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INTEGRATED APPROACH OF WATER QUALITY MONITORING AND HYDRAULIC PARAMETER ANALYSIS BASED ON BUILDING INFORMATION MODELING IN WATER DISTRIBUTION NETWORKS

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Abstract

Microbiological communities in building plumbing and water distribution systems (WDS) are water quality indicators with significant implications for public health, system efficiency and infrastructure maintenance. Thus, monitoring water quality and understanding WDS structures are essential for detecting contamination, assessing risks, and ensuring effective system management. However, some gaps exist, particularly in older buildings that often lack accessible floor plans, complicating WDS understanding. Furthermore, challenges in sharing and managing data on building structures and water quality analysis hinder collaboration and decision-making necessary for an adequate Water Safety Plan, increasing contamination risks. Finally, traditional assessments often focus primarily on microbiological aspects, overlooking hydraulic parameters, limiting comprehensive contamination mitigation, highlighting the need for a more holistic approach. An integrated approach is proposed to address the challenges by innovatively improving water quality and WDS management. This approach combines microbiological and hydraulic parameters analysis, supported by Building Information Modeling (BIM), enhancing coordination among professionals across various disciplines involved in water quality evaluation. It underlines the importance of considering water holistically, departing from the conventional fragmented approach to water quality assessment. By simultaneously analyzing both microbial and hydraulic aspects, water quality can be improved. BIM is a key element by streamlining data sharing and management, other than addressing the lack of correct and updated WDS layouts. In this context, BIM serves as a dynamic, shareable, and consultable model designed to contain several useful information for risk assessment. Integrating microbiological analysis with hydraulic parameter evaluation could ensure optimal water quality. This thesis shows how the proposed approach improves data flow and communication. Developing a model that correctly reproduces the WDS and includes the relevant information has proven useful for planning sampling campaigns, while integrating microbiological and hydraulic analysis identifies malfunctions within the WDS. This approach enhances water quality assessment, safeguarding public health, and optimizing infrastructure maintenance.

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List of Acronyms

BCYE	Buffered Charcoal Yeast Extract
BIM	Building Information Modelling
cfu	colony forming unit
Cys -	Without L-Cysteine
Cys +	With L-Cysteine
DICAM	Department of Civil, Chemical, Environmental, and Materials Engineering
GVPC	Glycine-PolymyxinB-Vancomycin-Cyckiheximide agar
HBIM	Heritage Building Information Modelling
HPC	Heterotrophic Plate Counts
ICC	Intact Cell Count
IFC	Industry Foundation Classes
ISO	International Standard Organization
Lp	*Legionella pneumophila*
NIR	Near Infrared Wavelength
PTFE	Polytetrafluoroethylene
RS	Reintegration System
TCC	Total Cell Count
UNI EN	Italian National Unification and European Committee
WBD	Water Borne Disease
WDS	Water Distribution System
WHO	World Health Organization
WSP	Water Safety Plan
WTS	Water Treatment System

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Chapter 1

Introduction

The chapter provides an overview of the thesis structure, and the PhD project is presented highlighting existing knowledge gaps and research needs, as well as the motivations for the project. At the end of the chapter, the research objectives are clarified, emphasizing their relevance and significance.

1.1 Structure of the thesis

The thesis presents five chapters, divided as follows:

Chapter 1 offers an overview of the research, identifying the current research gap and research needs relevant to the study. Additionally, it outlines the aim and objectives of the research.

Chapter 2 provides a more detailed background, together with a comprehensive literature review that describes the current state of the art in the field.

Chapter 3 and Chapter 4 report description, research methodology, results, discussion, and conclusion for Case Study 1 and 2, respectively. Each case study is analyzed independently, highlighting its findings and insights.

Finally, Chapter 5 consolidates the conclusions derived from the study. It emphasizes the work that has been done and outlines potential directions for future research, concluding the thesis.

1.2 Research gaps

Recognizing current knowledge gaps in water quality evaluation helps to identify areas where the current research is lacking or poorly investigated, to move the improvement measures in the right direction. The gaps described in this section are derived from a comprehensive literature review as well as firsthand experiences gathered during environmental monitoring activities.

It is commonly believed that the water supply system inside buildings provides clean and safe water. However, there is evidence that outbreaks of illness are related to water distribution systems (WDS) improper management, both on large and small scale (Scanlon et al., 2020; Walker and McDermott, 2021; Lawinger et al., 2023; Kunz et al., 2024).

Guidelines were developed to address risk management strategies to standardize building water system management and Water Safety Plan (WSP), and the majority mostly pertain to the control of *Legionella* spp. However, divergent perspectives and a lack of standardized guidelines for the practical management of a Building WDS were discussed *(Singh et al., 2020*). In fact, according to Logan-Jackson et al., there are no specific guidelines on microbiological contamination risk management applied to the point of entry or point of use for the residential building *(Logan-Jackson* *et al., 2023*). Moreover, Julien et al., by conducting a literature review and stakeholder workshop, discussed the need to establish a connection between water usage, design, material selection, and water quality through data-driven approaches to support risk assessment and management strategies *(Julien et al., 2020*). A review conducted by Proctor et al. explored the effects of water stagnation on large buildings WDS. It highlighted that, despite the availability of guidelines for corrective measures, various challenges and limitations have been identified and characterized in the process of recommissioning the building after the closures (*Proctor et al., 2020*). While buildings are considered sources of infections, limited research has been conducted to assist residential and building stakeholders in the remediation of contaminated water systems and maintenance of drinking water quality (*Logan-Jackson et al., 2023*). Although WDS and its components are known to have an impact on the water microbiological quality, microbiological contamination concerning WDS, and its hydraulic parameters is poorly investigated during the monitoring activities.

The integrity of well-managed distribution system is one of the most important barriers that protect drinking water from contamination (*El Attaoui et al., 2023*). However, the management of distribution systems in buildings often receives poor attention. Furthermore, the responsibility for managing water quality within buildings often falls to stakeholders and maintenance staff who may lack expertise in water quality management, monitoring, and evaluation (*Istituto Superiore di Sanità, 2012*). Another essential issue related to the detection and management of microbial contamination is access to the WDS layout to identify possible hazards along the pipelines. However, this critical aspect often represents a significant gap in environmental surveillance efforts. In particular, older buildings frequently lack updated information regarding WDS layouts and hydraulic components. Furthermore, routine and/or extraordinary maintenance programs are either not reported or poorly implemented. These challenges significantly hinder water quality assessment activities. Moreover, it could be challenging to set up an optimal monitoring network, considering that many buildings have aged water distribution infrastructure, including pipes and fittings. Managing and addressing the deterioration of infrastructure to prevent leaks, corrosion, and water quality issues is a significant challenge.

Water quality monitoring analysis generates a large data set, both in terms of amount and type. Consequently, handling large amounts and diverse data from multiple sources can be challenging. Establishing effective data management systems and integrating data from different monitoring programs and sources is crucial for informed decision-making. It is also crucial that professionals involved in water quality assessment have access to this data. The current state of data-sharing practices in building WDS often relies on manual methods, leading to inefficiencies and potential inaccuracies. The lack of standardized data formats, communication protocols, and secure sharing mechanisms exacerbates these challenges, slowing collaborative efforts among stakeholders, including building owners, facility managers, and technicians.

1.3 Research needs

There is a clear need to develop a water quality evaluation assessment strategy to address the challenges associated with managing and evaluating water quality within a building. The current approach to assessing water quality is often fragmented, with the different disciplines and sectors operating separately. This can lead to a lack of proper assessment and corrective actions in case of water contamination, reduced effectiveness in providing safe water, as well as deficiencies in managing the flow of information and data that could affect communication. An integrated approach that considers the various aspects affecting water quality as interconnected is therefore essential. These interconnections enable more effective preventive and containment measures by considering the complex dynamics and feedback among different disciplines and contexts. Addressing these challenges requires a collaborative and multidisciplinary approach involving researchers, engineers, technicians, and stakeholders. By developing robust methodologies and platforms for data sharing, WDS management improvement, and integrated microbiological and hydraulic water quality analysis, researchers can facilitate monitoring, maintenance, and decision-making processes to optimize water quality, and building WDS performance. Only through a holistic and collaborative approach could proper water system management and good water quality be ensured.

1.4 Aim and study design

The main aim of this PhD thesis is to introduce a novel approach for assessing the microbiological quality of water in a WDS together with an entirely new approach to system management.
The following initial issues served as a starting point for the project development:

- WDS is the artificial reservoir of several microbial infections;
- WDS are complex systems that are influenced by biological and hydraulic components, in addition to their material composition and pipeline design;
- WSP is the proper way to ensure good water quality;
- Risk assessment and risk management are essential to ensure the sustainability of drinking water;
- Risk assessment and risk management rely on the collaboration of various professional figures. Unfortunately, these figures frequently do not collaborate or communicate well in real settings, given the difficulties associated with obtaining information referring to the WDS;

- WDS layouts are often out of date, particularly for older buildings, where risk assessment plans are frequently absent or insufficient, which minimizes ordinary and extraordinary maintenance to be performed.

To achieve the aim, the study is focused on the following questions, attempting to address the necessity of overcoming the challenges presented in the previously mentioned issues:

Question 1: How can the evaluation of microbiological water quality be improved?
Question 2: How can information-related challenges be overcome to enhance the management of a water system?
Question 3: How can collaboration improve strategies for risk assessment?

Therefore, the research was structured to answer the previous questions, developing the following study objectives:

1. Review the WDS entirely, paying special attention to existing plans.
2. Evaluate water quality by combining microbiological analysis with hydraulic parameter measurements.
3. Optimize WDS management by using a digitized system that is not just a virtual representation, but it is a dynamic, consultable, and shareable 3D model that contains all the data required for analysis, documentation, and data storage.

The proposed approach has been defined as “Integrated approach” to water quality monitoring because it considers three distinct fields of study: distribution system 3D modelling, hydraulic engineering, and microbiology water analysis. Rather than considering them as separate components, this method views the study of water assessment as several interrelated pieces that together constitute a totality (Figure 1).

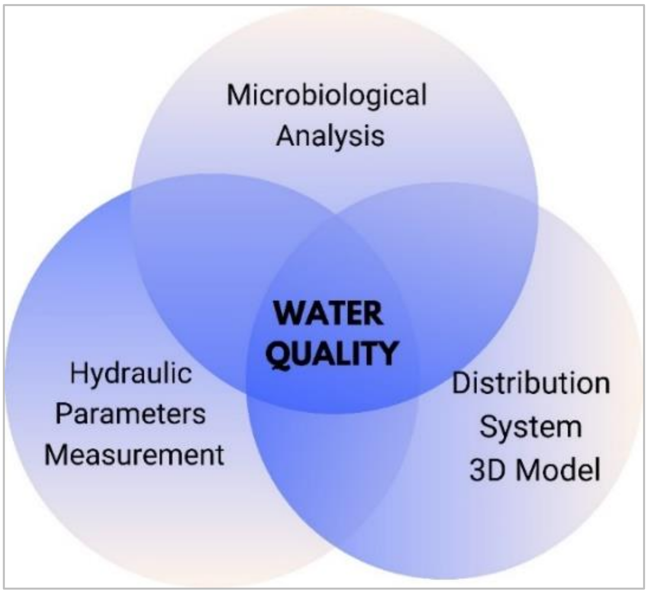


Fig. 1*: The integrated approach for water quality: monitoring as a result of the integrated analysis.*

More in detail, to prevent microbiological contamination and maintain the WDS functionality over time, hydraulic evaluations and microbiological analyses were carried out simultaneously. Then, to facilitate the digitalization and the 3D modelling, purpose-built tools and software such as Autodesk BIM software Revit® and IFC file format, enable the development of a digital model that integrates all relevant data regarding WDS components, structure, and management, which can be easily uploaded to a Cloud. This approach significantly enhances data sharing among stakeholders involved in the WDS management (Figure 2).

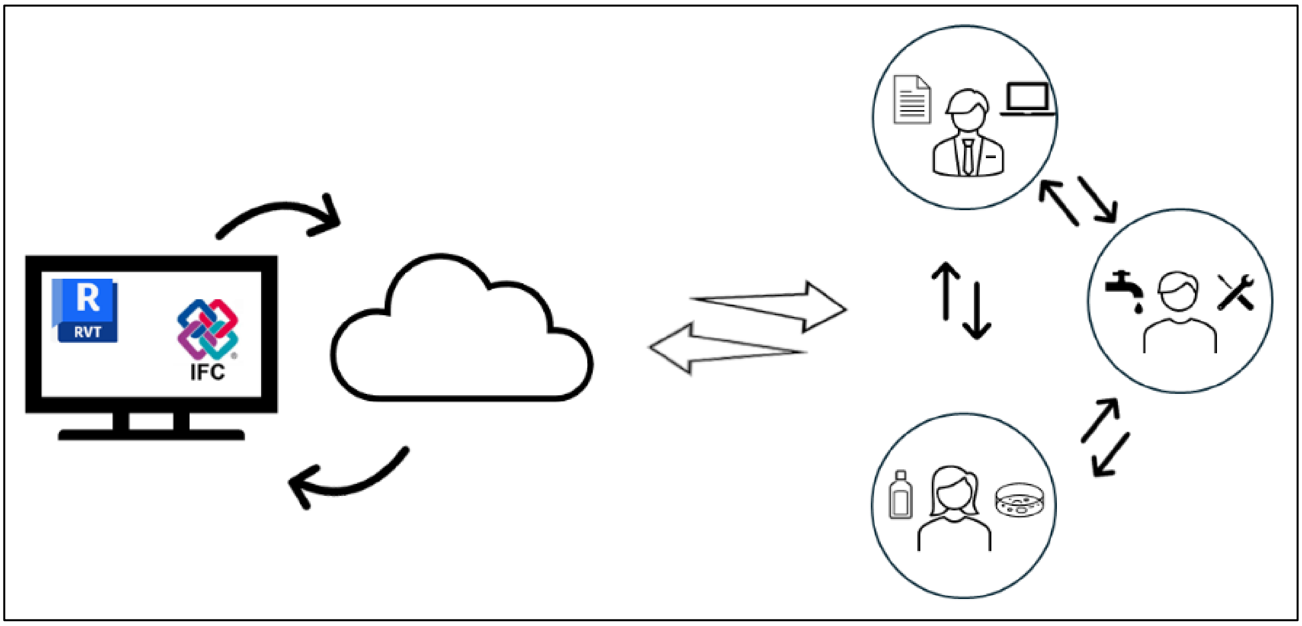


Fig. 2: *Data sharing pathway*

Two challenges in managing a WDS are intended to be resolved using this approach: (i) the lack of layout and other data necessary for risk management, and (ii) the challenges in coordinating and communicating amongst the professionals involved in the WDS management.

The ultimate objective is to get awareness about how effective this approach is able to preserve public health issues, ensuring the WDS operates correctly over time.

The approach is presented to implement a methodology to aid and support building water quality assessment, monitoring efforts, and professional figures to mitigate the impact of waterborne diseases and proper synergy with WDS.

Chapter 2

Background

The following paragraphs provide an overview of the background and current state of the art related to the topics under discussion in this thesis to place this research in its proper context.

2.1 Water quality

Water intended for human consumption can be considered safe and clean if it is free from any microorganisms, parasites, and any substances that represent a potential risk to human health, meeting the minimum requirements of microbiological and chemical parameters. This is what is stated in the current Italian reference directive for drinking water, Legislative Decree No. 18 February 2023 which implements the European Directive (EU) 2020/2184 *(Directive (EU) 2020/2184, 2020; Legislative Decree Feb 23, 2023)*.

Based on this definition, assessing water quality is critical as it significantly impacts public health prevention and it is determined by the water chemical, physical, and biological properties. As a consequence, water quality assessment ensures drinking water is free of dangerous contaminants, with particular emphasis on the microbiological part which determines its safety and suitability for human consumption, other than to support the management activities *(Behmel et al., 2016; World Health Organization, 2024*).

It is well known that water serves as a habitat for bacteria, archaea, viruses, fungi, and protozoa *(Lin et al., 2014; Shmeis, 2018; Inkinen et al., 2021*). These include pathogens or opportunistic pathogens, capable of causing illnesses in both healthy and immunocompromised people. Waterborne diseases (WBD) are illnesses resulting from exposure to contaminated water through ingestion, inhalation, or contact (*Leclerc et al., 2008*).

Microorganisms capable of growing within a WDS exhibit characteristics such as resistance to disinfectants, formation of biofilms, and survival in different environmental conditions (*Szewzyk et al., 2000; Siedlecka et al., 2021; Erdei-Tombor et al., 2024*). Therefore, the purpose of microbiological water quality assessment is to ensure that the water is free from microorganisms related to causing disease. Regular microbiological surveillance is essential to meet regulatory standards and understanding the microbial ecology of drinking water helping in safeguarding water safety and preventing WDB. Nonetheless, understanding the interactions between bacteria, viruses, and other microorganisms in water, remains an ongoing challenge, representing a barrier in our effort to ensure complete water safety.

Poor water quality can have severe and wide-ranging impacts on public health. According to the 2021 summary report, 52 WBD outbreaks were reported in the United States associated with 511 cases, 104 hospitalizations, and 10 deaths. Recreational water sites were the most associated with the outbreaks (62%) accounting for 56% of all the reported cases. *Legionella* spp. was the primary pathogen in half of the outbreaks causing 60% of the deaths, followed by Cyanobacterial toxins, *Campylobacter* spp., *Cryptosporidium* spp., and *Pseudomonas* (6%) (*Lawinger et al., 2023*).

While water quality monitoring primarily focuses on identifying microorganisms in water, it is impossible to monitor all potential pathogens. Water contamination by human or animal feces poses a significant risk factor since it can be a source of different bacteria responsible for WBD *(World Health Organization, 2004)*. However, it is important to point out that microbial drinking water safety extends beyond fecal contamination. In addition to fecal indicators, attention has recently been focused on other water-associated bacteria, like *Legionella*, known for causing Legionnaires' disease, a significant and potentially fatal infection that requires prompt action (Walker and McDermott, 2021; Zhang and Lu, 2021).

Indicator parameters and reference standards have been established for good water quality to assure the acceptability of water use for any specific purpose, with many including fecal indicators (Holcomb and Stewart, 2020; World Health Organization, 2021). These analyses play a crucial role not only in monitoring water quality but also in guiding WDS design and management decisions from the early planning stages. People involved in the design of WDS should be educated and trained in understanding every aspect of water system design that could potentially lead to microbial growth (*Walker et al., 2023a)*.

The criteria for safe drinking water are established by national and international recommendations and directives to prevent adverse public health consequences caused by potentially dangerous compounds in water. These standards are based on scientific evidence and risk assessments, and establish drinking water quality standards for aesthetic, chemical, microbiological, and radiological characteristics *(World Health Organization, 2021)*, with coliform bacteria often utilized as indicators of fecal contamination and potential disease presence (*Holcomb and Stewart, 2020*).

Water supply for consumers needs to comply with the quality criteria outlined by national and international guidelines. The reference microbiological parameters can differ across countries, depending on local directives. As mentioned before, Legislative Decree Feb. 23 No. 18 is currently in effect in Italy, and it transposes European Directive (EU) 2020/2184 *(Directive (EU) 2020/2184, 2020; Legislative Decree Feb 23, 2023)*.

According to the current Italian drinking water regulations, the main microbiological parameters to assess the water quality for human consumption include Enterococci and *E. coli*, whereas the indicative parameters are *Clostridium perfringens* (including spores), colony count at 22°C, and coliform bacteria. Additionally, *Legionella* spp. assessment has been included as an indicator for evaluating and managing in-house distribution systems *(Legislative Decree Feb 23, 2023)*. In Table 1 the minimum microbiological requirements are summarized, including limit value and parameter significance.

