struggles to implement the systems easily due to the lack of water related legislations, finances and the absence of governmental bodies that coordinate (Mwenge Kahinda & Taigbenu, 2011). The second most important aspect of rainwater harvesting is storage tank sizing, with the storage tank being the most expensive component of the system. An thorough analysis of tank sizing and cost benefit analysis is provided for a residential home in Portugal (Silva, Sousa, & Carvalho, 2007).

A void that remains in the field of RWHS research is to develop parallel working systems that are robust, resilient and proofed against faults. As will be shown in this paper, RWHS' may be prone to faults which could go unnoticed for an extended period of time (~6 months) which hinders their payback period, ecological benefit and adds to the 20-30% water wastage in European buildings.

3 Methodology

3.1 Previous Study

The formulation of the FDD methodology presented within this section was developed as a result of a fault found in a RWHS within the National University of Ireland, Galway (NUIG) engineering building. This fault was found by implementing an approach to low level fault identification developed by the *Waternomics* project.

The low level fault identification methodology was created by adapting existing energy management standards (namely ISO 50001, 50002 and 14046) Figure 1. The reason for adapting this standard based methodology is because of the need to create as much literature and procedures in the field of water management 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.

A full description of the low level fault identification methodology can be found in (Chambers, Mccaffrey, & Curry, 2015).

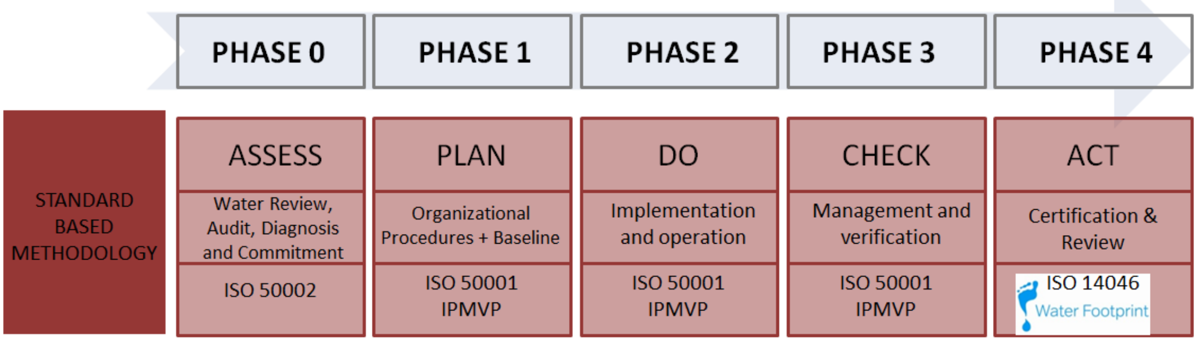

Figure 1: Standards based approach adopted by the Waternomics project.

3.2 FDD Methodology Selection

Table 1 presents the triad of approaches to FDD, namely Rule Based, Data Driven and Law Driven FDD. The identification of the most appropriate FDD type, or combination of types, was necessary before the concept FDD tool could be created.

The RWHS in the NUI Galway engineering building is a relatively simple system, in comparison to other machines which utilise FDD such Air Handling Units and automotives. It has limited moving parts, has a set delivery speed, does not deliver a varying temperature fluid and its overall operations are based on simple signals from one main controller panel. For these reasons, it is not necessary to apply the laws of thermodynamics and Newtonian equations, for example, to predict the operation of the system as in the case of law driven FDD. As a result of this, a law driven approach would be overly complex for the present system.

As outlined in Table 1, Rule base FDD is the most basic form of FDD, with basic on-off principles providing the basis for the rules. This compliments the relatively simple operation of a RWHS and will form the foundation of the FDD methodology developed herein.

In conjunction with Rule based FDD, Data Driven FDD will also be incorporated. This is due to the statistical nature of some of the associated RWHS signals that are required to characterise the operation of the RWHS at any one time. An important example of this is the rainfall data, which provides information on the availability of water for the system. Models and thresholds will be developed to indicate whether the rainfall quantity over a particular period of time is sufficient to allow the system to operate. Additional sensors may also be required in future to better inform the FDD tool.

In summary, a synthesis of Rule Based and Data Driven FDD will be utilised to create the concept FDD tool. Law Driven FDD will be over looked due to its excessive complexity.