***Table 1**: Microbial parameter to be measured in Italy according to the Directive.*

Microbial parameter	Limit value	Parameter type and significance
Enterococci	0/100 cfu/mL	Fundamental. Contamination of fecal origin.
E. coli		
Clostridium perfringens (including spores)	0/100 cfu/mL	Indicator. To assess the efficacy of disinfection and physical removal methods. To be measured if indicated as appropriate by the risk assessment.
Colony count at 22°C	Without variation abnormal	Indicator. To assess the efficacy of disinfection and the integrity of the distribution systems.
Coliform bacteria	0/100 cfu/mL	Indicator. To assess the cleanliness and integrity of distribution systems. To be measured based on risk assessment.
Legionella spp.	<1000 ufc/L	Specific risk assessment and management

Several methods are used for the microbiological analysis of water samples to detect and quantify the microorganisms, playing a crucial role in evaluating water quality and ensuring water safety, most of them based on culture techniques, following the directives *(Legislative Decree Feb 23, 2023*).

Currently, the membrane filtration technique is commonly used to search for these parameters. The method consists of filter an aliquot of water samples through a membrane filter which is then incubated on general or selective growth media allowing the isolation and enumeration of target bacteria (*Berg and Matin, 2021*).

However, there is growing support for the use of more and more molecular biology tools. PCR and its various applications allow quantifying the amount of specific DNA sequences with high sensitivity and specificity (*Oon et al., 2023*). Additionally, flow cytometry, laser-based technology, is used to analyze the physical and chemical properties of individual particles, including microorganisms allowing for the rapid enumeration and characterization of microbial populations (*Robinson et al., 2023*). Furthermore, Next-Generation Sequencing (NGS) techniques are increasingly for water sample analysis, providing detailed information on the diversity and composition of microbial populations (*Tan et al., 2015*). Another innovative approach involves the metagenomic analysis in which microbial nucleic acid is sequenced directly from environmental samples allowing for the detection of the microbial community present in the samples (*Nam et al., 2023*).

Techniques based on Matrix Assisted Laser Desorption Ionization Time of Flight Mass Spectrometry (MALDI-TOF MS) have been rapidly and successfully inserted into laboratory practices to identify microorganisms from typically difficult sources like water samples incrementing speed and ease (*Pascale et al., 2020*).

The choice of the method depends on the specific microbiological parameter under study, the needed sensitivity, and the available resources. These are the methods that are most often used for the detection of microorganisms in water samples; however, ongoing advances in technology continue to contribute to the development of increasingly sensitive and specific approaches (*Oon et al., 2023*).

To maintain good water quality, complete water management strategies are required, including regular monitoring by a team of trained professionals, proper sanitation practices, effective wastewater treatment, and public education initiatives.

2.1.1 Effective water quality sampling program

Robust water quality monitoring is essential for accurately evaluating water quality. Regular monitoring and maintenance of distribution systems are also essential to identify and address any potential issues that may arise over the time.

Conventionally, water quality monitoring relied on a regular sampling program, which traditionally involved collecting water samples and transporting them to a laboratory for routine analysis. Ensuring an appropriate sampling is essential to obtain representative samples. To address this need, the International Standard Organization (ISO) has developed a standardized procedure for microbiological analysis sampling on an international scale *(EN ISO 19458:2006, 2006*). Sampling served various purposes as outlined in ISO 19458. These include, first of all, assessing compliance with water quality standards, then characterizing contamination tracking contamination trends, and identifying sources of pollution (*EN ISO 19458:2006, 2006*).

Samplings involve collecting a series of water samples from different points along the WDS and building plumbing system, including the entry point of water into the building and various points of use such as taps or faucets. This approach helps to identify potential contamination sources within the building plumbing at the point of use. Additionally, sampling at the water storage tanks, reservoirs, and other storage units is critical to ensure the quality of stored water that then reaches the distribution system.

Designing a proper sampling plan is an important aspect of collecting representative samples and it necessitates a precise understanding of the buildings, the entire WDS, and each sampling point. This comprehensive knowledge enables the development of a sampling strategy that effectively describes the water quality throughout the system.

A robust sampling plan should consider different key elements. First, identify the locations within the buildings and along with the WDS where samples will be collected because the spatial distribution of the sampling point allows for analysis of different areas along the WDS with different usage, flow rates, and potential sources of contamination. Furthermore, establishing routine samplings for water quality monitoring is essential. Frequency may vary based on building use, occupancy, and regulatory requirements. In response to specific events, such as maintenance, or water quality parameters not compliant with the regulatory standards, additional sampling should be carried out. Another critical aspect relies on the maintenance of detailed documentation about the sampling plan, including locations, procedures, and results to improve and control the traceability, and data interpretation. To address this aspect, digital platforms for data management could facilitate the storage, analysis, and visualization of water quality over time.

Nowadays, ongoing research into advanced water quality monitoring technologies, including sensor innovations, artificial intelligence, and machine learning applications (*Kaddoura, 2022; Essamlali et al., 2024; Slongo et al., 2024*).

2.2 Water Safety Plans

Ensuring the microbial quality of drinking water requires the implementation of management plans to safeguard the water system and control the process, thereby minimizing the presence of pathogens. These measures ensure that the water remains acceptable for consumers and water quality safety cannot be discussed without mentioning Water Safety Plans (WSPs).

Introduced by the World Health Organization (WHO) in 2004, WSPs have become a regulatory requirement and it is aligned with guidelines on drinking water quality in many countries *(World Health Organization, 2004; Gunnarsdottir et al., 2012*).

More precisely, according to the WHO Guidelines, WSP is “the most effective means of consistently ensuring the safety of a drinking water supply is through the use of a comprehensive risk assessment and management approach that encompasses all steps in the water supply from catchment to consumers” (*World Health Organization, 2004*). Assessing the potential risks in drinking water systems provides the basis to identify many health-based targets that are used in the process.

WSPs represent a significant shift in the context of water safety approaches, moving from a mere surveillance approach to proactive prevention and management. WSPs involve understanding the entire system, identifying potential problem areas, implementing barriers and management systems to prevent issues, and ensuring the ongoing functionality of all system components *(World Health Organization, 2023*).

The WSPs are essentially systematic approaches to managing risk associated with drinking water, and it is readily evident that the process of risk assessment is a fundamental component of developing a WSP, providing the necessary framework for identifying, evaluating, and managing potential hazards.

In the context of water quality assessment, the initial phase of risk assessment involves identifying hazards that could compromise water safety, including both natural and human sources of contamination. Once hazards are identified, the likelihood and severity of adverse health effects associated with each hazard are evaluated, considering exposure pathways, and population susceptibility. Based on this information, risks are prioritized based on their potential impact on public health. Following risk characterization, appropriate risk management strategies to mitigate identified risks are applied, which may include implementing control measures, enhancing monitoring and surveillance programs, or developing emergency response plans. The goal is to minimize the likelihood of hazards occurring and to ensure the safety and quality of the drinking water supply (*World Health Organization, 2004*).

WSPs are commonly implemented by municipal water utilities responsible for supplying drinking water to urban and suburban areas. Given the size and scope of these systems, they necessitate robust risk management strategies to maintain water safety and quality standards. However, the complexity of WSPs should be adapted to the specific needs of each drinking water system (*World Health Organization, 2004, 2017*). For instance, healthcare facilities should develop WSPs to ensure patient safety and maintain water quality standards, while recreational facilities like swimming pools should implement WSPs to comply with regulations and prevent WBD.

WSPs include some important key components that are the responsibility of the provider. Firstly, the "system assessment" involves the examination of the entire supply system to identify the potential hazards that could compromise the water quality. The second component focuses on effective "operational monitoring", involving the regular testing and analysis of water samples at different distribution points to detect deviation from water quality standards and implement corrective actions promptly. The last component involves "management practices and communication strategies", which include the development and implementation of a precise management protocol for all water supply operations, maintenance, and emergency responses. Furthermore, establishing transparent communication with stakeholders, including consumers, regulatory authorities, and local communities, is crucial for addressing any water quality concerns and ensuring public confidence in the drinking water supply *(World Health Organization, 2017*). By integrating these three key components into their WSPs, drinking water suppliers can effectively manage risks, maintain water quality standards, and safeguard public health.

Regular review and evaluation of the WSPs ensure their ongoing effectiveness and relevance in the dynamic field of water supply management. Internal or external audits provide independent and systematic monitoring to ensure that the WSP is comprehensive, correct, effectively implemented, and effective (*World Health Organization, 2017, 2023*).

According to the WSP manual released by the WHO in 2023, water safety planning consists of four key stages: WSP development, operation, verification, and review. While WSP development is significant, the effectiveness of water safety planning depends on its consistent operation, verification, and review. These phases ensure the continual and successful execution of WSPs *(World Health Organization, 2023*). The critical aspect of WSP development is establishing a multidisciplinary team with the expertise needed to monitor the process. This team should collectively take on leadership roles and assume responsibility for developing and implementing the WSP. It should comprise individuals who understand the entire water supply chain, from catchment to consumers, and possess the skills to assess and manage risks effectively. Key members may include technical staff involved in daily operations, engineers knowledgeable in design and construction, management personnel, microbiological safety experts, water sampling and testing professionals, representatives from environmental and health agencies, and user group representatives (*World Health Organization, 2023*).

The second crucial aspect of water safety planning involves providing an accurate and concise description of the water supply system to assess associated risks effectively. This involves gathering relevant information and updating existing data as necessary. The system description should include details such as the water supplier and supply scale, boundaries of the WSP, intended uses of water, diversity of water users, catchment characteristics, current water sources, raw water intake and treatment processes, distribution systems, user interfaces, user practices, water demand, quality targets, historical water quality, system problems and uncertainties, extreme weather events history and trends, future trends including climate impacts and changes in demand, and potential alternative water sources with associated safety issues (*World Health Organization, 2023*). By bringing together this diverse array of expertise, the WSP team can effectively collaborate to develop a comprehensive plan aimed at ensuring the safety and quality of the drinking water supply (*World Health Organization, 2004*).

Differences in WSP implementation emerge between countries and the development level of the water supply. However, many benefits from WSP application are reported including system management improvement, increased awareness, communication between stakeholders, and of course improved water quality (*Serio et al., 2021; World Health Organization, 2023*).

To conclude, WSPs are indispensable tools for protecting public health and ensuring the provision of safe drinking water to communities. By identifying and managing risks, WSPs contribute to the overall well-being of people.

2.2.1 Water Safety Plans in Buildings

Water is the natural habitat of different microorganisms, but WDS provides them with high temperatures, nutrients, and protection. WSPs for buildings are the responsibility of the building owners, with the support of different professional figures such as architects, engineers, suppliers of plumbing components, plumbers, and so forth (*World Health Organization, 2011*). Plumbers are tasked with constructing building water systems according to the technical directives and standards, while building owners are responsible for the operation and maintenance of drinking water installation (*Schmidt et al., 2019*).

The WSP in the building should start with the formation of a multidisciplinary team comprising experts in various relevant fields (e.g. engineering, microbiologists). This team describes the drinking water plumbing system in all its components, identifying potential hazards and existing control measures. Risk assessment involves evaluating the significance of the identified hazards using a risk matrix and implementing additional control measures as needed. Verification of the WSP consists of testing water quality and assessing the effectiveness of the plan. Supporting programs, including staff training and emergency planning, are integral components. Continuous monitoring and periodic review ensure that the WSP remains effective in response to changes within the system and its operation *(World Health Organization, 2011; Istituto Superiore di Sanità, 2012; Schmidt et al., 2019*).

Unfortunately, water systems within buildings often lead to outbreaks of disease due to poor management *(Maynard, 2020*). Ensuring water safety faces challenges because many necessary actions fall outside the scope of drinking water suppliers. Various stakeholders play roles in managing water systems in buildings. While WSPs are very common for public water supplies, they are not typically extended to buildings. Responsibility for managing building water supplies falls on owners, managers, or maintenance staff, they may lack awareness of or adherence to water quality guidelines, necessitating educational support programs (*World Health Organization, 2017*).

Currently, the predominant focus on risk assessment and control measures in sensitive environments is often related only to *Legionella* spp. However, this approach fails to ensure comprehensive protection for people. It should be acknowledged that all potential waterborne pathogens and various sources can constitute a risk of infection. Thus, the attention should shift the attention from focusing only on a single microorganism to encompassing the wide spectrum of potential pathogens, ensuring an effective risk assessment *(Maynard, 2020; Proctor et al., 2022*).

One of the most significant challenges lies in managing water within buildings of varying types neglected for several reasons. First, the building water system operates independently of the main public water supply. Additionally, factors such as the building purposes (hospital or recreational), the presence of supplementary water sources, additional treatment at water entry points from the municipal system, and the vulnerability of building users must be taken into account *(World Health Organization, 2011; Istituto Superiore di Sanità, 2012*). At the regulatory level, there is clarity regarding the needs and the action along the entire water supply chain. However, related to individual buildings there are uncertainties regarding necessary measures and responsibilities for managing the water system. Moreover, the existing literature on risk analysis, particularly concerning the implementation of WSPs in buildings, is surprisingly lacking.

Documentation of the system plans describing the actions to be taken in normal operation, plans describing actions to take during incidents, plans on improvement, plans on upgrading, and communication plans are all to be included in the management plans. Implementing WSPs in buildings is essential to safeguard the quality of drinking water and protect public health, providing a structured approach to managing water systems within buildings. By promoting collaboration among stakeholders, enhancing awareness of water quality issues, and facilitating regular monitoring and review, WSPs help ensure the ongoing safety and sustainability of building water systems. However, challenges such as limits on resources and the need for broader adoption of WSPs remain.

2.3 Water distribution system: the impact and the importance of its management on water quality

A water distribution system (WDS) is part of a water supply network that transports drinking water from its source to consumers, ensuring that communities have access to safe drinking water for various purposes like drinking, cooking, sanitation, and hygiene (*Palma et al., 2024*).

The WHO uses a "water transmission system" to describe a network of pipes that transports water from treatment plants to service reservoirs. Conversely, the term "water distribution system" refers to a network of pipes responsible for delivering water from service reservoirs to consumers *(World Health Organization, 2014*). More in detail, the term building premise plumbing refers to plumbing fittings within buildings, as well as the service lines that connect them. Building premise plumbing, like larger WDS, is made up of pipes that deliver water to consumers and typically pass via fixtures at the point of use- these end-use devices, such as faucets, showers, taps, or toilets, regulate the flow of water in a pressure-dependent way (*Burkhardt et al., 2023*).

Despite the natural occurrence in the environment, waterborne pathogens are usually present in low concentrations in drinking water treatment plants. However, they can proliferate within the distribution networks and especially in building water systems. Chemical disinfectants that can control microbial growth are used in water treatment plants. In addition to disinfectants, water flows distributed in large distribution pipelines, where the low temperature and residual chemicals inhibit the growth of microorganisms along with the high flow rate and low growth surface area. When water comes within buildings, smaller pipelines, higher temperatures, low flow rate, stagnation, and higher surface area promote microorganisms' growth and biofilm formation. Thus, proper control of environmental factors is crucial to prevent WBD, especially in buildings hosting vulnerable people *(Proctor et al., 2022; Walker et al., 2023b*).

More in detail, WDS in a building plays a crucial role in maintaining water quality from its point of entry to the point of use. The presence of opportunistic pathogens in building plumbing, particularly *Legionella* and *Mycobacterium*, has been documented *(Proctor et al., 2022; Shen et al., 2022*).

The design, construction, and maintenance of these systems can significantly influence the quality of water delivered to various outlets within a building. Then, if considering its overall degradation, every component is potentially susceptible to microbiological contamination *(Vacs Renwick et al., 2019*).

It is not only outdated structures that pose risks for waterborne infections. Infections could stem from inadequate design, installation, and commissioning of the water system. Plumbing designs are regulated by building codes that often overlook microbial quality and biofilm, particularly as water conservation trends change water flow dynamics. Design decisions like pipe length and orientation influence water flow patterns and temperature. Novel plumbing designs aim to mitigate biofilm formation, but unintended consequences, like increased microbial colonization on fixtures, arise. In light of these, new plumbing systems should be tested for risks of microbial colonization *(Ra et al., 2020; Proctor et al., 2022*).

On the other hand, existing buildings face different challenges from the exceeding WDS lifecycle and subsequent deterioration, leading to compromised water supply reliability (*Vacs Renwick et al., 2019*). These challenges emphasize the critical need for proactive maintenance, investment in upgrades, and adherence to regulatory standards to ensure the delivery of safe water. Daily decisions on building WDS can significantly impact microbial growth. While factors like stagnation in lengthy pipelines may be hard to control, other such as maintaining optimal system temperatures are essential components of effective management strategies (*Proctor et al., 2022*).

These considerations lead to the assertion that WDS represents a potential artificial reservoir of infection able to promote the microorganisms spread and amplification, due to a wide range of factors.

Microbial drinking water quality can be altered in large buildings, especially after stagnation. Stagnant water in pipes plays a pivotal role in water quality management, yet it is often overlooked (*Bédard et al., 2018*). Stagnant water is associated with low or no flow and it is an ideal condition, especially in dead-end lines or infrequently used outlets, which can lead to microbial contamination and water quality deterioration (*Proctor et al., 2020; Ye et al., 2021*).

Stagnation can occur due to various factors, including low occupancy, infrequent water use, or inadequate system design. Stagnant water in pipes can become a perfect substrate for pathogens, especially in buildings without water management plans *(Proctor et al., 2020; Rhoads et al., 2022; Joshi et al., 2023*). Low occupancy levels in buildings occurred during holidays or periods of closure, often result in reduced water usage, allowing water to remain stagnant in pipes and fixtures for extended periods. In buildings with fluctuating occupancy levels or seasonal use, stagnant water becomes a significant concern, as periods of inactivity can promote microbial growth and degrade water quality. Stagnation within building plumbing leads to a reduction in residual disinfectant levels, an increase in cell count, the proliferation of pathogens, and an alteration in a bacterial community (*Proctor et al., 2020; Montagnino et al., 2022; Rahmatika et al., 2022*).

Poorly designed plumbing layouts may feature dead-end pipes, low-flow fixtures, or improperly sized pipes, all of which can promote stagnant conditions by impeding water circulation and causing localized areas of low flow. In such systems, water may stay for prolonged periods, facilitating the growth of bacteria and other contaminants. To mitigate risks associated with stagnation, proactive measures must be taken. Regular flushing of stagnant lines, periodic activation of unused outlets, and implementing water management plans are essential strategies to prevent water stagnation and maintain water quality. However, while flushing after long periods removes the immediate threat of exposure to potential contamination, experts are debating optimal flushing practices and the direct relationship between stagnation and *Legionella* (*Proctor et al., 2020; Rhoads and Hammes, 2021*).

When water remains stagnant in pipes or fixtures for extended periods, it can lead to increased contact time between the water and plumbing materials. This prolonged contact can promote the leaching of metals and other contaminants from pipes, fittings, and fixtures into the water supply. Corrosion not only compromises water quality but can also damage plumbing infrastructure, leading to costly repairs and potential health hazards for building occupants. Corrosion of pipes and fittings can introduce contaminants into the water, affecting its taste, odor, and overall quality *(Rhoads et al., 2017; Wojtkowska et al., 2022; Ghoochani et al., 2023*).

Pipe material also affects microbial growth, however, long-term studies on pipe material effects are limited. Broadly, pipeline materials are classified into metallic, such as copper, zinc, and iron, and plastic like PVC and polyethylene. Pipe materials interact with disinfectants commonly used in buildings WDS with positive and negative effects on microbial growth. For example, plastic does not react with residual disinfectant by certain types of polyethylene and PVC may slowly react with it. By contrast, copper catalyzes the decay of free chlorine and monochloramine (*Cullom et al., 2020*). Plastic pipes have been found to release organic carbon, yet they generally require less disinfectants and have fewer interactions with water chemistry. On the other hand, iron pipes can supply nutrients to opportunistic pathogens either directly or indirectly, leading to a significant demand for disinfectants and the formation of scales conducive to biofilm growth. Although copper pipes are recognized for their antimicrobial attributes, the evidence regarding their effectiveness in controlling opportunistic pathogens is inconclusive *(Cullom et al., 2020*). Older pipes may have accumulated deposits or scale on their interior surfaces, potentially affecting water quality.