3.3 Approach to FDD Development

The motivating assumption that this methodology proceeds under is that; In a mechanical system controlled from a programmed control board such as a RWHS, a malfunction of the system as a whole must be the result of one or more elemental components failing in the system. With all of the possible basic faults that could occur in the system identified, signals and readings from the system can be utilised to identify the offending basic broken component. This will then direct the repair work that needs to be completed to restore the system to its optimal running state.

The significance of the methodology development is that it is transferring *intermittent expert judgement* relating to the RWHS to a *continuous automated process*. Instead of irregular checks on a RWHS from maintenance personnel who might not necessarily be fully informed about the system, this methodology integrates all of the known knowledge relating to the optimal operation of the RWHS and provides continuous auditing to ensure minimal downtime between faults in a way that manual inspection can't.

An example of the transfer of expert judgment to a programmed automated process would be the following:

- **Irregular site audit by maintenance personnel:** Assuming that all signals are working properly, if the weather station on the roof of the engineering building indicates that there is enough rainfall to fill up the storage tank to capacity and the Pressure Indicator in the underground storage tank indicates that the tank is completely empty then there could be a blockage in the pipe which delivers water from the roof of the engineering building to the underground storage tank
- **Continuous automated process inspection:**

IF Rainfalll > X mm/week
And Storage tank Pressure < X N/mm^2
Then Inspect pipe for blockages

To apply this methodology to the whole system and thus develop a robust FDD algorithm that can detect (within reason) any fault that may occur in the structure, possible component faults and potential signals available from the RWHS need to be identified. The signals will then be queried by an FDD algorithm for set tolerances and a combination of results from these queries will provide the best possible recommendation towards identifying the offending fault.

3.4 Fault Tree Analysis Diagram

Basic component faults were identified using Fault Tree Analysis (FTA) techniques. FTA is a top down, deductive failure analysis in which an undesired state of a system is analysed using Boolean logic to combine a series of lower-level events. This analysis method is mainly used in the fields of safety and reliability engineering in understanding how systems can fail and to identify the best ways to reduce risk. With this being a "top down" analysis, a fault tree can be developed by considering each of the components within the system and understanding how components might fail. An example of an FTA relating to the RWHS can be seen in Figure 2.

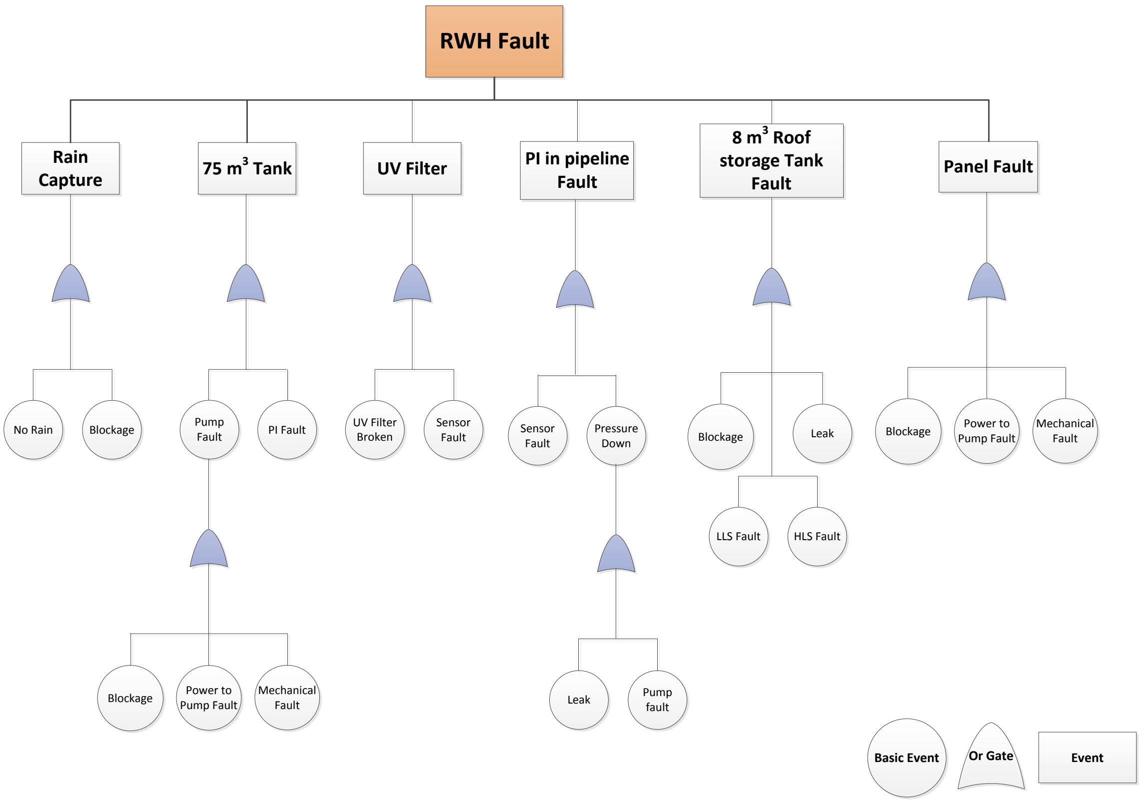

Figure 2: FTA of the RWHS in the NUIG engineering building.

3.5 System Inputs and Outputs

The input and output signals of the RWHS are what provide information about the system, to the FDD algorithm. By understanding the basics of the system's normal operating states, conditions relating to the RWHS signals can be queried on their own and in conjunction with each other so that a particular fault can be identified and later rectified. Therefore, to facilitate detection and diagnosis of the basic fault event in the system, the available input and output signals of the set-up must be known and understood.

A list of input and output signals for the RWHS can be seen in Table 2. The underlined text in Table 2 indicates that the signals are not available at present, but are deemed to be potentially useful in fault finding for this project and could be ascertained at a later time.

Table 2: Available and potential signals relating to the NUI Galway RWHS

No.	Signal
1	*Rainfall Data*
2	Pressure Readings from the 75 m^3 Storage Tank
3	*Power Signal from Pump*
4	UV Filter Sensor
5	Pressure in Pipe between Underground and Roof Storage Tanks
6	Grey Water top-up meter
7	High/Low Level sensors in the 8 m^3 Header Tanks

3.6 FDD Conditions

The signals of Table 2, in conjunction with knowledge of the system's operating states and its associated working thresholds; such as average rainfall at a time of year and total day to day water usage, can be used to identify faults. These conditions are outlined in Table 3. The underlined text represents generic thresholds for the normal operation of the RWHS which vary for time of year, day of the week etc.

Table 3: NUI Galway RWHS Signal conditions

No.	RWHS Conditions
1	Rainfall > *X mm/week*
2	Pressure Indicator in 75 m^3 Tank Specifies > *X* m^3
3	Power to Pump Operational
4	UV Senor Reads Working
5	Pressure In Pipeline > *X* N/mm^2
6	Grey Water meter > *X* m^3*/week*

3.7 FDD Rules

The FDD ruleset presented applies IF/THEN logic to the signal conditions of Table 3. For each rule, the algorithm queries whether each condition is true, false or irrelevant at a particular time.

One principle must be understood as context for understanding the FDD rule set:

Sequential Principle: The RWHS presented, is for the most part, made of components working *in series* with each other. Unlike a HVAC system which relies on chiller and boiler sections working in parallel, most of the RWHS elements rely on the preceding components to operate functionally. In light of this, the fundamental methodology consists of a general sequential principle, meaning that:

1. Rule queries will proceed from the origin of the system through the successive components until its end periphery.

Fundamentally, this means that the FDD algorithm will begin its queries at the start of the RHWS of Figure 3, from the Rain water capture through the individual components to the header tanks. An assumption that derives from this linearity principle is that each fault query will assume that the rules preceding them have been passed. This is the main reason for the irrelevant conditions seen in Table 4.

An example of how to read the table will now be given for Rule 3, Pump Blockage/Mechanical Fault:

- Signal conditions 1 and 2 are irrelevant. According to the sequential principle, if the pump is being queried, then the rules preceding it must have passed their queries i.e. it was found that there was enough rain and that there were no blockage in the pipe between the roof and the storage tank.
- Signal conditions 3 and 4 are deemed true. At the particular time when the system is being queried, the power to the pump and the UV sensor were found to be operational.
- Signal conditions 5 and 6 are deemed false. At the particular time when the system is being queried, the pressure in the pipeline and the grey water that is passed through the meter are both below a set threshold.

If this combination of results to the rule queries is realised, then it can be said that the fault is most likely a Pump blockage/mechanical fault.