Another significant factor influencing microbial growth within building WDS is temperature. Elevated temperatures in WDS are known to promote microorganisms' growth and accelerate chemical reactions. Consequently, water temperature should be maintained outside the ranges of growth of most opportunistic waterborne pathogens. A typical building WDS presents a separate hot and cold-water system. In optimizing, a cold-water system, minimizing stagnation and ensuring insulation are essential. Keeping cold-water systems separate from hot-water networks helps to prevent heat gain. Similarly, designing a hot-water system to prevent stagnation and ensure the insulation of the pipes effectively is crucial to reducing temperature loss and ensuring efficient operation *(World Health Organization, 2011*). In these systems, hot water should be heated at 60 °C and distributed at a minimum of 55 °C while the cold water stored and distributed below 20 °C.

Microorganisms to grow and reproduce need a range of temperatures and water became an important condition for bacteria spread (*Qiu et al., 2022*).

In WDS, particularly in areas where water remains stagnant or experiences low flow rates, elevated temperatures can provide an environment for these microorganisms (*Zhang et al., 2015*).

This can lead to biofilm formation and microbial contamination of the water supply, potentially posing health risks to consumers. Various definitions of biofilm in literature shares a common issue: they describe biofilm as a biologically active matrix adhering to the surface, comprised of cells and their extracellular polymeric substances. Within this matrix, bacteria can multiply and produce organism polymers that contribute to biofilm formation (*Erdei-Tombor et al., 2024*). Biofilms provide protection and nourishment for bacteria. In well-maintained buildings WDS, biofilms are typically thin and contained. However, biofilms pose a concern as they become difficult to remove and may resist disinfectants. Poorly managed systems are subjected to biofilm development on various components. Once established, biofilms are hard to eradicate and can compromise disinfection efforts. Effective disinfection regimes maintaining adequate disinfectant levels are crucial for controlling biofilm formation and preventing microbial contamination in building water systems (*World Health Organization, 2011*).

2.4 The importance of communication and collaboration in water quality management

Water quality risk assessment is the foundation for every WSP (*Walker, 2023*). Ensuring water safety regarding pathogens in drinking water is the responsibility of several groups of professionals. These groups include diverse professional backgrounds underscoring the need for comprehensive awareness and collaboration on various sides to effectively address the complexities of pathogen-related risks in drinking water *(World Health Organization, 2023*).

From the previous paragraphs, it is evident that a fundamental element for an effective WSP is robust communication and easy data sharing, as well as an understanding of the WDS. Open and transparent communication among all WSP team members and stakeholders is essential to ensure accurate risk assessment and efficient water system management. Timely and accurate data sharing among the various involved figures provides a comprehensive view of the water system and helps to identify potential issues or risks. Furthermore, a solid understanding of the WDS, including its components, water flow, or potential contamination points, is crucial for developing focused risk management strategies and ensuring water supply safety.

It should be underlined that risk assessment involves the identification and determination of potential events that may be related to the presence of microorganisms in WDS, representing a hazard to human health, while risk management refers to all measures aimed at removing or containing the risks identified in the assessment process *(World Health Organization, 2017; van den Berg et al., 2019*). Risk assessment relies on a multidisciplinary team, ranging from public health to water-use devices and equipment expertise, to analyze potential risks and identify prevention and control strategies. There are various strategies for risk assessment and management to ensure comprehensive water quality evaluation. These strategies encompass a range of approaches, including comprehensive monitoring programs, analysis protocols, and effective management practices *(World Health Organization, 2011*).

For sharing, implementing, and verifying if the planned preventive and containment measures maintain water quality, the activities of the different professionals involved are closely connected to an integrated system of data and information from different sources and institutions. As a result, water systems technicians, engineers, chemists, and biologists need to be continuously trained. Strong strategies should be developed and prioritized in a context where communication is fundamental to the transmission of information. All figures involved in WSP should have open channels of communication for facilitating the sharing of data. Effective communication makes work easier and ensures that all team members are aligned regarding risks and mitigation strategies. Everyone may assume collective responsibility for their role and contribute to the achievement of WSP purposes when they are informed and involved. This collaborative approach increases trust and confidence while also strengthens risk management. Establishing and maintaining clear and transparent communication facilitates stakeholders to share information, problem-solving, and cooperative work to ensure the safety and reliability of water supply systems.

To carry out an effective risk assessment in healthcare settings, a detailed understanding of the water system installation is also required. This understanding should take into account all of the building water uses, the patient groups exposed, and the type and implications of any contamination (*Maynard, 2020*).

From conventional disinfection methods, measures to mitigate the growth of microorganisms, especially *Legionella pneumophila*, have expanded to include building and plumbing system design interventions. Initially, these methods required trained operators and were like the measures used at treatment plants. Nonetheless, there has been a change towards maintenance-free strategies integrated into building design by architects and engineers. It is preferable to use maintenance-free engineering controls, prioritizing hazard removal, when reducing exposure rather than depending only on individuals' activities. Thus, the effective implementation of these engineering strategies involves collaboration among various professions, with architects, plumbers, building code officials, and building managers needing clear communication (*Proctor et al., 2022*).

It is imperative to maintain open lines of communication with building occupants on the results of water quality testing, necessary actions, and preventive measures.

2.5 Building Information Modeling

BIM can be considered an important innovation in the field of architecture, engineering, and construction industry. Traditional methods of building design, construction, and management have been completely revolutionized by BIM, which has increased efficiency, collaboration, and sustainability (*Datta et al., 2023; Pan et al., 2024*). It has redefined how a project is designed, constructed, and managed. In fact, the BIM approach has established a fundamental shift in how data and information are managed. By integrating 3D digital models, informative datasets, collaborative workflows, and multidisciplinary data, BIM enables professionals involved in construction projects to operate efficiently allowing for real-time collaboration. This integration speeds up project schedules, optimizes costs, and reduces the possibility of errors *(Nguyen and Adhikari, 2023; Pan et al., 2024*).

BIM, utilizing advanced technological platforms, introduced new operational processes, methods, and procedures, along with a novel approach to managing data and information. It can be defined as a representation process that creates and provides a multi-dimensional view of the building data throughout the life cycle of the building *(Borkowski, 2023*).

BIM is a digital representation of the physical and functional characteristics of a building. As such, it serves as a shared knowledge resource of information about a structure that provides a reliable basis for the many decisions to be made during its life cycle. By providing a centralized and integrated platform, BIM enhances communication, reduces errors, and facilitates more informed decision-making. The object in the BIM environment is not only a geometric representation but a data collector with a specific meaning. BIM is more than just a tool, it is an operational methodology for planning, designing, constructing, and maintaining a building using a model that contains all the information regarding the entire life cycle of a building, from planning to demolition. In fact, BIM should be viewed as a process rather than a technology or software; instead, the software serves as a tool to support this process (*Borkowski, 2023*).

A core premise of BIM is the collaboration of the stakeholders at various stages of a building life cycle to add, extract, update, or modify information within the BIM process. BIM serves as a shared digital representation based on standardized protocols to facilitate interoperability *(Azhar et al., 2012*).

Expanding beyond its traditional role in the design and construction phases, BIM proves its utility passing into the post-occupancy period becoming a valuable tool for Facilities Management and Building Operation, providing a centralized platform for managing all aspects of the building's ongoing performance (*McArthur, 2015*). The letter 'M', for example, can be associated with words like “Model” and “Management”, depending on whether it refers to the “product” describing the building or the “management and control” of the models or information. Currently, “Modeling” is the term that captures every aspect of the building process. Furthermore, there is a distinction between “Modeling” and “Model”. Modelling refers to the process of storing, managing, integrating, and generating information on a construction project, while Model is the core of the process, serving as a digital representation that gathers information from various disciplines and is continuously updated at every key project stage. The objective is to allow all participants involved in the project to optimize their actions and share information effectively, ensuring collaboration (*Modeling, Model, and Management: the three M’s of BIM and the right BIM tools; Sbiti et al., 2022*).

The BIM models are composed of parametric objects, i.e. virtual building components that are identified by modifiable parameters, such as dimensions. These virtual objects may also contain other types of data, such as material information (*Pocobelli et al., 2018*).

The comprehensive nature of BIM not only enhances the precision and intricacy of design processes but also facilitates virtual simulation and evaluation of multiple solutions. This capability contributes significantly to elevating the overall quality of the outcomes. In essence, BIM represents more than just a technological advancement; it represents a shift towards a more efficient, collaborative, and sustainable approach to building design and construction. Utilizing BIM brings about significant benefits such as time and cost savings, reduction of errors, and increased simplicity in design processes. Designers can work more efficiently by inputting objects with specific properties, leading to fewer errors and easier generation of complex models compared to traditional CAD methods *(Datta et al., 2023*).

The progressive evolution of BIM can be depicted through a series of levels as illustrated in the BIM Evolution/Maturity level diagram (*Bew and Richards, 2008*). Starting at Level 0, characterized by no collaboration and solely on 2D CAD, the evolution continued with Level 1, where the introduction of 3D models supplements the traditional 2D method. Level 2 represents a significant advancement marked by enhanced collaboration and coordination across disciplines, setting the stage for more efficient project delivery. Level 3 states a fully integrated, singular BIM model that resides in a centralized repository, facilitating data exchange and comprehensive project management. Currently, the AEC industry is generally at Level 2, recognizing the potential and benefits that BIM offers to project execution and oversight *(Siddiqui et al., 2021*).

BIM was developed for the design of new constructions, encompassing all processes and tools associated with this methodology. The first experiments aimed at creating BIM models of existing buildings were conducted on historic and monumental structures. The main objective was to establish a database to store the created models, which included a range of technical and informative data. BIM applied in the digitalization of existing heritage is known as Heritage BIM (HBIM). HBIM is an extension of BIM involving the development of a 3D model of historic building, incorporating detailed material properties, color and construction information, and historical details. The historical data and archival records gathered as part of the HBIM process offer a rich background for comprehending the growth and significance of the structure. Physical surveys of the building are then conducted, using technologies such as laser scanning and photogrammetry to record precise geometric data. These technologies offer high-resolution point clouds that serve as the basis for reconstructing building 3D geometry. Subsequently, the collected data is processed to create a detailed 3D model using specific software. This involves aligning and merging point clouds to create a unified, high-fidelity representation of the building. This final model incorporates all the information necessary for the management and planning of interventions on historical heritage. The HBIM model is not merely a digital replica but a repository of valuable information crucial for effective heritage management. It integrates material properties, construction techniques, and historical context, providing a holistic view of the structure. This comprehensive model serves as a resource for conservation planning and structural analysis *(Girelli et al., 2019, 2020; Rocha et al., 2020; Mora et al., 2021*). HBIM offers the advantages of preserving and enhancing cultural heritage through integrated representation. However, HBIM involves significant challenges, including complexity in data collection and the integration of often fragmented or incomplete information.

Linked to the HBIM is the Scan to BIM approach. This approach involves the use of laser scanner and photogrammetry to convert the existing condition of a building into a BIM model and it is useful for both new construction and restoration of existing buildings (*Rocha et al., 2020*). The advantages of Scan to BIM include high accuracy in representing the actual state of the building and the ability to detect deformities or deterioration. However, this process can be expensive and requires specialized skills to manage the data collected.

Starting from January 1, 2025, the updated Italian Legislative Decree n.36 of March 2023 established as mandatory the adoption of BIM for projects exceeding one million euros. This requirement applies to both the design and execution phases of new construction projects and renovations on existing structures, excluding routine and major maintenance tasks (*Legislative Decree March 31, 2023*).

The decree further underscores the significance of interoperability and the value of open formats that characterize BIM.

As commonly noted, BIM represents the hub for information integration and exchange, in a unified manner, across project participants using a 3D model as a platform. All the BIM model development software collect and store data in their native formats. This means that users will be unable to open the file unless they have access to it or the appropriate version of the software. To make information available to project users, a simple and accurate interoperability mechanism based on data exchange has been developed. Interoperability, or the ability of different projects and organizations to collaborate, is an essential component of the BIM approach. As demonstrated, BIM serves as the central hub for integrating and exchanging information among project stakeholders, using a digital 3D model as a platform to facilitate this unified approach. To improve the interoperability, the OpenBIM program supported by buildingSMART was proposed (*Building smart*). With the OpenBIM program, data management and models are not dependent on specific software or format. They have developed various approaches to improve software interoperability, the most well-known of which is the file format Industry Foundation Classes (IFC) (*Juan and Zheng, 2014*).

IFC provides the geometric information and non-geometric properties of the building components, as well as details on the connections between these components, encompassing all data structures across various stages of the building life cycle. As a result, IFC is a format that ensures that data can be freely shared and exchanged without loss of data or information. It is an open, neutral file format that is not controlled by any specific software manufacturer and exists solely to facilitate interoperability across the many operators. The main advantage of the IFC format is its ability to enable collaboration among various parties involved in the construction process by allowing them to exchange information through a standardized format. This results in improved quality, reduced errors, cost savings, and time efficiency, with consistent data and information across the design, construction, and maintenance phases. The geometric and non-geometric entities can be viewed, analyzed, and modified by different software that supports this format. Exporting project data created using BIM methodology into an IFC file means transferring data between different applications. The IFC format is open, free, and well-documented. By providing an IFC-compliant interface for export and import, software vendors can ensure interoperability with hundreds of other BIM tools and applications.

Concerning complex buildings or infrastructures, an additional step to ensure the accuracy of the IFC file model could be the use IFC model checking tools like Solibri (Solibri Inc., Finland). Solibri is a software designed for validating and checking BIM model, assuring the quality of the exported model, by analyzing every component of the project. With Solibri, it is possible to validate the IFC files to confirm they adhere to the correct structure including the proper names, unit, object and category membership. In conclusion, to verify that the IFC files generated by BIM software have the correct structure, they can be imported into Solibri for validation (*Solibri.com*).

2.7 Hydraulic parameters

Hydraulic parameters play a significant role in water quality evaluation as they influence the transport, dispersion, and mixing of contaminants within water other than to influence the design and functionality of the WDS (*Liu et al., 2017; Yao et al., 2023*). Understanding the hydraulic parameters such as water pressure and flow rate helps assess the overall dynamics of water quality and the WDS efficiency and effectiveness.

Water quality investigations frequently focus on microbiology or chemistry. There are a few insights into the connection between microbiology and hydraulic aspects that are critical for a better understanding of what occurs in building plumbing (*Palmegiani et al., 2022*). According to Palmegiani et al., the majority of existing governing equations are far more developed for the main WDS or wastewater system than for building plumbing, for example. This represents a limitation because building plumbing presents a series of specific features, including stagnation caused by differences in water use, pipe materials, microbial ecology, and chemical composition. All of these have an impact on the concentration of the contaminants in water (*Palmegiani et al., 2022*).

It was shown that the microbiological quality of water coming from a shower or a faucet can be different both at the point along the distribution system and at the point where water enters the building distribution system (*Ling et al., 2018; Palmegiani et al., 2022*).

From a hydraulic perspective, therefore, several parameters should be considered when monitoring water quality in a building plumbing such as flow rate, pressure, pipe diameter, and materials should be calculated and optimized.

Generally, studies regarding pressure and flow rate within a building plumbing are carried out to ensure water demand response at the various points of system use. The flow rate of each plumbing feature in a building is affected by variations in service pressure, pressure-flow value, and building demands (*Burkhardt et al., 2023*).

Flow rate plays a crucial role because the rate at which water flows through a system not only indicates how much water is delivered but also significantly affects the transport and dispersion of pollutants. Water quality is closely influenced by how long water stays in WDS. Over time, disinfectants added at the treatment facility lose their effectiveness in controlling pathogen growth. Slow water flow increases residence time and also reduces the friction along pipe walls, encouraging biofilm formation, while extended residence time allows more reaction between water and pipe materials. Understanding the link between system design, water residence time, and its effect on water quality is crucial for maintaining safe drinking water (*Persily et al., 2020*).

According to Lehtola et al., biofilm formation is increased with higher water flow velocity, but the effect changed with different pipe material properties: copper exhibited some antimicrobial characteristics that limited biofilm growth. In contrast, polyethylene provided a more favorable surface for microbial attachment and growth. Additionally, the increased flow velocity enhanced nutrient transfer, further accelerating biofilm formation development, especially in polyethylene pipes (*Lehtola et al., 2006*). Moreover, fluctuations in water pressure affect flow rates other than water quality and the potential for biofilm growth (*Burkhardt et al., 2023*). For example, *Legionella* spp. is frequently associated with low pressure, especially in warm water systems. This is because stagnant or slow-moving water at temperatures between 25 and 45 °C creates conditions for *Legionella* proliferation (*Sciuto et al., 2021*). *Pseudomonas* spp. can occur and they form biofilms and grow in stagnant or low-flow areas (*Said et al., 2013*).

As a consequence, accurate assessment and adjustment of these hydraulic parameters are essential for preventing common problems such as insufficient water supply, pipe bursts, or inefficient drainage. In light of what has been introduced so far, it is natural to say that monitoring the water pressure and using pressure-regulating valves could be helpful to ensure pressure levels and prevent drops that can lead to contamination. Minimizing stagnation is another critical point to prevent contamination.

Designing a plumbing system with minimal dead ends and encouraging use is useful for preventing stagnation other than flushing the system regularly, especially in low-use areas. Finally, regular inspections and building plumbing maintenance could help in identifying leaks, corrosion, or areas where biofilm may be forming.

In conclusion, a deep understanding and meticulous management of hydraulic parameters are key to optimizing both water quality management and plumbing system performance. Through a combination of advanced modeling, interdisciplinary collaboration, and adherence to best practices, engineers can develop systems that are efficient and effective.

Chapter 3

Case Study 1

The chapter was published as “New Frontiers in Water Distribution System Management and Monitoring: First Development of a Water Safety Plan Based on Heritage Building Information Modeling (HBIM) in Neptune Fountain, Bologna, Italy. Pascale MR, Roggio DS, Barbieri E, Marino F, Derelitto C., Girolamini L., Bragalli C, Bitelli G., Cristino S, *Water*, 2024, 16 (15), pp. 1 – 25. DOI: https://doi.org/10.3390/w16152075”.

The Chapter provides an in-depth exploration of Case Study 1, the Neptune Fountain in Bologna, Italy offering some additional details beyond the material already included in the published paper.

A historical overview is provided and its WDS is described both before and after a significant and innovative restoration phase in 2017. Moreover, this Chapter details the materials and methods used for the research conducted on the Fountain aiming to achieve the main purpose of the study. Finally, the results are presented and discussed.

Case Study 1: The Fountain of Neptune in Bologna, Italy

The Neptune Fountain represents the PhD pilot project from which the groundbreaking research concept and purpose originated.

BIM approach and novel management strategy for a historical symbol, like the Neptune Fountain in Bologna, shows significant progress in several areas. While it innovatively manages the water system, it also focuses on the preservation of historical heritage over time, and the maintenance of high-water quality in line with the WSPs, safeguarding public health.

The 2017 Fountain restoration utilized novel techniques and innovative survey process management. A highly advanced and integrated project was designed based on cooperation among interdisciplinary teams that could consider the features of the ancient Fountain. The Neptune Fountain 3D survey was made possible by the methods outlined in the next paragraphs. The University of Bologna Geomatics group at the Department of Civil, Chemical, Environmental, and Materials Engineering (DICAM) from the University of Bologna, enabled the development of georeferenced mapping of the data about the monument elements and the pipes *(Apollonio et al., 2017, 2018; Girelli et al., 2019, 2020*).

Central to this restoration effort is an innovative project that has revolutionized diagnostic and restoration operations on precious marbles and bronzes. This system is designed to creatively, effectively, and easily collect, share, manage, and analyze all data and information related to diagnostics and restoration (*Girelli et al., 2019*). By directly engaging with the 3D model, restorers identified damaged areas and proposed solutions, this method demonstrated a remarkable combination of invention and practicality (*Girelli et al., 2019*).

The comprehensive approach began with the Neptune Fountain, aiming to integrate water quality monitoring and hydraulic analysis with the understanding of the infrastructure and operation, taking advantage of the potential offered by the BIM models. Drawing from the experience of digitizing marbles and bronze, the design of the new WDS was accomplished by recognizing that the preservation of the Fountain is linked to the water properties.

The main purpose of this case study was to develop an innovative approach for monitoring microbiological quality through a so-called "Integrated" approach. This approach combines microbiological analysis, hydraulics parameter measurements, and the support of the Scan-to-BIM approach to enhance WDS management.

3.1 The Neptune Fountain

The Neptune Fountain is an important and iconic monumental civic fountain located in the heart of Bologna, Italy. Situated in its homonymous square, the Fountain represents an invaluable treasure for the Bologna citizens (Figure 3). The Fountain is not only a stunning work of art, but it embodies the rich Bologna history and cultural heritage. The surrounding area is a popular destination for both locals and visitors who visit the city every day other than to be a point for different events and meetings in the city.

Fig. 3: *Fountain of Neptune, Bologna, Italy*

Commissioned by the Cardinal Legate Charles Borromeo and supervised by Bishop Pier Donato Cesi, the Fountain is a Renaissance masterpiece intended to symbolize the glory of Pope Pius IV and the power of the Catholic Church: The Pope ruled the world as Neptune ruled the seas, representing Neptune, the Roman god of the sea, in a ruling pose with his trident and outstretched hand.

The Fountain was built between 1563 and 1565 by the Sicilian architect Tommaso Laureti and Flemish artist Jean de Boulogne, also known as Giambologna. The Fountain was designed to be an impressive demonstration of an extraordinary municipal water system, as well as a symbol of effective governance of the newly elected Pope, Pius IV.

Characterized by a symmetrical design, the Fountain features a main marble basin resting on three marble steps, crowned by the bronze figure of Neptune, approximately 320 cm high, standing on a marble pedestal at its center, the *castellum*. Below Neptune, four cherubs holding dolphins, represent the major rivers of the then-known continents, the Ganges, Nile, Amazon, and Danube. Four Nereids adorn the lower part of the *castellum*. Papal symbols and emblems are present throughout the structure (*Comune di Bologna; Gaiani, 2017*).

Water has always been the leading element of the Fountain design, with 38 nozzles emerging from the bronze sculptures to create a unique water play. The main basin collects all the water from these jets (*Bragalli et al., 2017*).

However, regular maintenance actions for proper functionality were required from the beginning. These actions are all connected to water, which is the Fountain's main weakness. Indeed, beginning in the 18th century, several restorations were carried out throughout time to mitigate the Fountain's progressive state of degradation, mostly of which was caused by the presence of water. Over time, water has facilitated bacterial and algae growth, leading to biofilm formation on the surface, as well as contributing to limescale accumulation and bronze corrosion (*Bragalli et al., 2017*).

The most current restoration started in 2016 and finished in 2017, not only did crucial repairs to the marble and bronze elements but also emphasized the significance of maintaining good water quality and maintaining a functional WDS and treatment system to preserve the maintenance work completed. The last restoration introduced innovative survey methodologies and process management techniques, involving collaboration among biologists, engineers, restorers, architects, and art historians. A 3D model of the Fountain was developed to collect, share, manage, and analyze all the data related to restoration actions, by combining various geomatic techniques (*Girelli et al., 2019, 2020*).

3.2 Neptune Fountain Water Distribution System

The Fountain features a recirculation system designed to maintain continuous water flow within it. This system is comprised of two main systems: The Water Treatment System (WTS) which collects water from the Fountain that needs to be treated, and Reintegration System (RS) which refills water lost during the normal Fountain operation.

Water for the Neptune Fountain comes from a technical room in the Palazzo d'Accursio basement, located next to the Fountain. From here, water is pumped with sufficient pressure to supply the nozzles, and the water flow is distributed into smaller pipes corresponding to each Fountain jet near the niche in the tunnel leading to the Fontana Vecchia in the 16th century.

The water that overflows from the main basin is directed back to the underground technical room via the Fountain, accumulating in a basin via a gravity-driven pipeline. The RS is connected to the municipal water network, enabling the reintegration of water loss due to evaporation or when the Fountain's main basin is emptied. Finally, the treatment systems responsible for purifying the recirculating water before it is returned to the Fountain are located below ground.

3.2.1 Neptune Fountain Water Distribution System before the restoration

None of the original components comprising the water supply system were present in the Fountain WDS in operation during the 2016 restoration. Unfortunately, comprehensive plans and documentation detailing the design and precise functionality of the Fountain WDS up to 2016 were unavailable. Thus, the reconstruction of the scheme and understanding of WDS operations relied largely on inspections conducted to approximate their configuration and functioning.

The existing WDS included a very simple water reintegration and recirculation system. Essentially, an entry point for aqueduct water was designated to compensate for the water loss during the Fountain operation. From there, the water passed through a softener into a storage tank and then directed to the Fountain. Conversely, water from the Fountain was directed into a plastic storage tank with a float mechanism to regulate reintegration volumes. Finally, a pump sent the water to the Fountain. Chlorination was manually performed in the plastic storage tank as a disinfection treatment. WDS inspections revealed malfunctions of some WDS components, necessitating the replacement of the WTS. This replacement was imperative not only due to the aging of the components but also to ensure the proper administration of disinfectants. Discussions emphasized the critical need to strike a balance between the disinfectant's potentially corrosive effects on marble and bronze materials and its efficacy in containing microbial contamination in water. Moreover, potential sources of contamination, such as bird droppings entering the Fountain and the possibility of water contact with visitors, were considered. These considerations led to replacing the looped WDS and the related WTS to prevent and contain microbial contamination rather than ensure long-term reliability and minimum maintenance.

3.2.2 Neptune Fountain Water Distribution System after the restoration

The comprehensive layout of the current Neptune Fountain water system is shown in Figure 4, illustrating that recirculation within the Fountain is possible using the two systems.

WTS and RS provide the water required for the Fountain delivery line, which is then distributed into seven nozzle supply lines. The recommended total design flow rate for the Fountain during the restoration is 2.35 L/s.

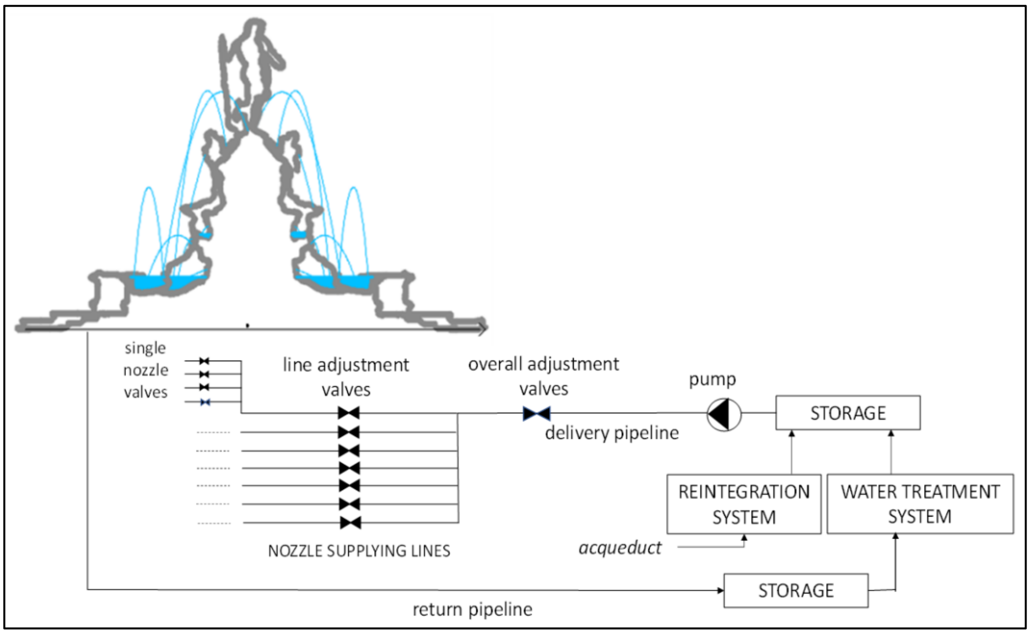


Fig. 4: *Representation of the current operation of the Neptune Fountain (the light blue lines represent the water game trajectories) (Pascale et al., 2024)*

In particular, the separation of WTS and RS within the WDS Fountain allows for distinct treatment processes that the water needs. Water circulating through the WTS undergoes treatment before being reintroduced to the Fountain, aiming to mitigate bacterial contamination. Meanwhile, RS refills lost water volume by sourcing water from the municipal aqueduct, which is subjected to filtration and reverse osmosis to minimize salt content and reduce residual chlorine levels. A valve system, located in a tunnel under the Fountain, allows the trajectory of the nozzles to be corrected and adjusted, ensuring dynamic water games.

The layout of the new WDS was elaborated with AutoCAD 2023 version T.53.0.0 ($^{©}$2022 Autodesk, Inc.) and is shown in Figure 5 distinguishing a simple scheme of the WTS in green pipelines and RS in blue pipelines. Additionally, Figure 5 indicates the components that were integrated into the system to enhance disinfection treatment and reduce microbial contamination. The functions of these added components are detailed in Table 2. It should be noted that certain WDS components are shared between the WTS and RS.

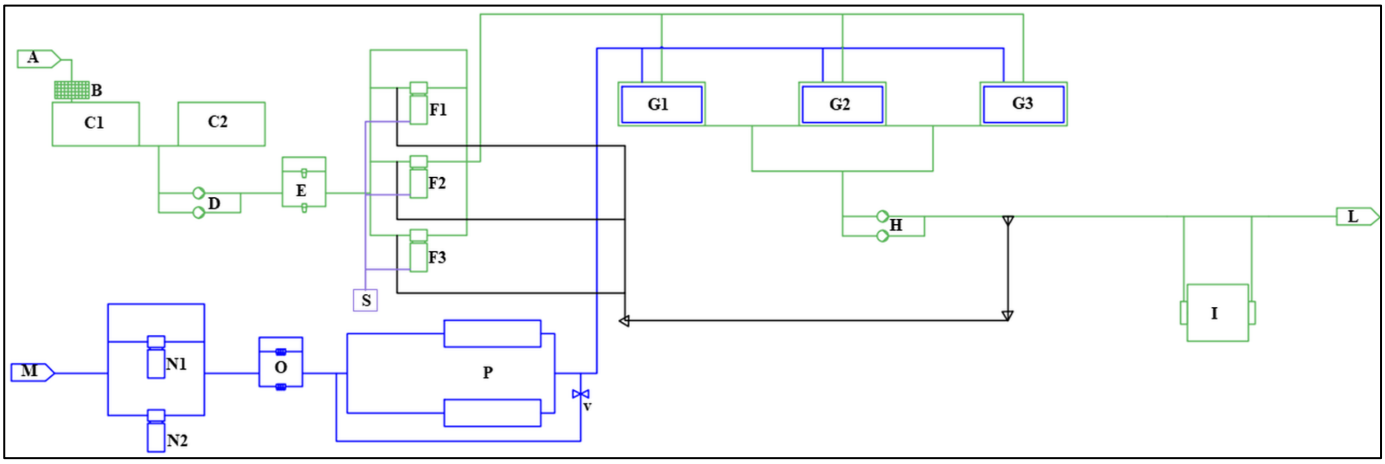


Fig. 5: *Neptune Fountain: WDS layout for WTS (green lines) and RS (blue lines) with the indication of the components listed in Table 2.*

***Table 2:** List of WTS and RS components along with their specific functions and technical characteristics.*

WDS part	Components ID	Functions and technical characteristics
WTS	A	Incoming pipes collect water entering the system via the Neptune Fountain.
	B	Rotating screener to remove particulates and coarse filtration of water. Maximum flow rate: 18 m^3/h
	C1 – C2	Two parallel-connected polyethylene storage tanks, each with a capacity of 1600 L.
	D	Two pumps are designed to pressurize the system pushing the water from C1 – C2 into the system's later components. Their activity is based on the level in C1 – C2 and preset outlet pressure.
	E	Self-cleaning filters capture the solid particles and reduce turbidity by allowing heavier particles to settle into the filter storage container. Porosity: 100 µm Flow rate at $\Delta P = 0.2$ bar of 25 m^3/h and at $\Delta P = 0.5$ bar of 30 m^3/h
	F1 – F2 – F3	Three in-series sand filters aimed to reduce turbidity and suspended materials overall while providing filtration using mineral layers of granular anthracite and silica sand. Operational flow rate: 5 m^3/h Operational pressure range: min 2 – max 8.3 bar
WTS and RS	G1 – G2 – G3	Three parallel-connected polyethylene storage tanks each with a capacity of 2000 L.
	H	Two pumps are designed to pressurize water to the Fountain and ensure the flow rate for sand filters F1 – F2 – F3 backwashing.
	I	UV Lamp emits light at 254 nm and 400 J/m^2 to eliminate any form of contamination.
	L	Pipeline for the return of the treated water to the Fountain.
RS	M	Entry point for the municipal aqueduct
	N1– N2	Two parallel mixed media filters composed of silica sand and mineral granular activated carbon to dechlorinate water. Operational flow rate: 3,5 m^3/h
	O	Eight cartridge filters with a porosity of 5 µm and a maximum flow rate of 4,8 m^3/h
	P	Reverse osmosis system aimed to remove salts from water with osmotic membranes also reducing the microbial presence.

3.2.3 Water path description within WTS and RS

The water path in the WTS and RS is specifically described in the bullet points below, according to the layout shown in Figure 5.

Regarding the WTS path (green lines in Figure 5): (i) incoming water from the Neptune Fountain (A) undergoes coarse filtration via the rotary screener (B) before being collected in the two storage tanks (C1-C2) for the decantation phase.

(ii) Water is forced forward in the system by the pressure generated by the two pumps (D). Water, from the storage tanks (C1-C2), passes through the self-cleaning filters (E) and is directed to the sand filters (F1-F2-F3).

(iii) Following the self-cleaning filters (E), water undergoes further filtration through the three sand filters (F1-F2-F3) which utilize multiple mineral layers of granular anthracite and silica sand to minimize turbidity and suspended substances, reducing the microbial concentration.

The operation of the two pumps (D) is important at this stage because they provide the flow rate and pressure required for the operation of the three in-series sand filters (F1-F2-F3).

(iv) After sand filter filtration, water is collected into three polyethylene storage tanks (G1-G2-G3). Floats within the tanks (C1-C2) and (G1-G2-G3) monitor the minimum required water level for pump operation and protection.

(v) From the storage tanks (G1-G2-G3), two pumps (H) drive water to a UV lamp treatment (I).

(vi) Finally, treated water is directed to the Fountain across the main pipelines (L).

The proper operation of the pump H is important not only for the hydraulic operation of the UV lamp but also for regulating the trajectory of water that comes out of the 38 nozzles in the Fountain.

Concerning the RS (blue pipeline in Figure 5), which addresses water lost through evaporation, filter washing, and possible leakages. Water reintegration is activated by float switches in the storage tanks (G1-G2-G3). When the float reports a water level below the set threshold for the pump operation, water is drawn from the municipal aqueduct (M). In this way, the storage tanks (G1-G2-G3) are filled with pure water, restoring the water to a sufficient volume to ensure the operation of the Fountain, maintaining adequate volume for Fountain operation, and regulating recirculation water replacement times. In the RS system, water is refilled following the next path:

(i) Water from the municipal aqueduct (M) is dechlorinated by the two parallel mixed media filters (N1-N2), and filtration through the parallel cartridge filters (O). In this system, an important treatment occurs through the reverse osmosis process (P) which deprives salt from the water to prevent bronze and marble deterioration. Osmotic membranes reduce microbial presence, preventing contamination of the produced osmotic water. A bypass valve (v) at this level, allows to reintegrate only osmosis-treated water, or with a mixture of osmosis-treated and dechlorinated water.

(ii) Osmotized water is collected in the storage tanks (G1-G2-G3), where is mixed with the water filtered by the sand filters (F1-F2-F3). Again, before being sent to the Fountain, water is treated with the UV lamp (I).

To conclude the description, it is necessary to state that although WTS and RS are two separate systems with distinct roles in water treatment, they ultimately converge to form a unified system beginning at the G1-G2-G3 water tanks and following the same route to the Fountain, leading in UV lamp treatment (I).

3.2.3.1 Sand Filters backwashing

The final stage of water treatment before it is gathered in the G1-G2-G3 tanks, designated for storing clean, treated water, involves sand filtration along the WTS. To maintain the efficacy of the sand filters (F1-F2-F3), an automatic and programmed backwash is scheduled twice a week. For this process, water from storage tanks (G1-G2-G3), a mixture of osmotized water from RS and water filtered by the sand filters (F1-F2-F3) themselves, is utilized. At the end of the backwash cycle, wastewater is discharged into the sewer (S), as indicated by the purple pipelines in Figure 5.

Each backwashing cycle lasts 15 minutes, requiring a flow rate of 6.8 m^3/h, thus necessitating 1.7 m^3 of water. The required flow rate for each sand filter's scheduled backwashing is provided by the two pumps (H). As a result, these pumps play an important role for the proper hydraulic Fountain operation, as well as the correct backwashing of the individual sand filters (F1-F2-F3).

3.3 Case Study 1: Research Methodologies

The section provides an overview of the methodologies employed in this case study including sample selection, instrumentation, experimental studies, protocol implementation, and the development of a WSP.

3.3.1 Microbiological sample points identification on Neptune Fountain WTS

A precise sampling plan is imperative to accurately identify and describe all water sampling points. These points should be strategically chosen to ensure a representative sample aligns with the sampling program goals. Clear specification of sampling objectives facilitates the selection of appropriate sampling locations. The sampling points along Neptune Fountain WTS to evaluate microbiological water quality were chosen to analyze the effectiveness of each water treatment stage, including filters, osmosis, and UV lamp systems. In addition, samples were also collected from the Fountain main basin to evaluate the quality of water accessible to people.

The list and description of all the sampling points are reported in Table 3 and schematized in Figure 6. Notably, as the WTS and RS converge at the accumulation tanks G1-G2-G3, sampling points 5A, 5B, 11, and 12 are common to both systems.

***Table 3**: Position, list, and description of sampling points for microbiological analysis on Neptune Fountain WTS*

Position on the WDS	**Microbiological sampling points ID**	**Sampling points description**
RS System	1	Water delivery by municipal aqueduct (M)
	2A	Mixed media filter (N1) outlet
	2B	Mixed media filter (N2) outlet
	3A	Cartridge filters (O) outlet – point A
	3B	Cartridge filters (O) outlet – point B
	4A	Osmotized reintegrated water in reverse osmosis process (P) outlet section
	4B	Dechlorinated, filtered, and osmotized reintegrated water in reverse osmosis process (P) outlet section
WTS and RS System	5A	Storage tank (G2) outlet
	5B	Storage tank (G3) outlet
WTS System	6	Return from the Fountain
	7	Water outflow from the rotary screener (B) in the storage tank (C1 – C2)
	8A	Storage tank (C1) (bottom discharge)
	8B	Storage tank (C2) (bottom discharge)
	9	Self-cleaning filter (E) outlet
	10A	Sand filters (F1) outlet
	10B	Sand filters (F2) outlet
	10C	Sand filters (F3) outlet
WTS and RS System	11	UV Lamp (I) inlet
	12	UV Lamp (I) outlet

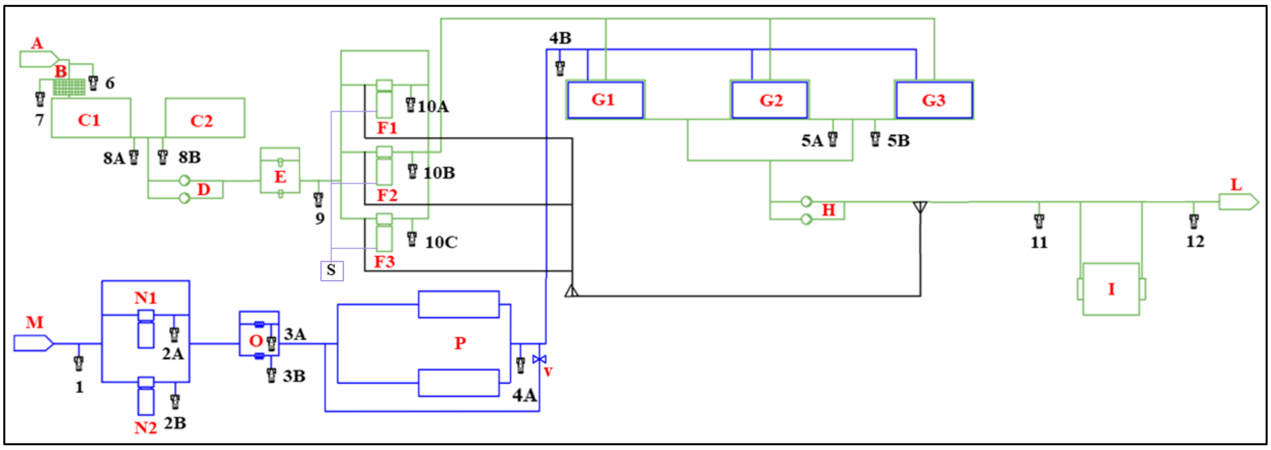


***Fig. 6:** Neptune Fountain WTS layout including sampling points for microbiological analysis for WTS (green lines) and RS (blue lines).*

3.3.2 Water sampling for microbiological analysis

Once sampling points were identified and a sampling plan was established, water samples were collected in accordance with Italian National Unification and European Committee (UNI EN) International Standard Organization (ISO) 19458:2006 for microbiological testing (EN ISO 19458:2006, 2006). A volume of 500 mL was taken from each selected water sampling point using sterile polytetrafluoroethylene (PTFE) bottles.