Table 4 : Outline of RWHS FDD Rules

Table 3. Outline of FDD Rules							
Rule No.	**Rules, Based on Condtions**	**Conditions are Either True, False or Irrelevant i.e >>**			✓	✗	–
		1	**2**	**3**	**4**	**5**	**6**
1	No Rain	✗	–	–	–	–	–
2	Blockage between Roof and 75 m^3 tank	✓	✗	–	–	–	–
3	Pump Blockage/Mechanical Fault	–	–	✓	✓	✗	✗
4	75 m^3 tank Pressure Indicator PI Fault	–	✓	✓	✓	✗	✗
5	Power to Pump issue	–	–	✗	–	✓	✓
6	UV Filter Broken/Needs Servicing	–	–	–	✗	✗	✗
7	UV Sensor Fault	–	–	–	✓	✗	✗
8	Pressure Vessel Broken	–	–	–	–	✗	✗
9	PI in Pipeline Sensor Fault	–	–	–	–	✗	✗
10	Leak in Pipeline leading to low pressure	–	–	–	–	✗	✓
11	Tank Leak	–	–	–	–	✓	✓
12	Roof Header Tank Blockage	–	–	–	–	✓	✗
13	GWS Panel Fault	✓	✓	✓	✓	✓	✗

4 Case Study

4.1 NUI Galway Engineering Building

The case study for this paper is the National University of Ireland, Galway Engineering Building, located in the west of Ireland.

The building was commissioned and first occupied in 2011. During the teaching term it houses approximately 1,100 undergraduate and postgraduate students and in the order of 100 staff. The building houses lecture halls, classrooms, offices, laboratory facilities, a café, 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. Eleven individual water meters were installed during construction and these measure various aspects of the water network including total mains water use (averaging 32,000 L/day) down to an individual drinking fountain (averaging 15 L/day). Currently, NUI Galway is subject to a flat water tariff there of €2.45/m^3 consumed; € 1.19/m^3 for water supply and €1.26/m^3 wastewater charge. The key water users include domestic hot water (DHW) for showers and hand wash basins, grey water (GWS) from the rainwater harvesting for the toilets and urinals, potable mains water (MWS) for the water fountains and café and stored mains water (CWS) for laboratory equipment and experiments.

4.2 Description of RWH System in the NUIG Engineering Building

The rain water harvesting system collects rainwater from the roof of the engineering building, stores it and then makes it available for use in the Grey Water Service (GWS) (toilet and urinal flushing) in place of paid-for mains water. Its configuration in the NUI Galway engineering building is that of an *indirectly pumped* RWHS. Thus rainwater is collected from a roof and then stored in an underground tank. The water from the underground tank is then pumped to a header tank at the highest point available in the building. From this elevated header tank, water is gravity fed to the connected appliances. If the storage tank empties, then the header tank is topped up by stored mains water (CWS) so that the GWS can continue to operate.

4.3 RHWS System components

This section will outline the operation of the RWHS in the NUI Galway engineering building. It will do this by describing the components in their linear order, with the aid of the simplified schematic drawing in Figure 3.

The RWHS system is made up of the following components:

- Rain catchment area (4.3.1)
- Underground storage tank (4.3.2)
- Filtration System (4.3.3)
- Pipeline PI, Pressure Vessel Water Meter (4.3.4)
- Header Tanks (4.3.5)