Upon collection, all samples underwent measurement of water temperature using a digital thermometer coupled with a liquid thermistor probe (XS Temp 7 Vio PT 100 Thermometer from –200 to +999 ˚C; Eutech Instruments Pte Ltd., Singapore). Simultaneously, the levels of total and free chlorine were assessed to measure the disinfectant concentration from the municipal supply. These measurements were performed with a chlorometer (Orbeco-Hellige, Inc., 6456 Parkland Drive, Sarasota, FL, USA, Mini Analyst, Series 942, Model 942-001) and expressed in mg/L.

Subsequently, the samples were transferred out of direct light and stored in the fridge at 4 °C until the analysis was conducted on the same day, or at the latest, the following day.

Microbiological analyses were conducted shortly before the restoration (2016), but there was no environmental monitoring plan, and the WDS was in a damaged condition. Following the WDS replacement, a microbiological water quality monitoring plan was developed, initially targeting one sampling per year. Hence, the first set of analyses were carried out to test the new WTS and RS in 2018. Unfortunately, the planned sampling campaigns in 2019 and 2020 were missed because of extraordinary maintenance programs on Fountain marbles and bronzes, as well as the onset of the SARS-CoV-2 pandemic.

In 2021, a series of sampling campaigns (S) was carried out in spring (S1), in autumn (S2), and after extraordinary maintenance (S3) prompted by non-compliant results from the autumn sampling campaign (S2).

3.3.3 Microbiological analysis

To assess the water quality of the Neptune Fountain, microbiological analysis was conducted following the Italian Legislative Decree 31/2001 and the subsequent implementation of European Directive 2015/1787 transposed with the Italian Decree dated June 14, 2017 *(Legislative Decree Feb 2, 2001; Ministerial Decree 14.06.2017, 2017*).

These directives indicate that heterotrophic plate counts (HPC) at both 22 °C and 37 °C are to be analyzed using cultural methods and expressed as colony forming unit (cfu)/mL. Pathogenic bacteria such as *Enterococcus* spp., *Pseudomonas aeruginosa* (*P. aeruginosa*), total coliform bacteria, *Escherichia Coli* (*E. coli*), and *Clostridium perfringens* (*C. perfringens*) were researched in water samples. In addition, *Staphylococcus aureus* (*S. aureus*) contamination was also considered as an additional indicator parameter considering the high exposure of visitors to water *(Istituto Superiore di Sanità, 2007*). The results were reported in cfu/mL and compared to legislative limits: 100 cfu/mL for HPC at 22 °C, 20 cfu/mL for HPC at 37 °C, and 0/100 mL for pathogenic bacteria. Each parameter was analyzed following the specific ISO.

The standard plate method was used for HPC analysis, where bacteria growth was observed on plates after adding a warm liquid medium to sterile Petri dishes containing 1 mL of the water sample.

For the assessment of bacterial indicators, the membrane filtration technique was employed. This method utilizes filter systems connected to vacuum pumps and membranes of varying porosities, depending on the analysis required. Cellulose nitrate membranes with a pore size of 0.45 µm were used in these analyses (Sartorius Italy S.r.l., Firenze, Italy). The membrane is placed on the sterilized filter ramp using sterile tweezers. The sample was concentrated on the membrane that was then placed on a selective growth medium for bacterial indicator growth.

Table 4 provides a summary of the microbiological parameters, including corresponding growth media, incubation time and temperature, and reference ISOs.

Table 4*: Culture medium, incubation time (h) and temperature (° C), and the referred ISO used for microbiological parameter analysis.*

Microbiological parameter	Culture medium	Incubation (h) and (° C)	ISO
HPC 22 °C	Plate Count Agar (PCA) (Biolife, Milan, Italy)	72h 22 °C	UNI EN ISO 6222:2001 (*UNI EN ISO 6222:2001, 2001*)
HPC 37 °C		48h 37 °C	
Enterococcus spp.	Slanetz Bartley Medium (Enterococcus Agar) (Thermo Fisher Scientific, Diagnostics, Ltd., Basingstoke, UK)	48h 37 °C	EN ISO 7899-2:2000 (*EN ISO 7899-2:2000, 2000*)
P. aeruginosa	*Pseudomonas* C-N Selective Agar (Cetrimide Agar) (Thermo Fisher Scientific, Diagnostics, Ltd., Basingstoke, UK)		UNI EN ISO 16266:2008 (*UNI EN ISO 16266:2008, 2008*)
E. coli and coliform bacteria	Chromogenic Coliform Agar (CCA) (Thermo Fisher Scientific, Diagnostics, Ltd., Basingstoke, UK)	24h 37 °C	UNI EN ISO 9308-1:2017 (*UNI EN ISO 9308-1:2017, 2017*)
C. perfringens	m-CP Selective Agar (Thermo Fisher Scientific, Diagnostics, Ltd., Basingstoke, UK)		UNI-EN-ISO 14189 (*UNI EN ISO 14189:2016, 2016*)
S. aureus	BrillianceTM Staph 24 Agar (Thermo Fisher Scientific, Diagnostics, Ltd., Basingstoke, UK)		Unavailable*

*A reference ISO for its detection in water samples is not available.

Following the incubation time, the suspected colonies were subjected to biochemical typing using various kits including the Crystal Enteric/Non-Fermenter ID kit (Crystal E/NF) or BBL Crystal Gram Positive ID kit (Crystal GP) (Becton Dickinson Cockeysville, MD, USA), the Remel RapID NF Plus system, RapID SS/u system and Rapid ANA II (Thermo Fisher Scientific, Diagnostics, Ltd., Basingstoke, UK), according to the manufacturer instructions. Additionally, identification was conducted using the MALDI Biotyper System (Bruker Daltonik GmbH, Bremen, Germany).

Some sampling campaigns also involved the *Legionella* spp. isolation, to enhance the WSP. The gold standard culture technique outlined in ISO 11731:2017 was used for *Legionella* analysis (*ISO 11731:2017, 2017*). For *Legionella* spp. enumeration, 200 µl of untreated water samples were directly smeared on selective Glycine-PolymyxinB-Vancomycin-Cyckiheximide (GVPC) agar (Thermo Fisher Scientific, Diagnostic, Ltd., Basingstoke, UK). One liter of the water samples was filtered and concentrated on a 0.22-µm polyethersulfone membrane (Sartorius, Bedford, MA, United States). After filtering, the membrane was placed in ten mL of buffer solution and mechanically agitated to facilitate the resuspension of the deposited material. The remaining bacteria attached to the membrane were then mechanically separated. Subsequently, 100 µl aliquots were seeded onto GVPC plates and heat treatment was applied to decontaminate the sample. In the final stage of the analysis, heat treatment at 50 °C for 30 minutes eliminated competing bacterial flora due to the heat resistance of *Legionella* spp. Another decontamination method involved treatment with an acid solution. After the heat decontamination, 100 µl aliquots were seeded on GVPC plates.

The GVPC plates were incubated for 15 days at 35±2 °C with 2.5% CO_2 and examined every other day. Colonies with typical or atypical morphology were enumerated and subcultured on buffered charcoal yeast extract (BCYE) agar, with (Cys+) and without (Cys-) L-Cysteine (Thermo Fisher Scientific, Oxoid, Ltd., Basingstoke, U.K.). *Legionella* spp. colonies were differentiated based on their growth on Cys+. The only two exceptions are *Legionella oakridgensis* and *Legionella spiritensis* which can grow also in the absence of Cysteine (*ISO 11731:2017, 2017)*.

Identification of colonies was performed using *Legionella* latex agglutination test kit differentiating between *Legionella pneumophila* (*Lp*) serogroup 1, *Lp* serogroups 2-14, and seven non-*Lp* species (Thermo Fisher Scientific, Ltd. Basingstoke, UK), according to the manufacturer instructions.

Identification using the MALDI Biotyper system (Bruker Daltonik GmbH, Bremen, Germany) was performed to distinguish the presumptive *Legionella* spp. colonies as previously described *(Pascale et al., 2020*).

3.3.4 Hydraulics sample points identification on Neptune Fountain WTS

Monitoring hydraulic parameters was essential to continuous pump operation, maintain water flow to the Fountain, and prevent water leakage. Optimizing water treatment parameters could only begin within a framework of stable and calibrated hydraulic operations. Therefore, water flow and pressure were monitored to control the WDS functionality and their impact on water quality. In this case, the hydraulic sampling point was strategically chosen to assess the pump operation and ensure proper water flow to the Fountain.

Table 5 provides a list of hydraulic sampling points along with their descriptions, while Figure 7 illustrates the locations of these sampling points.

***Table 5:** Hydraulic sampling points located on the WTS and their description.*

Hydraulic sampling point ID	Sampling points description
PM1	Pressure monitoring downstream pumps (H)
PM2	Pressure monitoring before the UV Lamp (I)
PM3	Pressure monitoring sending to the Fountain
FM1	Flow monitoring downstream pumps (H)
FM2	Flow monitoring sent to the Fountain
FM3	Flow monitoring for sand filters (F1-F2-F3) backwashing

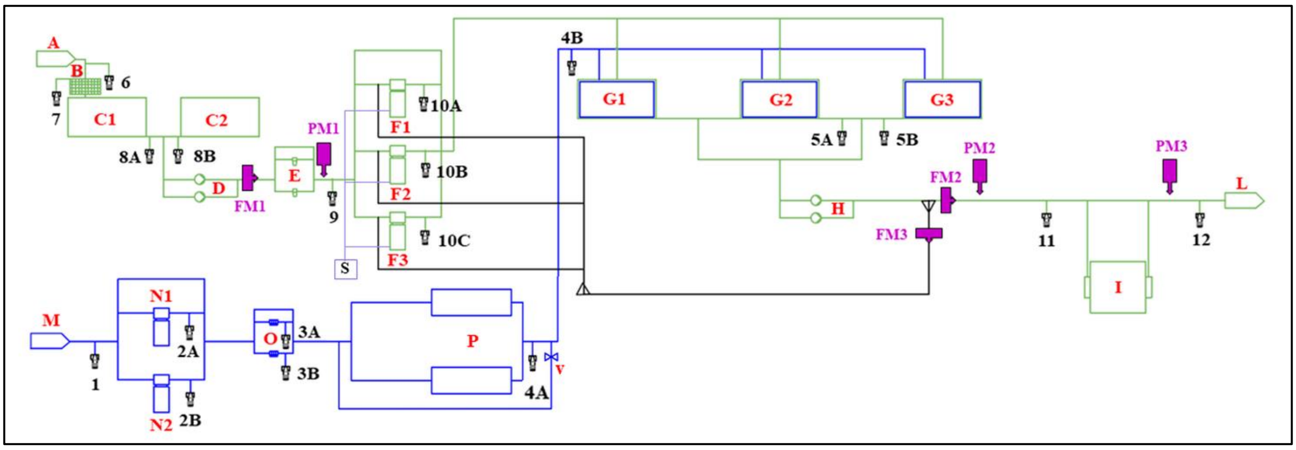


***Fig. 7:** Neptune Fountain WTS layout including sampling points for hydraulic parameters measurements for WTS (green lines) and RS (blue lines).*

3.3.5 Hydraulics parameters measurements

The WDS of the Neptune Fountain consists of the collaborative operation of WTS and RS. Ensuring proper regulation of the water pressure and flow parameters is essential to the Fountain's overall functioning.

As previously explained in Paragraph 3.2.3, several pumps ensure the recirculation of water within the Fountain. Therefore, it is crucial to align hydraulic operating parameters with the technical requirements of the two types of filters, as well as the nozzle operation and water demand for the system's overall operation. Monitoring water pressure and flow rate is essential during both normal operation and filter backwashing to assess the accuracy of the required values and the overall operation of the Fountain's WDS.

For pressure measurements, two Endress-Hauser piezoresistive-type pressure transducers, with FS 10 bar and an accuracy of 0.5% FS were used. Transducers were installed on biochemical sampling points and drain points utilizing ¼" diameter silicone tubing. Analog signal from the mA transducer was obtained at a frequency of 10 Hz using a portable cDaq and a National Instrument card. A Labview program averaged the analog signal per second and transformed it into a pressure signal.

On the other hand, the water flow rate was measured using an ultrasonic device (transmitter and receiver) of the clamp-on type—that is, installed on the pipe. This device operates by generating an ultrasound beam of a specific frequency through repetitive voltage pulses applied to the transducer crystals. The ultrasound transmission occurs both downstream and in the reverse direction, and the transmission rate through the liquid is affected by its speed. The difference in transmission times is directly proportional to the liquid velocity.

3.3.6 Scan to BIM approach

The integration of two distinct geomatics techniques, digital terrestrial photogrammetry and structured light projection scanner was used to model the WTS and RS. More specifically, a Scan-to-BIM approach was applied to develop an "as-built" model based on 3D survey data covering about 35 m^2.

The Scan-to-BIM workflow for the Neptune Fountain comprised four main steps: (i) Project designation, (ii) data collection, (iii) data survey processing, and (iv) BIM model return.

(i) Site inspections were crucial during the project designation to assess geometric characteristics and potential obstacles such as lights and reflective materials, which could complicate data collection.

(ii) During the data collection phase, the Mantis Vision F6 Smart hand-held scanner, operating in near-infrared wavelengths (NIR) was employed to capture data at a rate of about 8 frames per second (60,000 points per frame). Five-point clouds were created by the scanner using roughly 5500 frames. The area of interest needed to have 27 targets positioned at various heights and a Multi-View Structure-from-Motion method was performed to permit the data fusion with the scanner-derived dataset. The RGB data was obtained using a Sony DSC-RX100M7 digital compact camera capturing 224 images. To mitigate interference from neon lights with the F6 scanner, the survey was conducted with the lights turned off, resulting in a total of five scans comprising 5,432 frames.

This model served as the foundation for subsequent BIM modeling to integrate information about each component for management purposes. For the application of the Scan-to-BIM approach and better management during BIM geometric restitution, the textured mesh was converted into a point cloud data resampled by setting the average point spacing to 2.5 mm.

Subsequently, the point cloud was linked to Autodesk BIM software Revit® (Autodesk Ink., version 2021.1.1) through Recap pro 2021.1 software (.rcs format). To streamline modeling and improve accuracy and efficiency, the FARO As-Built plug-in for Autodesk Revit® was used to model the components. The plug-in incorporated semi-automatic element recognition algorithms to suggest corresponding BIM objects overlaying them directly onto the point cloud model. The result was a highly precise Historic Building Information Modeling (HBIM) model with an average tolerance of a few millimeters.

Figure 8 reports the post-processing that allowed to obtain an accurate geometric model coupled with RGB information.

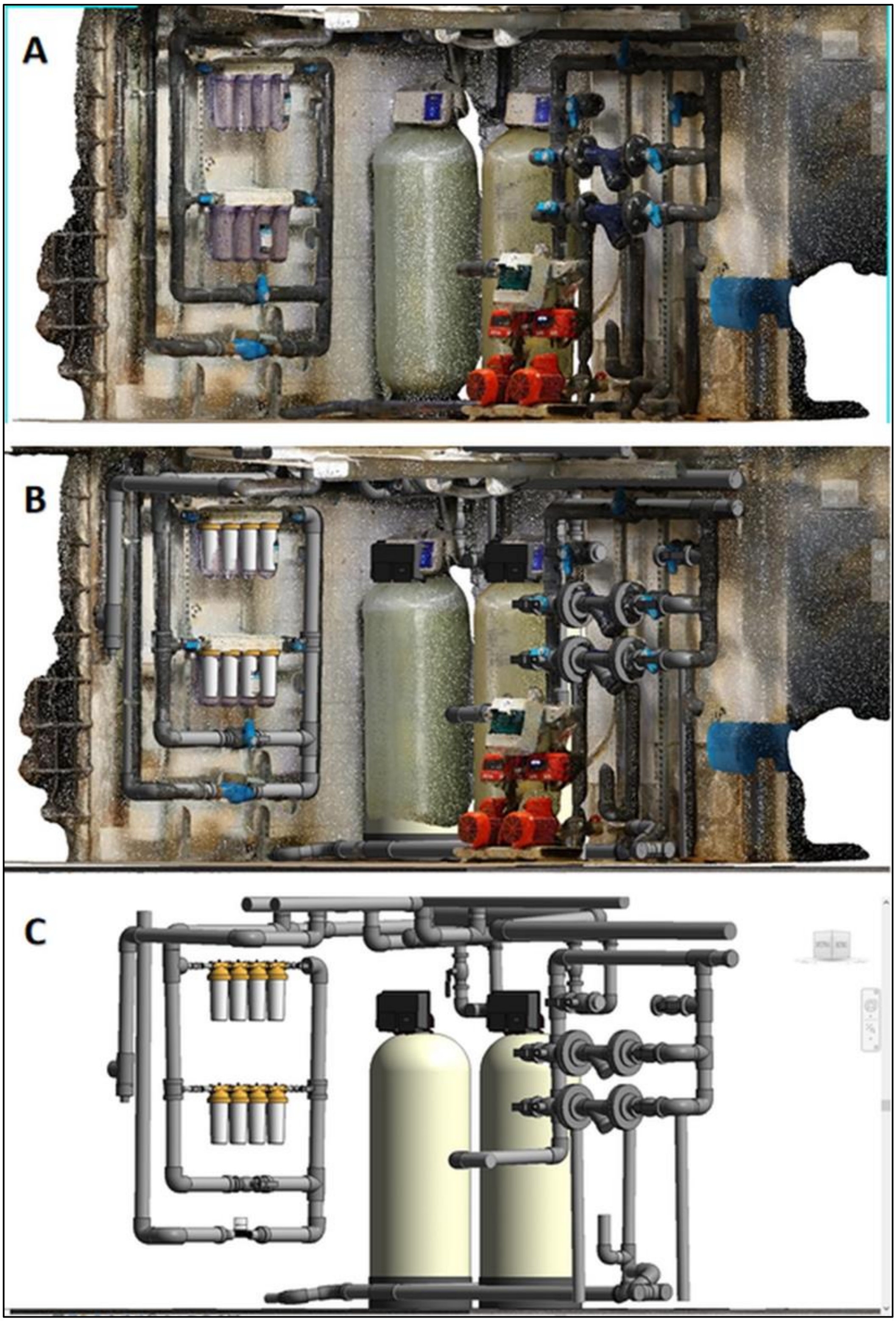


***Fig. 8**: Post-processing steps for a section of the Neptune Fountain's RS from the point cloud to the HBIM model: (A) 3D point cloud model; (B) 3D point cloud model vs HBIM model; (C) final HBIM model.*

3.4 Case Study 1: Results

In the following subsections, the results obtained from the integration of the methodologies described above are presented. Specifically, the microbiological analysis was performed during several sampling campaigns, together with the analysis of hydraulic parameters measurements and the results of the Scan-to-BIM approach.