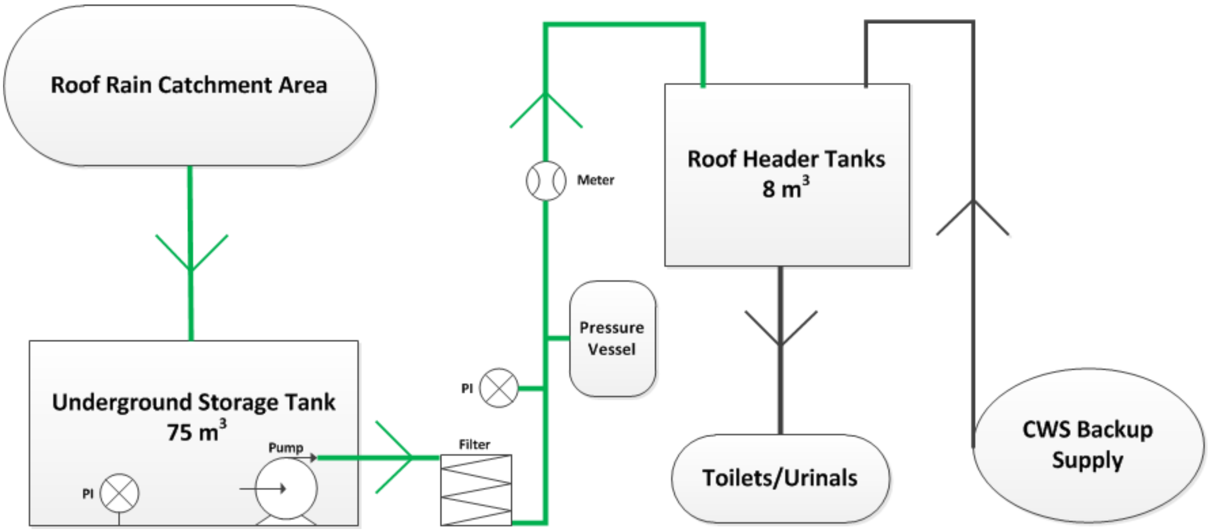

Figure 3: Schematic representation of the NUI Galway engineering building RWHS

4.3.1 Rain Catchment area (NEB roof)

The first element of the RWHS is the rain catchment area. The catchment area of the NEB rainwater harvesting system consists of the foot print of the building, less the low roof on the north face of the building. The total area of the catchment surface is 5188 m^2.

The collected water is transferred down through a system of pipes to a 75 m^3 underground storage tank. The quantity of water that is available from the roof of the building, for a particular period of time, can be estimated using the equation below;

$$A_{roof} * H_{rain} * C_r = V_{rain} \quad (1.1)$$

Where, A_{roof} is the total area (sq. meters, m^2) of the building's roof, H_{rain} is the height of rain (millimetres, mm) that is reported to have fallen for a particular period of time by, in this case, an on-site weather monitoring station and C_r is the rain run off co-efficient. The rain runoff co-efficient makes allowances for water lost as a result of splashing, material absorption, evaporation and other miscellaneous losses. Each material has a different C_r value. With the profile of the Engineering building being made up of 80% impervious tiles and 20% grass lawn the co-efficient can be taken as 0.68. (Lancaster, 2013)

4.3.2 Underground storage tank

The 75 m^3 underground storage tank stores the water transferred to it from the catchment area. If the tank reaches capacity, the water exits through a non-return valve into a hydro break chamber. The hydro break chamber then releases the water into the municipal sewer network.

As can be seen in Figure 3, the underground storage tank encases a Pressure Indicator (PI) sensor as well as a submersible pump. The PI measures the height of the water level in the storage tank and reports back to the GWS panel, whether there is sufficient rain water available for the grey water service. The submersible pump operates by pumping water to the header tanks on the roof of the building as required.

4.3.3 Filtration system

When the water from the underground storage tank is being pumped to the header tanks, it passes through a set of micron filters and an ultraviolet lamp to remove solid particles and bacteria respectively.

4.3.4 Pipeline PI, Pressure Vessel and Water meter

The water then passes through another PI and a water meter. The PI measures and communicates the pressure in the pipe back to the GWS panel, while the water meter measures the amount of rainwater that is pumped to the header tanks. The pressure vessel ensures that the water receives ample pressure when being pumped up through the four stories of the engineering building to the header tanks.

4.3.5 Header Tanks

Two header tanks exist on the roof of the engineering building. The two header tanks (8 m^3 each) are located on the west and east sides and service the toilets and urinals on those sides respectively. The water level in the tanks is monitored by two float switches, high level and low level. When the water height drops below the high level switch, it calls on the GWS to top up with the submersible pump from the storage tanks. If there is not sufficient water or if there is a fault so that the RWHS cannot top up the roof storage tanks, the water height will drop below the low level switch. When this happens, the backup CWS is called upon to replenish the header tanks to ensure that the toilets and urinals can continue operating. The toilets and urinals are serviced directly from these roof storage tanks.

4.4 Fault Identified

The reason for the interest in the RWHS in the NUI Galway Engineering building was due to a significant and persistent fault that was found in the system in November 2014. The fault resulted in 150 m^3 of treated mains water per month being used unnecessarily (~15% of total mains water usage in the building per month). The fault had been present in the system for 6 months months up to November 2014 when it was found. The fault was particularly interesting as it did not impede the operation of the system due to the CWS backup but was adding additional costs to the water bills for this building.

Figure 4 plots the volume of water available for the RWHS based on local weather data (Mét Eireann, 2015) and equation (1.1), as well as the quantity of rainwater pumped to the header tanks for usage in the GWS. Clearly, the system has failed in the past, at the end of 2012 and the beginning of 2013 and that the system has not worked properly since the middle of 2014 until May 2015. This is in no way because of lack of rainfall, as the graph clearly shows that there is ample rainfall for every month since its commissioning at the start of 2012. This directed the focus of this study to the development of the concept FDD methodology of section 4.

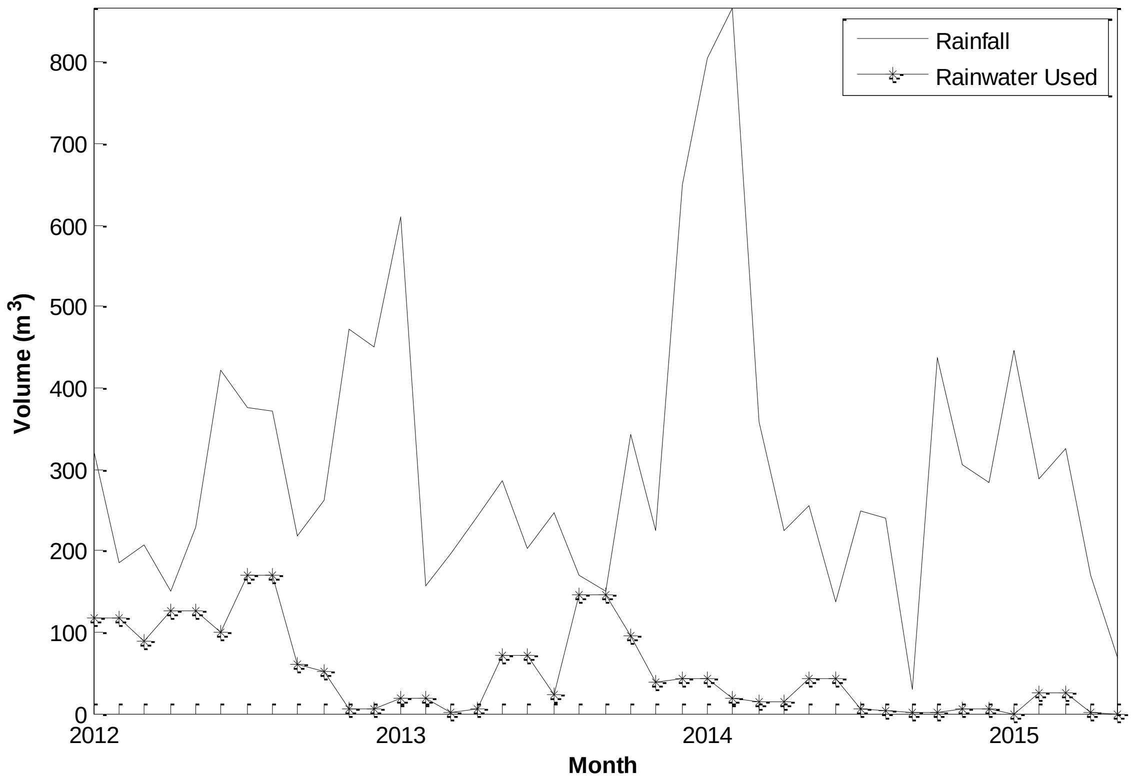

Figure 4: Quantity of rainfall and rainwater pumped to header tanks per month, 2012-2015.

The fault was found as part of implementing the *Waternomics* methodology developed in a previous study as described in section 3.1 herein. In accordance with the *Assessment of Building Water Network* step outlined in the previous study, the engineering buildings BMS was inspected and an apparent fault was found as can be seen in Figure 5. As an observation and verification step, the header tanks on the roof of the Engineering building were visited physically to confirm the observation made on the BMS. The fault was witnessed physically when the header tanks were noticed to be topping up with backup CWS instead of GWS, even though there had been plentiful rainfall in the preceding days and weeks.