It is important to underline that pre-restoration sampling results are briefly mentioned and not elaborated upon extensively. This is because their significance lies primarily in setting the stage for subsequent discussions, underlining the importance of including the WDS in the restoration process. Microbiological analyses have highlighted the presence of contamination within specific points in the WDS. Notably, the examination of hydraulic parameters, such as water pressure and flow rate has led to a substantial reduction in contamination levels.

3.4.1 Microbiological analysis results

In the analysis conducted before the restoration, all the microbiological parameters were found to be within regulatory limits. This compliance can be attributed to the elevated chlorine levels observed, reaching peaks of 2.88 mg/L for free chlorine and 5.88 mg/L for combined chlorine. It is noteworthy that the levels of free available chlorine, responsible for sanitizing water for human consumption, did not exceed the value of 0.2 mg/L.

These findings underscore the necessity of limiting chlorination usage and implementing a dedicated dosing system, particularly considering the high corrosion observed in the WDS pipelines and the significant deterioration observed on the marbles and bronzes. Consequently, based on these analyses, the decision was made to replace the WDS.

Table 6 illustrates the details of the microbiological contamination for each Module for the different sampling campaigns. A contamination range (minimum and maximum) for each sampling point in the modules was displayed.

The first stage of analysis was carried out in 2018. Some microbiological parameters were over the limit prescribed by the directive, as shown again in Table 6. Regarding the water coming from the aqueduct (sampling point 1), no contamination was detected, while the contamination becomes more evident in the Mixed media - Activated Carbon Filters (2A and 2B), where high values of *P. aeruginosa* (7 cfu/100 ml in sampling point 2A) and *C. perfringes* (1 cfu/100 ml sampling point 2B) were found. High contamination by HPC and *P. aeruginosa* as well as fecal coliform, was found at sampling point 4A, which corresponds to the water outlet from the reverse osmosis system, which presented a water temperature of 12.8 °C. In the post-osmosis tanks (sampling points 5A and 5B), however, HPC decreases while *P. aeruginosa* contamination remains (3 cfu/100 ml at sampling point

5A and 1 cfu/100 ml at sampling point 5B) and then disappears after UV lamp treatment and then up to the "clean" fountain.

Regarding the water return line from the Fountain, in general, water inevitably presents a high level of contamination that decreases passing through the various treatments until downstream of the UV lamp, where no level of contamination is found.

In sampling points 4A, 10A, 10B, and 11, *Staphylococcus gordonii* contamination was discovered in place of *S. aureus* contamination with a concentration of >100 cfu/mL, 1 cfu/mL, 2 cfu/mL and 25 cfu/mL respectively, whereas in sampling point 5A, *Staphylococcus constellanus* contamination at a concentration of 11 cfu/100mL was discovered.

The measures of chlorine were in line with the directive and the mean water temperature of all the sampling points was 16.8 °C.

The results of the S1 (Table 6) showed no contamination in the aqueduct reintegration water, whereas the activated carbon filters (sampling points 2A and 2B) have HPC values at 22 and 37 °C above the regulatory limits. Moreover, *S. aureus* (1 cfu/100ml) was found in sampling point 2B.

The sampling point 4B, which collected “mixed” water, coming from the osmosis system and water from the aqueduct dechlorinated and filtered, had only HPC values at 37 °C above the regulatory limits.

Contamination of *C. perfringes*, *E. coli*, Enterococci, and *S. aureus* on the other hand, remains in accumulation tanks 5A and 5B before turning on the UV lamp. The UV lamp is a treatment that removes all types of contamination.

Regarding the Fountain return line, sampling point 6 allowed detection of the presence of *C. perfringes*, *E. coli*, Enterococci, and *S. aureus* as well as a large number of bacterial colonies that grow at 22°C. *C. perfringes*, *E. coli*, Enterococci, and *S. aureus* are still present at the weir water outlet (sampling point 7). After applying the UV lamp treatment, contamination is no longer detected at any of the places examined along the water return line from the Fountain.

In S1 water from the Neptune outside basin was examined further on the north and south sides of the Fountain (data not shown). *C. perfringes*, *E. coli*, Enterococci, coliform bacteria, and *S. aureus* were all found here. In particular, the north side of the Fountain with a water temperature of 9.7 °C presented 6 cfu/100 mL of *C. perfringes*, 4 cfu/100 mL of *E. coli*, 2 cfu/100 mL of Enterococci, and, 1 cfu/100 mL *S. aureus*, while the south side of the basin revealed high contamination of HPC values at 22°C (660 cfu/mL), 5 cfu/100 mL of *C. perfringes*, 2 cfu/100 mL of *E. coli*, 1 cfu/100 mL of Enterococci and *S. aureus*. On the south side of the basin, the water temperature was 9.7°C. At the Fountain basin level, no *Legionella* species were found.

The chlorine concentration found was within the permitted limits at all points in the WDS where it was researched, and the mean of the water temperature (12.2 °C) was also in line with the regulations. During the S2 monitoring, the basin underwent extensive repair and cleaning, making it impossible to sample specific points (such as the water returning from Neptune, the water leaving the rotary screen, and the water in the tank). Except for *E. coli*, the results showed that all points related to storage tanks, sand filter outlets, mixed media filters, osmotized water outlets, and UV pre-lamps have positive results for microorganisms' presence, as shown in Table 6. The contamination is once again contained by the UV lamp before the water is discharged into the Fountain. The chlorine concentration revealed was within the normal range and the mean temperature of the water collected from the different sampling points along the WDS was 18.5°C. As a result of these findings, the WDS was remedied to repair the WTS and prevent the buildup of microbiological contaminants in the osmotized water tanks and sand filters.

In the S3, the contamination was reduced to regulatory levels at points connected to the storage tanks, sand filter outlet, osmotized water outlet, and UV pre-lamp, as shown in Table 6. The only remaining non-compliant sites are the cartridge filters in the RS line (sampling points 3A and 3B) with fecal coliforms present and mixed media filters with HPC values at 22 and 37 °C significantly above the reference level.

However, the chlorine concentration was above the maximum limit (0.2 mg/l) at points 4B (0.386 mg/l), 11 (0.544 mg/l), and 12 (1.410 mg/l), while the mean water temperature was 19.7 °C.

***Table 6:** The microbiological parameter analysis results in the WTS Neptune Fountain after restoration (2018), during the monitoring (2021 – S1 and S2) after extraordinary maintenance activity (2021- S3).*

Sampling points	Years	Microbiological parameters Range of contamination: min – max							
		HPC at 37 °C cfu/ml	HPC at 22 °C cfu/ml	*P. aeruginosa* cfu/100 ml	*C. perfringens* cfu/100 ml	Fecal coliforms cfu/100 ml	*E. coli* cfu/100 ml	*S. aureus* cfu/100 ml	Enterococci cfu/100 ml
Module I – Primary reintegration water treatment (sampling points: 1, 2A, 2B, 3A, and 3B)	2018	1 – 612	1 – 221	0 – 7	0 – 1				
	2021 (S1)	4 – 668	1 – 332					0 – 1	
	2021 (S2)	1 – 64	1 – 87	31 – 61		0 – 57			
	2021 (S3)	1 – 3280	2 – 5200	0 – 1		105 – 140			
Module III – Reintegration Accumulation (sampling points: 4A and 4B)	2018	810 – 1204	712 – 980	88 – 125		6 – 15			
	2021 (S1)	163 – 225	58 – 79						
	2021 (S2)	23 – 303	28 – 374	7 – 125		100 – 300		0 – 10	
	2021 (S3)	1 – 1	2 – 4						
Module VII – Accumulation (sampling points: 5A and 5B)	2018	15 – 79	24 – 37	1 – 3					
	2021 (S1)	11 – 12	96 – 97		9 – 19		2 – 3	1 – 8	2 – 7
	2021 (S2)	79 – 346	50 – 356	13 – 135		1 – 310		0 – 10	
	2021 (S3)	1 – 1	1 – 2						
Module IV – Return from the Fountain (sampling point: 6)	2018	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	2021 (S1)	35 – 69	750 – 1100		5 – 14		3 – 6	6 – 15	0 – 1
	2021 (S2)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	2021 (S3)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Module V – Pre-treatment (sampling points: 7, 8A, 8B and 9)	2018	2 – 327	9 – 340	10 – 20					
	2021 (S1)	4 – 768	258 – 436		10 – 21	0 – 9	3 – 27	4 – 36	0 – 4
	2021 (S2)	121 – 162	221 – 890	10 – 42	0 – 1	5 – 150		0 – 2	
	2021 (S3)	1 – 4	2 – 3						
Module VI – Primary treatment (sampling points: 10A, 10B and 10C)	2018	79 – 155	156 – 340	10 – 12					
	2021 (S1)	29 – 40	125 – 175		6 – 9		2 – 7	6 – 15	0 – 7
	2021 (S2)	6240 – 28000	6720 – 60800	22 – 136	15 – 44	100 – 125		0 – 110	23 – 156
	2021 (S3)	0 – 1	2 – 5						
Module VIII – Secondary treatment (sampling points: 11 and 12)	2018	1 – 38	4 – 62	0 – 1					
	2021 (S1)	1 – 7	1 – 131		0 – 15		0 – 2	0 – 6	0 – 6
	2021 (S2)	2 – 136	1 – 136	0 – 115		0 – 120			
	2021 (S3)	1 – 1	1 – 1						0 – 17

Note: Empty cells correspond to a negative result; n.d.: not detected.

3.4.2 Hydraulic parameters measurements results

The closed-circuit hydraulic system of Neptune Fountain (Fig. 4) is a pressurized system from the storage (C1-C2) of the return water line up to the nozzles, including WST and RS (Fig. 5). Instead, the return pipeline from the Fountain works by gravity.

The hydraulic monitoring provided quantitative information on the overall hydraulic operation of the Neptune Fountain, on the imposed pressure and flow values by the two groups of variable speed pumps (D) and (H) (Fig. 5).

The pumps (D) determine the operation of the self-cleaning filters (E) and the sand filters (F1-F2-F3) in terms of pressure and flow rate. The results of the monitoring PM1 (Fig. 7) indicated operating conditions lower than what indicated in the technical specifications of the filters (F1-F2-F3) with a flow rate measured in FM1 that determines a flow equal to 4.8 m^3/h for each filter, lower than the required 5.0 m^3/h; furthermore the pressure imposed by the variable speed pump $p < 2.5$ bar results equal to the minimum the required value requested for the cleaning of the filters (F1-F2-F3) and this could compromise the maintenance of the quality of the circulating water.

Furthermore, the pumps (H) determine the operation of the Neptune Fountain and, therefore, the correctness of the trajectories of the water jets; finally, the pumps (H) condition the operation of UV lamp (I). The correct setting of the pumps (H) and the nozzle supplying lines regulation valves (Fig. 5) is essential for maintaining a good state of conservation of the Fountain. Indeed, in addition to the aesthetic aspect, correct trajectories of the jets do not create intersections of the water jets with the marble or bronze surfaces in the central parts of the Castellum, thus avoiding the proliferation of algae in these areas and the run-off of external surfaces, potentially contaminated by bacteria because of environmental and anthropic external factors.

FM3 flow rate measurement (Fig. 7) quantitatively confirmed what seemed to emerge observing the Fountain's water trajectories, i.e. a lower value of the overall operating flow rate equal to approximately 1.50 L/s (5.395 m^3/h) compared to the value design equal to 2.35 L/s (8.46 m^3/h). This confirmed the importance of monitoring-based management of the WDS. The results of the hydraulic monitoring are summarized in Table 7.

***Table** 7: Average hydraulic parameters resulting in the Neptune Fountain WTS during the monitoring*

Sampling points		**Hydraulic parameters** Range of operation: min – max	
		Flow (m^3/h)	**Pressure** (bar)
Module V – Pre-treatment	FMI	6.700	
	PM1		1.68
Module VII – Accumulation	FM2	5.395	
	PM2		2.05
Module IX – Sending to the Fountain	PM3		1.97
Module X – Other	FM3	4.800	

3.4.3 Water Treatment System and Reintegration System 3D model

The outcome of the Scan-to-BIM approach was an informative parametric 3D model of the Fountain WDS, accurately reflecting its current state.

Upon importing the point cloud into Recap and setting a local reference system using a specialized "As-Built" tool capable of automatically assessing certain geometric features, the creation of a realistic model for the system began. Procedural tools were then utilized to model the detected elements such as pipes, components, and hydraulic parts. These elements were converted into Revit® families and enriched with information for their description. Finally, the 3D modeling and integration of individual element characteristics were completed by assigning them to their respective WTS or RS. The digital model obtained using Revit® software is shown in Figure 9. In Figure 10, the IFC model on BIM Vision® software of the entire water system of the Fountain is shown.

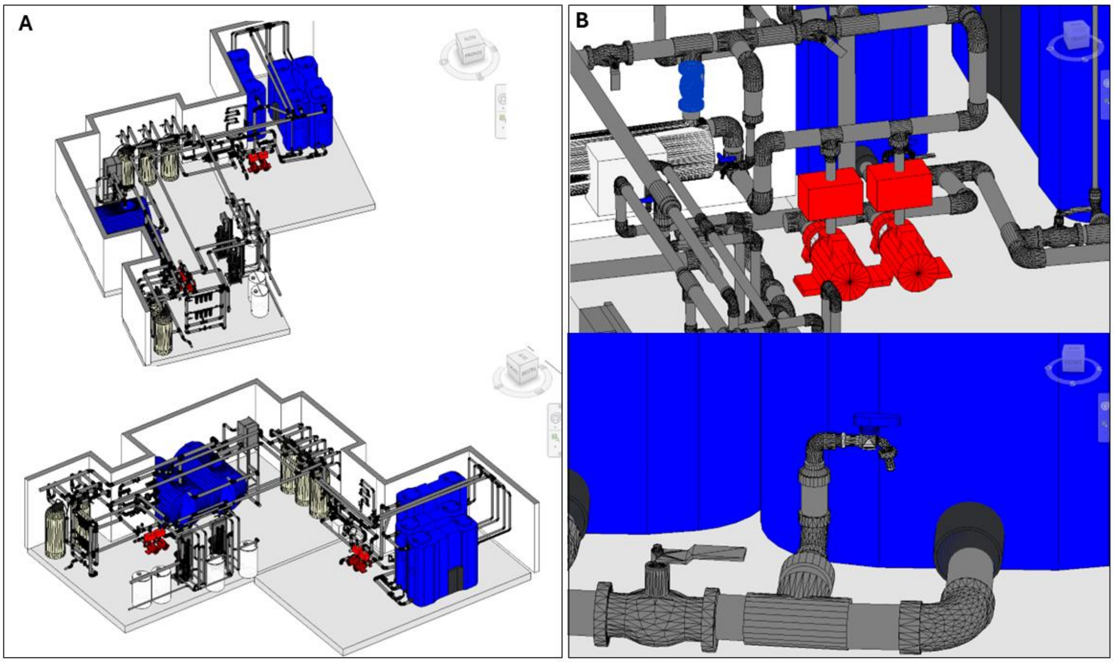


Fig. 9: *Neptune Fountain WDS model on Revit® software: A) General views and B) Details of some components*

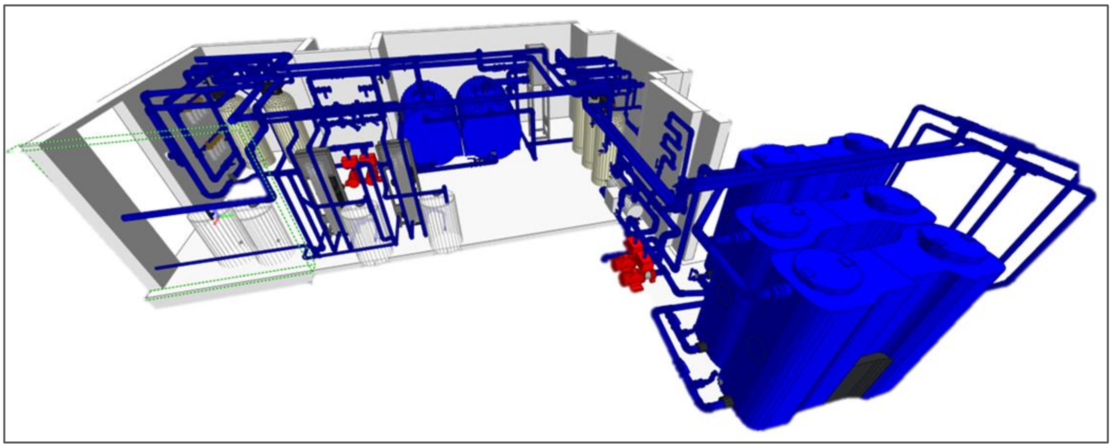


***Fig. 10**: Entire Fountain water system visualization on BIM Vision® software*

Further classification of the components was made by identifying both WTS and RS subsystems called "Modules", each of them corresponding to a specific water treatment and distinguishable within the model by different colors, as shown in Figure 11. The details of the different modules are shown in Table 8. A dynamo visual programming tool was used to implement material and color information to objects allowing identification of Modules and components constituting WST and RS. The obtained detailed plan of the WTS and RS allowed to solve the problem of lack of floor plans.

After the 3D modeling in the HBIM environment, it was possible to archive the information relating to the single component and prepare a dynamic structure for data updating and maintenance plan.

Particularly, it was possible to process and obtain a detailed plan of the WTS and RS. Moreover, the 3D model allows to distinguish between the two main treatment systems (Fig. 11). Moreover, Figure

11, in the lower part shows, with different colors indicated in the legend, the individual Modules labeled thanks to the 3D model processing.