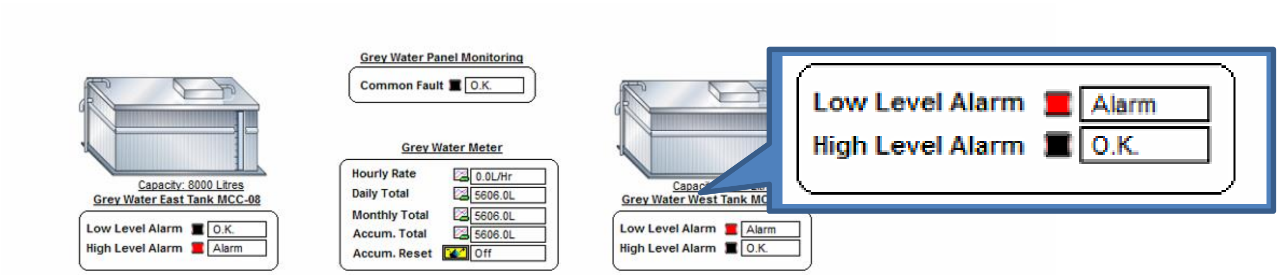

Figure 5: Header tanks fault shown on BMS GUI.

In accordance with the *Record all Faults encountered* step outlined in the previous study, the fault was recorded and characterised under the template headings provided in (Chambers et al., 2015). This has since been forwarded to the NUIG maintenance staff and the process of repairing the system is underway as of this writing.

5 Conclusions and discussion

5.1 Water Crisis and ICT

Climate change, increased urbanization and increased world population are several of the factors driving global challenges for water management.

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.

5.2 FDD and Water Systems

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 due to the fact that they both service people in buildings, can be measured and managed from Building Management Systems (BMS'), have high operational performance requirements and can be prone to faults (which may go unnoticed for extended periods of time) which impair their efficiency. Thus HVAC's FDD success combined with its similarity to water networks can provide the basis for the application of FDD in the water sector.

An important contrast between the application of FDD in HAVC and in water networks are the economic drivers. Traditionally, more emphasis has been allocated towards the conservation of energy than in the case of water, due to the higher unit price and demand response. With the aforementioned impending water crisis however, this trend is set to shift, and so any efforts in reducing water consumption should be deemed insightful and "ahead of the curve" and not irrelevant.

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. However here has been limited, if any literature to date on the development and application of FDD in water networks in buildings.

5.3 Rainwater Harvesting and FDD

Rainwater Harvesting is an additional service available within building water networks. These systems are gaining increased popularity across Ireland in both the residential and commercial sector. This is because of impending water charges for public houses and because of an onus on private enterprises to have a green and environmentally friendly public relations image. Although RWHS implementations are increasing a void that remains in the field of RWHS research is to develop parallel working systems which will ensure that they are more robust, resilient and proofed against faults, in the same way that HVAC systems have done.

As was shown in the case study herein, a fault in a RWHS can lead to 15% waste of a building's global usage, may be invisible to the building managers and have the potential to go unnoticed for an extended period of time. The fault presented in this study was found as a result of implementing a fault finding methodology developed in an earlier study by the *Waternomics* project.

It is concluded that a malfunctioning RWHS is an applicable system to implement FDD, for the first time, to a building's water network. This is due to the systems simplicity and magnitude of effect that a persistent fault has on decreasing a building's water usage efficiency.

5.4 Development of Expert-Based FDD System

A synthesis of Rule Based and Data Driven FDD will be utilised to create the concept FDD tool. Law Driven FDD will be over looked due to its excessive complexity.

The motivating assumption that this methodology proceeds under is that; In a mechanical system controlled from a programmed control board such as a RWHS, a malfunction of the system as a whole must be the result of one or more elemental components failing in the system. With all of the possible basic faults that could occur in the system identified, signals and readings from the system can be utilised to identify the offending basic broken component. This will then direct the repair work that needs to be completed to restore the system to its optimal running state.

The significance of the methodology development is that it is transferring *intermittent expert judgement* relating to the RWHS to a *continuous automated process*. Instead of irregular checks on a RWHS from maintenance personnel who might not necessarily be fully informed about the system, this methodology integrates all of the known knowledge relating to the optimal operation of the RWHS and provides continuous auditing to ensure minimal downtime between faults in a way that manual inspection can't.

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