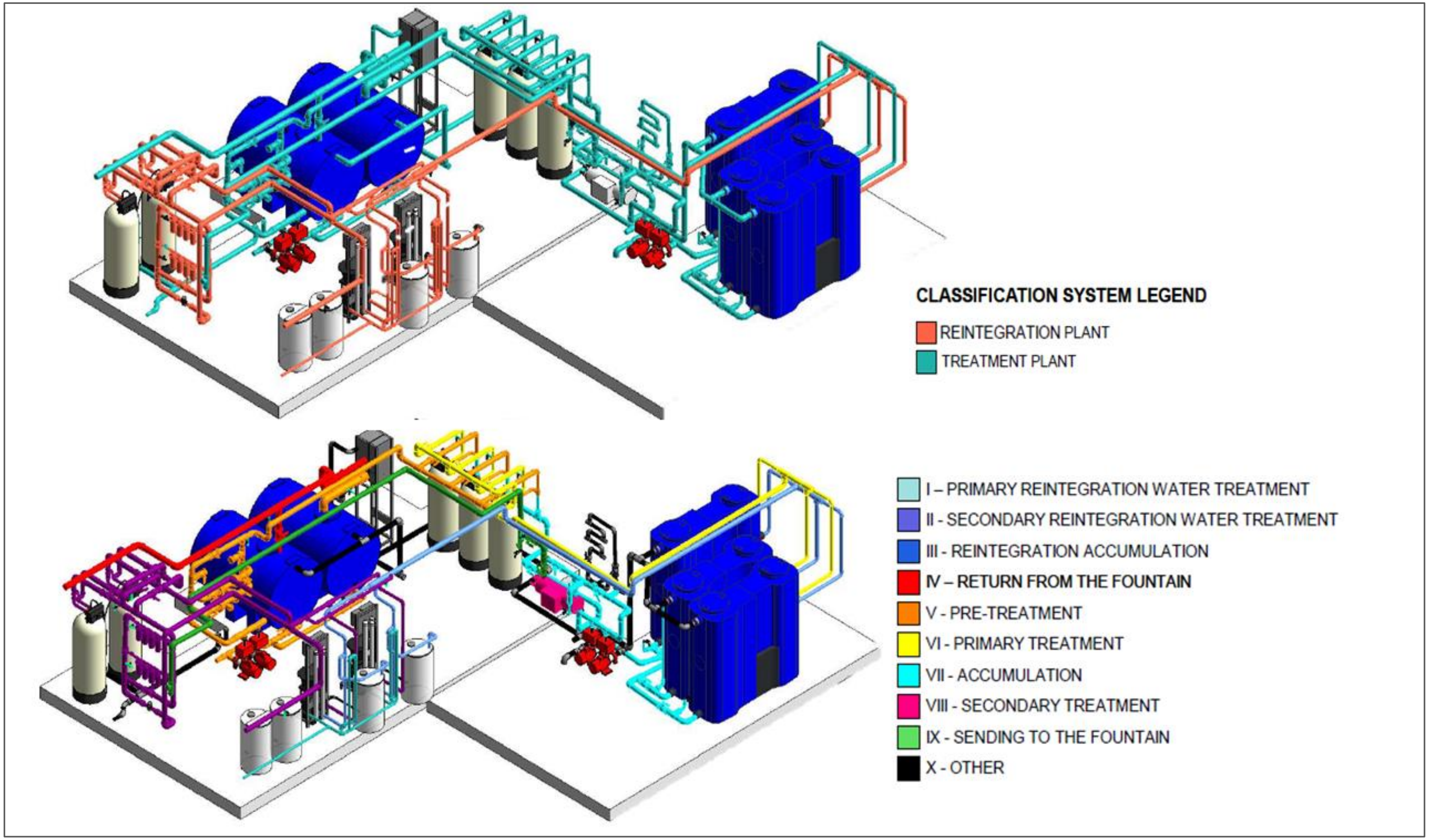


Fig. 11*: Neptune Fountain WTS 3D model: the two main treatment systems and the subsystems called Modules.*

Table 8: *Details of RS and WTS modules. The colors used for the explanation in the Modules match those in Figure 11.*

RS	**MODULE I – PRIMARY REINTEGRATION WATER TREATMENT** From the municipal aqueduct (M), two parallel mixed media filters (N1-N2), and eight 5-micron cartridge filters (O), and it ends at the reverse osmosis process (P) inlet section. Sampling points: 1, 2A, 2B, 3A, 3B.
	MODULE II - SECONDARY REINTEGRATION WATER TREATMENT From the reverse osmosis process (P) inlet section it ends at the reverse osmosis process (P) outlet section.
	MODULE III - REINTEGRATION ACCUMULATION From the reverse osmosis process (P) outlet section it ends at the storage (G1 – G2 – G3) inlet section. Sampling points: 4A, 4B.
WTS	**MODULE IV – RETURN FROM THE FOUNTAIN** From Neptune Fountain basin (A) it ends at rotary screener (B) inlet section. Sampling points: 6
	MODULE V - PRE-TREATMENT From the rotary screener (B) outlet section, storage tanks (C1-C2), through self-cleaning filters (E) and it ends at sand filters (F1 – F2 – F3) inlet section. Sampling points: 7, 8A, 8B, 9.
	MODULE VI - PRIMARY TREATMENT From sand filters (F1 – F2 – F3) inlet section and it ends at storage (G1 – G2 – G3) inlet section. Sampling points: 10A, 10B, 10C.
	MODULE VII - ACCUMULATION From the storage (G1 – G2 – G3) inlet section, two pumps are in parallel (H) and it ends in two directions: at the UV lamp inlet section and the line used to wash the sand filters (F1 – F2 – F3). Sampling points: 5A, 5B.
	MODULE VIII - SECONDARY TREATMENT From the UV lamp (I) inlet section it ends at the UV lamp (I) outlet section. Sampling points: 11, 12.
	MODULE IX - SENDING TO THE FOUNTAIN The UV lamp outlet section ends at the beginning section of the transport pipe to the Fountain.
	MODULE X - OTHER All parts that should be turned off at steady state in WST and RS.

As can be seen, the Modules were organized based on the different functions.

The initial stage of dichlorination and water filtration from the municipal aqueduct is named “Module I - Primary reintegration water treatment”.

The “Module II - Secondary reintegration water treatment”, on the other hand, corresponds to the Reverse Osmosis System, aimed to reduce salt concentrations in the newly dechlorinated water to prevent corrosion on the Fountain's marbles and bronzes.

“Module III - Reintegration accumulation” directs water to the specific storage tanks.

“Module IV - Return from the Fountain” is the WTS component where unclean water is returned from the Fountain.

Within “Module V - Pre-treatment”, water undergoes coarse cleaning to eliminate macroscopic residues before being stored and pumped through self-cleaning filters to the sand filters, reducing turbidity and minimizing suspended contaminants.

“Module VI - Pre-treatment” oversees the operation of three sand filters, preparing water for storage in tanks designated in Module III.

“Module VII - Accumulation” directs water to either the UV lamp or the backwash filters.

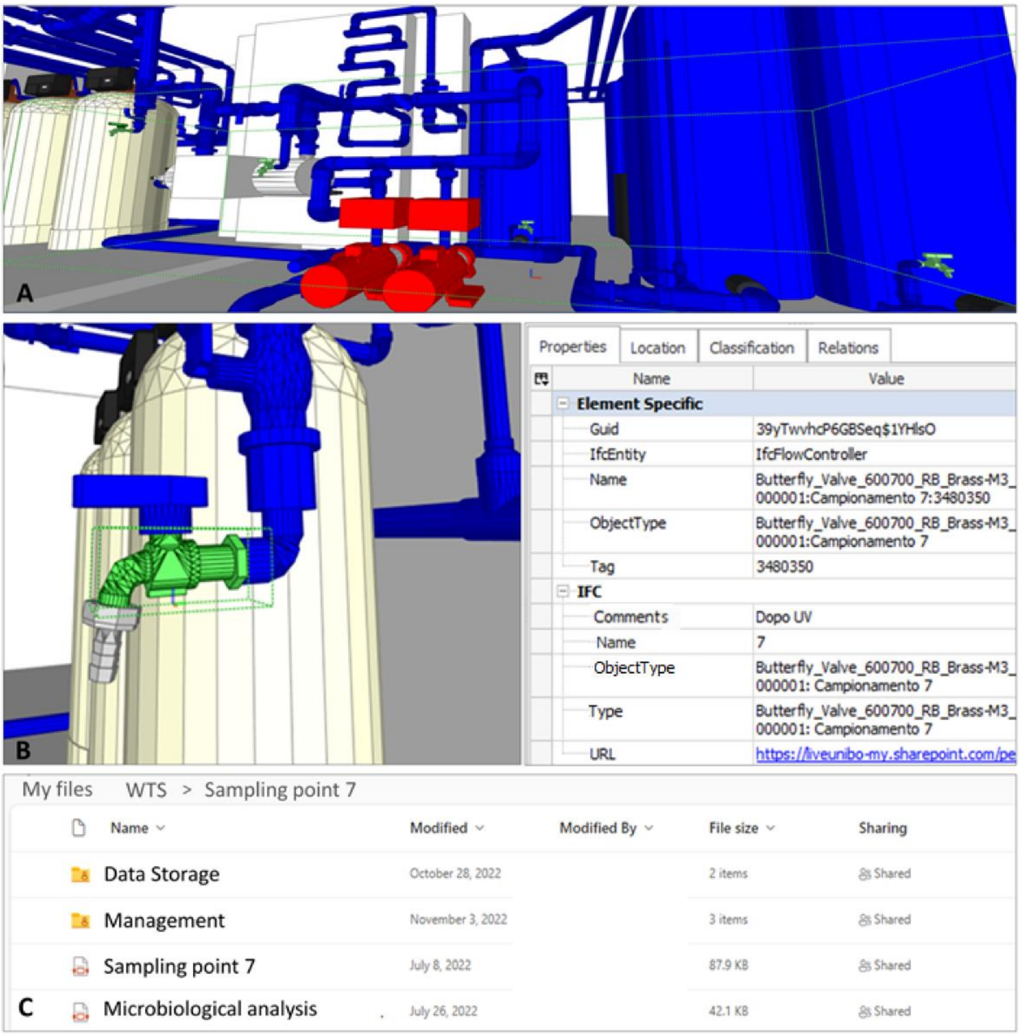
“Module VIII - Secondary Treatment” includes the UV Lamp inlet and outlet, while “Module IX - Sending to the Fountain” returns water to the Fountain.

Finally, “Module X – Other”, collects all the WTS components that are inactive during the normal system operation.

Another important result, which is consequent to modelling in a BIM environment, is the export of the project in a .ifc format, a type of format that is accessible to all and easy to view using free viewers. BIM Vision® 2.26.2 software was used in this study to move virtually through the project by interacting with and sharing information about each component of the project (Figure 10).

To facilitate online access to the HBIM application and update the database with the results periodically carried out, each sampling point was linked to a URL address containing the corresponding documents. To update the data obtained from periodic sampling by sampling points (water taps) and subsequent microbiological analysis the URL type parameter to BIM objects “sampling points” was implemented (Figure 12).

The exported IFC file then presented the URL parameter through which the database containing this information can be accessed, according to an external server-based data structure (e.g., One Drive) as shown in Figure 12. This made it possible to access the same folders associated with individual sampling points and consequently to view the contained file, which was updated to the last tap operation performed. Thus, all information was maintained in a single database that can be shared and accessible by all experts participating in WDS management.



Name	Value
Element Specific	
Guid	39yTwvhcP6GBSeq$1YHlsO
IfcEntity	IfcFlowController
Name	Butterfly_Valve_600700_RB_Brass-M3_ 000001:Campionamento 7:3480350
ObjectType	Butterfly_Valve_600700_RB_Brass-M3_ 000001:Campionamento 7
Tag	3480350
IFC	
Comments	Dopo UV
Name	7
ObjectType	Butterfly_Valve_600700_RB_Brass-M3_ 000001: Campionamento 7
Type	Butterfly_Valve_600700_RB_Brass-M3_ 000001: Campionamento 7
URL	https://liveunibo-my.sharepoint.com/pe

My files WTS > Sampling point 7

Name	Modified	Modified By	File size	Sharing
Data Storage	October 28, 2022		2 items	Shared
Management	November 3, 2022		3 items	Shared
Sampling point 7	July 8, 2022		87.9 KB	Shared
Microbiological analysis	July 26, 2022		42.1 KB	Shared

Fig. 12: ***A)*** *Section of WTS 3D visualization on BIM Vision® software;* ***B)*** *Identification and selection of sampling points along the WTS and IFC tree structure, enabling the display of pertinent information (such as material, type, properties, classification, etc.) upon clicking on a specific point, along with URLs linking to storage folders.* ***C)*** *Illustrative instance of storage folders linked to individual sampling points and their corresponding files.*

3.5 Case Study 1: Final Considerations

The section will carefully discuss the implications of the findings and conclude, aiming to link them to the research objectives. This section will delve into the significance of the results, explore their implications for water quality monitoring and management, and highlight areas for further research. By critically examining the findings, it aims to provide insights that can inform practice, policy, and future research directions.

It can be anticipated that the study performed on the Neptune Fountain is a significant turning point for the water quality evaluation from different perspectives. Firstly, it signifies a groundbreaking approach in considering the comprehensive implications of water quality within a fountain, incorporating both public health concerns and the system's operation. This perspective underscores the need to evaluate not just the visual and structural aspects of fountains, but also the safety of the water that can come in contact with the people. Moreover, it underscores the historical and cultural significance of the Fountain, emphasizing the architectural masterpiece and cultural heritage deserving of preservation and enrichment for future generations.

Furthermore, it represents the first case of integrating hydraulic measurements and microbiological analyses to assess the microbiological quality of water, providing a more holistic and in-depth understanding of the system. Lastly, this case study is a fundamental advancement as it introduces the application of BIM to support water quality management and evaluation, providing tools and innovative technologies for accurate management of Fountain data and information.

3.5.1 Discussion and Conclusions

Public fountains are significant attractions of parks and squares, providing creative spaces for people and animals, but they can also contribute to water pollution *(Modrzewska et al., 2019; Carpio Vallejo et al., 2023*). Although not for drinking, water in ornamental or public fountains should be of good quality for human health due to potential contact, and for preserving the fountain materials. Scientific studies have investigated the presence of numerous microorganisms in the fountains such as Giardia, *Legionella* spp., *E. coli*, *S. aureus*, and *Salmonella (Burkowska-But et al., 2013; Santos et al., 2020; Pompeu Martins et al., 2021; Salinas et al., 2021; Chatziprodromidou et al., 2022; Zhang et al., 2022*). Furthermore, many fountains have closed circuits, which create an environment suitable for microbial development within the pipes. The issue may increase the possibility of microbial contamination of water within the fountain water system. These findings emphasize the need to assess water quality in these contexts, other than to set up a monitoring plan. However, there are currently no defined recommendations setting criteria or standards for water quality testing in ornamental fountains, resulting in a gap in their administration and maintenance.

The case of the Neptune Fountain allowed to demonstrate the applicability of the integrated approach proposed in this thesis in assessing water quality.

The recent restoration of Neptune Fountain is notably significant due to its considerations of water related risks, which led to the implementation of WSP. Recognizing that the proper and safe operation of the WDS components is crucial for enhancing the Fountain's magnificence, particular attention was paid to their operations. Moreover, water filtration systems and osmosis pre-treatment, when combined with physical UV lamp activity can prevent microbiological contamination. Newly, given the value of developing a highly accurate 3D model for monument restoration *(Apollonio et al., 2017,* *2018; Girelli et al., 2019, 2020*), the development of the 3D model described in this manuscript was evaluated for the WDS as well.

The 2017 restoration underscored a crucial aspect of preserving marbles and bronzes of the supported Neptune Fountain: the intrinsic connection between their conservation and the chemical, physical, and microbiological water properties. Maybe for the first time, this restoration marked a significant shift, considering the Neptune Fountain not as a static artistic complex but as a dynamic complex where water plays the central role.

Water is the vital component of the Fountain and is also its the primary agent of deterioration over time, together with environmental factors. Its presence provides the growth of bacteria and algae, linked with biofilm formation on the Fountain surface, representing a constant challenge throughout its history (*Bragalli et al., 2017*). In addition to this issue, fountains frequently use closed-circulation systems, lacking microbiological contamination control systems. Therefore, water promotes microorganism growth, posing a risk both to public health and the Fountain's historical heritage preservation.

These challenges necessitate a proactive approach, combining regular monitoring with a comprehensive maintenance plan. Such measures are indispensable for ensuring structural integrity and effective conservation of the Fountain. Moreover, monitoring the quality of Fountain water holds implications for safeguarding the individuals who interact with it. Despite sporadic assessments, such as those for *Legionella* spp. in cases of legionellosis outbreaks, a standardized guideline for microbiological monitoring of pathogens in decorative fountains remains conspicuously absent, barring a few exceptions in hospital and community settings *(Italian National Institute of Health, 2015*).

When writing this thesis, with this case study, it is proposed for the first time that an original approach to document and monitor the operation and maintenance of such an important Fountain, to ensure the long-term conservation of the monumental historical heritage. Moreover, in this way, it was possible to understand and improve water quality by identifying potential risks and defining the water system using information that is not routinely available to building managers or that may be routinely collected *(Proctor et al., 2022*). Indeed, the microbiological results revealed high contamination at some critical points along the WDS, compromising its performance. As a result, having a WSP to help maintain good water quality in a fountain should be considered and researched further.

Moreover, an implementation of the WDS 3D model can easily share and manage data, and compensate for some lack of plant knowledge, by incorporating qualitative and quantitative microbiological evaluations of the plant up to the hydraulic components. By simply associating URLs to sampling points, that link back to cloud storage, it facilitated communication across different professional skills and, as a result, WDS management. The goal was to return a functional model that could be updated as engineering and microbiological evaluations progressed. Having a model that accurately represents the WDS allows the various professionals involved in the WDS management to access more specific guidance and information to develop effective monitoring plans and to make integrated decisions that consider the correlation between the hydraulic operation and the prevention of risks related to microbiological water quality.

Additionally, the advantage of having a digital model that is easy to share, and access lies in its ability to address a common challenge in environmental monitoring plans: the difficulty in obtaining the layouts and information related to a WDS. The digital model facilitated rapid consultation of essential data, streamlining the monitoring process and enhancing overall operational efficiency.

Thanks to this approach, microbiological analyses performed over the years have revealed WDS malfunctions that would not have been detected otherwise. Even more significant were the assessments made by combining microbiological and hydraulic parameter analysis. Indeed, because of this integrated study, it was discovered a potentially system-critical aspect lay in the fact that pumps (H) (Figure 5), which normally supply the Fountain, also feed the washing phase of sand filters (F1-F2-F3). As a result, during sand filter backwashing, the pumps must provide sufficient flow and pressure to feed the Fountain and wash the filter. According to the results of the 2021 sampling, the water pressure used to backwash the filters, as well as the duration of washing were insufficient to ensure their washing. Microbiological results confirmed filter contamination and the need to improve their cleaning.

Furthermore, another critical aspect that emerged from the Fountain functionality and maintenance, was linked to the storage tanks (G1-G2-G3) (Figure 5). In these storage tanks, the water returned from the Neptune Fountain and filtered by sand filters (F1-F2-F3) is mixed with reverse osmosis-purified water that comes from RS. Moreover, the water used for sand filter backwashing is drawn from the same storage tank. The microbiological contaminants present in the storage tanks are transferred in the two pipelines: one directed through the UV lamp (I), where the contamination is eliminated, and the second one is used for filter backwashing that in this case, met contaminants. As a result, a continuous cross-contamination between filters and storage tanks occurred. These results obtained have been useful as an important input for the responsible staff supporting them in the development of the new protocol.

The results obtained were uploaded on the WTS 3D model and shared with hydraulic engineers, the restorers, and the municipality, to improve the Fountain WSP and Fountain water quality.

Starting from the extraordinary maintenance program, a new maintenance plan was developed, based on the following points: (i) at the level of Module VII, the pressure pumps (H) were reset with new values; (ii) the frequency of filter backwashing was increased from two to three times per week, and the amount of time spent washing was increased from 15 to 30 minutes; (iii) the carbon (N1, N2) and cartridge filters (O), were replaced with new one set; (iv) the storage tanks (C1, C2) of Module V and VII (G1, G2, G3) were completely emptied and mechanically sanitized with chlorine; (v) the by-pass valve on osmosis system (P), was closed to avoid the mixture with the municipal water: in this case the whole WDS was supplied only with osmotic water.

The approach underlined in this research was the importance of increasing WSP development which can be done in a very innovative way. In addition, this approach could be viewed to maintain costs of WTS components that would deteriorate without the simple and immediate maintenance that comes from simply assessing the system's proper hydraulic functioning. Preventive measures are therefore promoted.

The restoration of the Neptune Fountain can be viewed as an efficient starting point for the development of a platform based on a 3D model that can serve as the tool behind the documentation of restoration as well as the management of ordinary and extraordinary maintenance involving the entire WDS, to guarantee simpler and more effective interventions, the identification of which can thus begin from a multidisciplinary knowledge shared between the different professionals who necessarily must operate together in the context of the Neptune Fountain. The BIM model facilitated collaborative workflow among the various professionals involved, enabling continuous comparison and advancement of technical assessments. Based on the Neptune Fountain experience, it is intended to demonstrate how an integrated approach between the microbiological and hydraulic components in the management of any WDS, to be managed and analyzed interactively on a 3D model, is the appropriate method to prevent and contain microbiological contamination, while ensuring the correct and functional operation of the system.

Several significant benefits derive from the proposed approach. Firstly, the challenge of outdated or incomplete architectural and hydraulic layouts is addressed, which is crucial for effective water quality monitoring. Access to accurate digital models facilitates management processes, making them more efficient and faster. This method also improves data sharing and availability, establishing efficient data flows that ensure clear communication among stakeholders. As a result, it promotes collaboration among professionals involved in WDS management and monitoring, leading to more comprehensive evaluations of WDS and enhancements in their functionality and efficiency. Furthermore, the approach allows for practical visualization of pipelines and sampling points, enabling specific tracking of microbiological populations. Lastly, by reducing reliance on fragmented data and paper reports, the approach supports the long-term operation and functionality of building plumbing systems, ensuring sustained performance and safety over time.

Chapter 4

Case study 2

The chapter presents the second case study focusing on the development of two fictitious 3D models using the BIM approach for research purposes. The Case Study started from microbiological data acquired from a previous water quality monitoring plan already included and published as a part of a master thesis research by Zhang 2021 (*Zhang, 2021*). The Case Study then articulated in order to outline the framework that led to the development of a strategy aimed at enhancing data sharing and developing more robust building plumbing management practices. Finally, the chapter delves into the result presentation and discussion. Moreover, while the thesis is being written, the case study is also being prepared for submission to a high-impact scientific journal.

Case study 2: A methodological approach for optimizing building plumbing management, data sharing, and water quality.

Water microbiological contamination within buildings is a public health concern due to the potential transmission of waterborne diseases and affects the effective operation systems and maintenance of infrastructure.

Water quality monitoring is essential as it is based on microbiological data on water contamination that need to be collected and analyzed. Moreover, it serves as a basis for identifying possible risks and making decisions to preserve public health, in compliance with water quality regulations.

Water quality often depends on the building plumbing organization and structure *(Leslie et al., 2021; Walker et al., 2023a*). Consequently, effective building plumbing management is crucial both for the safety and cleanliness of the water and for the system operation. However, the complexities related to building plumbing management, combined with issues such as older structures, lack of paper plans, communication protocols, and secure sharing procedures, provide substantial challenges to stakeholders, in the context of water quality.

One of the main challenges in optimizing building plumbing management is effectively sharing and utilizing data on water usage, distribution, and quality. Traditional data management approaches for building plumbing often involve separate systems and fragmented information, resulting in inefficiencies and limited insights into system performance. There is a need for methodological approaches that improve the building plumbing management practices while also facilitating data analysis and sharing among stakeholders and professionals involved in the water quality assessment process. In response to this challenge, the main purpose of this case study is to provide a methodological approach aimed at optimizing Building plumbing management and microbiological results interpretation and contextualization.

This research aims to provide the stakeholders with the tools and insights needed to improve decision-making, reduce the microbiological contamination risk, and improve water quality management procedures by implementing strong data management strategies based on BIM advances.

4.1 Rationale for the choice of Buildings and main objectives of Case Study 2

As mentioned in the previous paragraphs, building plumbing has an impact on microbiological water quality, therefore, it is important to know its layout, organization, and fixtures. Actually, in the field of building plumbing management and data sharing research, having access to updated building floor plans is an obstacle to accurate and detailed insights. Due to restrictions related to data security and privacy, or simply the lack of paper plans, it may be difficult to obtain such information, especially in sensitive environments, like commercial or private buildings. Given these limitations, this case study involved 3D models' fictitious buildings. The buildings were designed specifically for the study, with architectural and plumbing models based on generic data and real-world design concepts. Therefore, while based on real building structures, the 3D models are not a replica of existing buildings that inspired the study.

The request was for building plumbing that was closely aligned with the study objectives regarding water quality assessment. It was intended to create a system that could be easily integrated with an external cloud storage, allowing data collection and analysis. The buildings and the building plumbing were designed in their simplest form, providing the starting point and essential elements to start the project development process, with a particular emphasis on its interoperability with external cloud storage to enable accurate water quality assessment and monitoring system performance, other than to digitalize the traditional paper layouts.

Currently, concerning the design and construction aimed at maximizing water quality and system operation, there are several gaps related to decision-making tools. Different research studies highlight that BIM can address this gap enhancing cooperation and improving work efficiency *(Oraee et al., 2022; Teo et al., 2022; Lee et al., 2023*). However, BIM potential to enhance microbiological water quality and plumbing management in buildings is yet to be well established.

The main objective of this fictitious case study is to investigate the applicability of a methodological approach that integrates water quality monitoring data within building plumbing and BIM models for data management and storage. The ultimate ambitious goal was to develop an effective strategy that can be applied in similar contexts, offering an innovative solution for challenges related to the lack of accurate building documentation. In addition, this case study aims to materialize the proposal of the integrated approach focusing on the impact of the distribution system on microbial communities.

4.2 Research Approach

The proposed framework aimed to shift from the traditional approach to water quality analysis to a more holistic approach and provide the stakeholders with a tool for building plumbing optimization and management. It comprises five main phases: (1) to develop a building plumbing 3D model, transitioning traditional infrastructure into a digital format for enhanced studies; (2) to create a digital archive in cloud storage of all the relevant data; (3) to monitor the water quality, addressing both microbiological and hydraulic aspects, ensuring quality and safety; (4) to integrate the data obtained from the monitoring within the model, enabling comprehensive insights into system dynamics and performance and implement the maintenance protocols; (5) to visualize the results in the BIM software interface and generate reports, offering intuitive access to data and facilitating informed decision-making.

4.3 Case Study 2: Methodology of research framework

The section provides an overview of the research process and explains the procedure starting from the conceptualization of the BIM model to exporting it into an IFC file format. This procedure followed a series of subsequent steps, as clearly illustrated in Figure 13, and detailed in the following paragraphs.

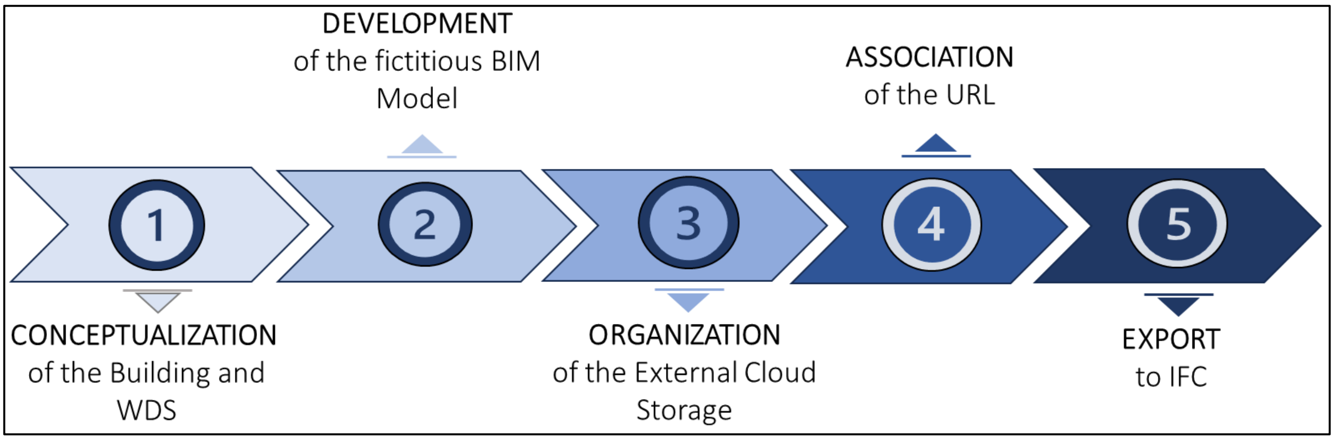


***Fig. 13:** Followed and subsequent steps for model development.*

Additionally, this section details the water sampling campaign and the microbiological analysis. The water sampling and analysis were conducted in a previous study, which served as the foundation for the conceptualization and execution of the current case study (*Zhang, 2021*). In this way, it underscored the importance of prior research in guiding subsequent investigations, highlighting the evolution of scientific research and the advancement of knowledge.

4.3.1 Overview of the fictitious architectural and plumbing layouts within the buildings

Two fictitious single-storey public buildings, chosen as representative models of appropriate complexity, were utilized to demonstrate the proof of concept of the proposed methodological approach. The development of these buildings started from microbiological data collected in a previous water quality monitoring plan (*Zhang, 2021*).

The conceptual 2D layout of the two fictitious buildings is shown in Figure 14.

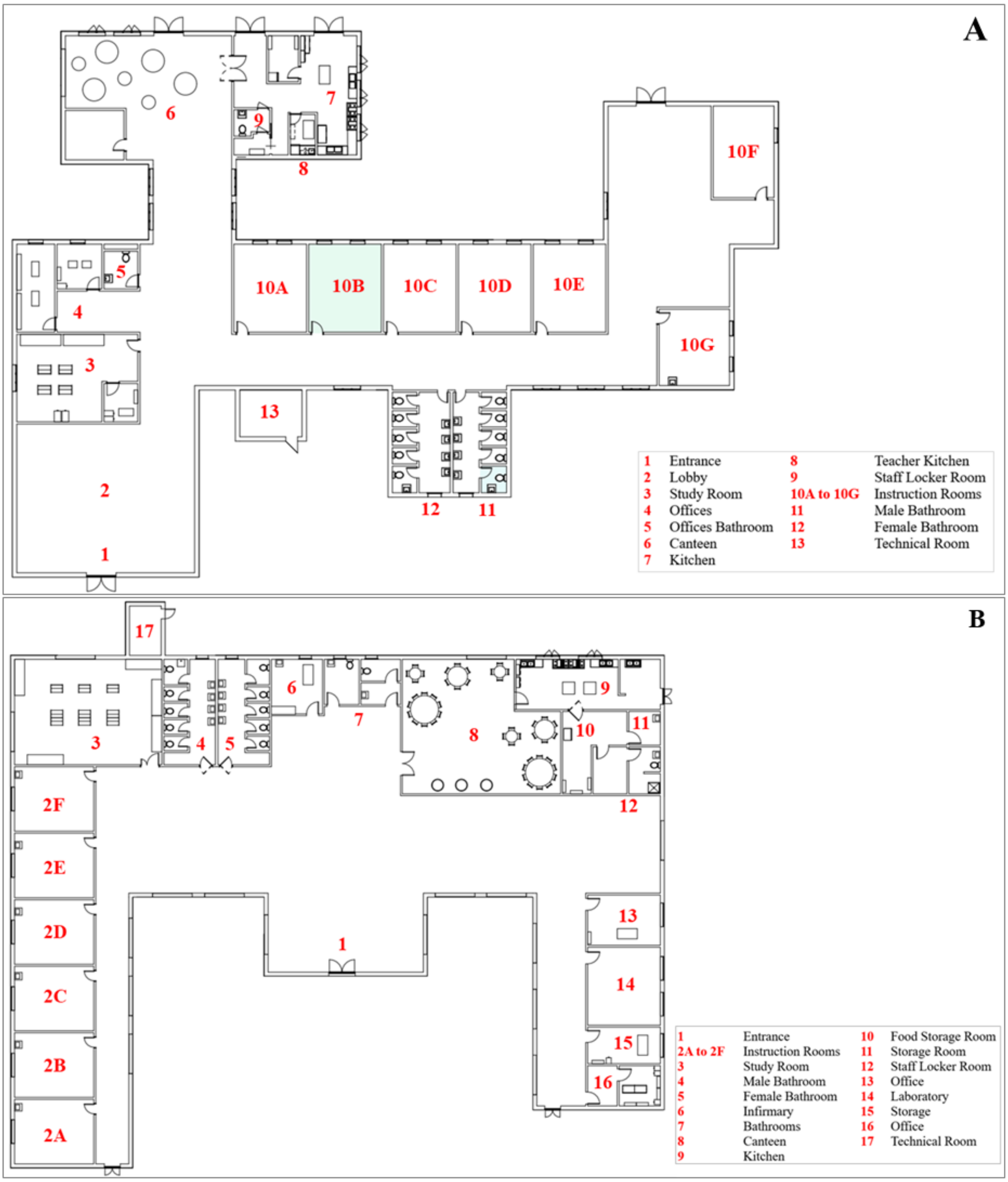


Fig. 14: *Layout of the two fictitious buildings, with their corresponding section legends:* ***A)*** *Building 1,* ***B)*** *Building 2.*

In particular, Building 1 (Fig 14A) was designed to be a versatile environment capable of representing various activities and services. The room layout and distribution with sinks within Building 1 were planned based on the previous sampling plan developed for water quality monitoring.

Specifically, Building 1 consists of an entrance hall with a large lobby, followed by a study room and offices, served by a bathroom equipped with a single sink. The canteen is connected to a kitchen with two sinks, with an additional smaller kitchen also equipped with one sink. The kitchen staff locker room includes an anteroom with a sink and a bathroom with a sink and shower. There are also seven instruction rooms, with one of them located in the southern part of the building being equipped with a sink. Finally, male and female bathrooms are present, each of which is equipped with four sinks, together with an additional sink present in the bathroom dedicated to people with disabilities.

Building 2 (Fig 14B) follows the same concept as Building 1, employing a design strategy aimed at representing the requirements of a public structure within a simulated environment utilizing a BIM model. The structure features a central entrance, with two principal lateral wings, each designated for distinct purposes. On the right side of the building, there are six instruction rooms, each furnished with an internal sink, alongside a separate study area. The primary bathrooms are divided into male and female facilities, accommodating four sinks in each and an additional sink in the restrooms designated for people with disabilities. Positioned centrally within the building is an infirmary, supplemented with two bathrooms equipped with sinks. Initiating the right wing of the building is a canteen area linked to a kitchen equipped with three sinks, along with a food and storage room. Adjacent to this, a locker room for staff members is provided, inclusive of both sink and shower. The last part of the right-wing is reserved for office, storage, and laboratory spaces.

On the other hand, the plumbing systems of the fictitious building was represented in its simplest possible form, to simulate the distribution of water samples taken during a previous monitoring plan (*Zhang, 2021*).

The plumbing system is essential to ensure a reliable and continuous flow of both cold and hot water to meet the daily needs of the occupants. The goal of this design was to provide a solid and easy foundation for the case study, focusing on the management and application of a methodological approach to water quality monitoring. Figure 15 shows the schematic building plumbing, where it is possible to distinguish in red the hot-water system and in blue the cold-water system, originating from the technical room.

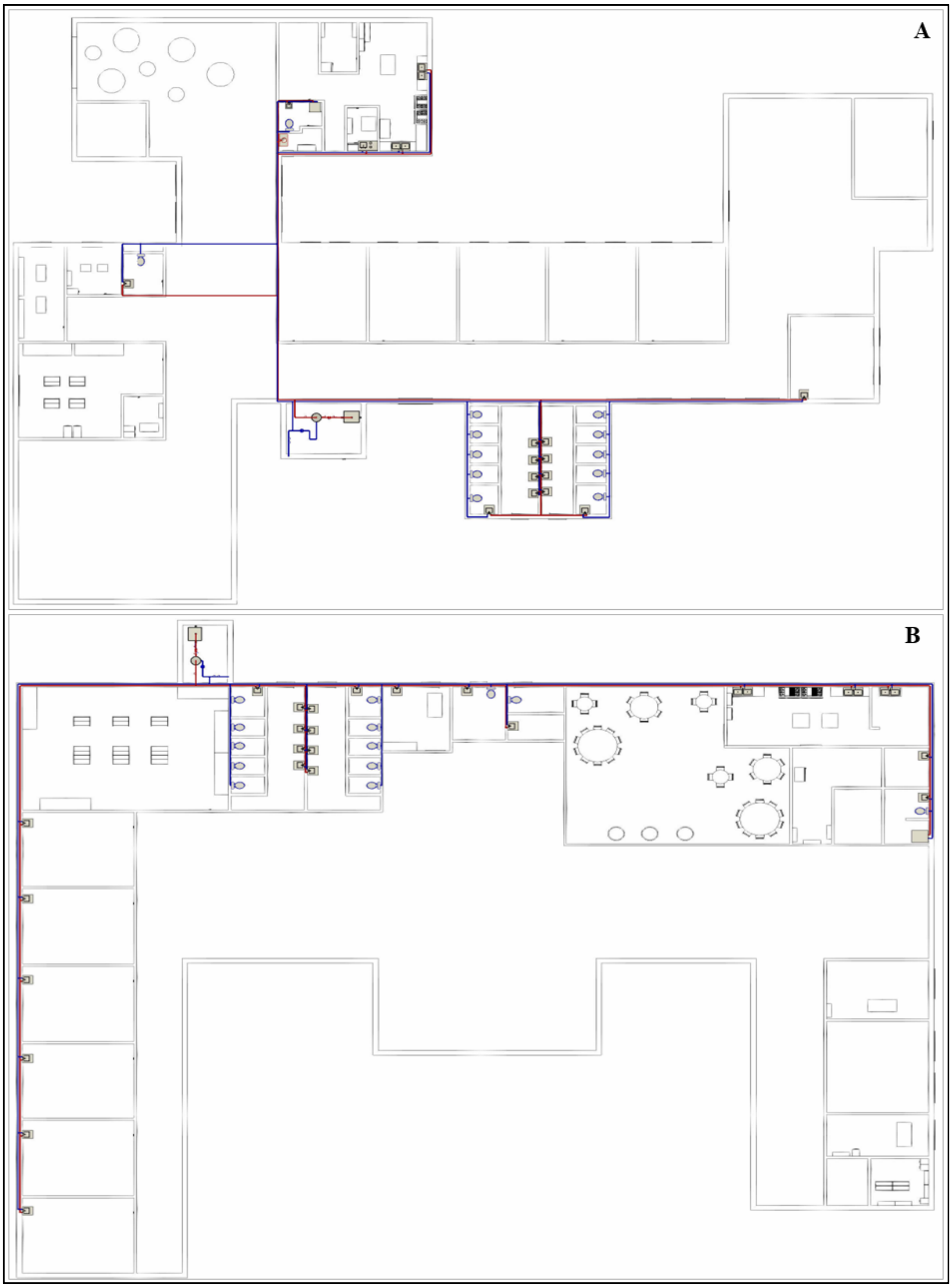


Fig. 15: Schematic layout of the two fictitious building plumbing: ***A)*** *Building 1 and* ***B)*** *Building 2. The red and blue pipelines represent the hot and cold-water distribution, respectively.*

Therefore, very simply, for each Building, the cold-water network originates from the municipal main water supply. The supply pipe branches out to form a cold-water distribution network that provides water for drinking and sanitary purposes. Then, a pipe for cold water from the supply enters the water storage tank, designed for storing water and connected to a gas boiler, which acts to heat the water stored inside the tank. The gas boiler is a fundamental component of the system, as it ensures that the water stored in the tank is always ready for use and at the desired temperature.

From the outlet of the water storage tank, a branching network of pipes distributes hot water to various plumbing features present in the building. These pipes form a network that connects faucets, showers, sinks, and other hydraulic devices.

4.3.2 BIM model development

The first step in any BIM project is to define the model objectives. The BIM model contains many types of information, such as geometric, structural, equipment, and material information. Considering the objective of this study, the BIM model does not need any structural, electrical, or other such information; therefore, this information was excluded, and only the building geometric information with the plumbing information for drinking water supply was considered in the model.

As mentioned before, the case study is based on fictitious BIM models inspired by real buildings.

The architectural model with realistic geometry has represented the real initial task of the case study. BIM software Autodesk® Revit® 2024 (Autodesk Ink., version 2024.0.1) has been used to develop the models. The geometry of each building component was defined, ensuring a minimum essential level of development. This process involved a specification of the elements, including their shape, position, specific construction system, purpose, and assembly method using the software basic commands.

Briefly, a building basic plan was established that defined the structure outer perimeter (Figure 14). The inside area was then divided into rooms following the conceptualization of the two Buildings in Figures 14, considering the space and functional needs of the project. After that, the walls were defined with the correct thickness and height, and then, using the tools available in the Autodesk® Revit® software, families of doors and windows were placed in the floor plan. Finally, the model was edited and refined to make it as realistic and accurate as possible by adding materials and components to improve the visual model rendering.

The fictitious building plumbing was modeled again using Autodesk® Revit® 2024, and in this case, it was essential to link the developed architectural model to a hydraulic modeling project. This linkage is a critical step because the building plumbing is directly dependent on the interior spaces and layout of the building elements. Using the advanced drawing and modeling tools provided by Autodesk® Revit® 2024, the piping along the rooms was traced, distinguishing the hot and cold-water pipelines. The location of the various plumbing fixtures, such as sinks, showers, and faucets, was carefully planned and placed within the model, and once the main piping was added, special attention was paid to the proper connection of the plumbing fixtures. This step is crucial to ensure consistent and efficient plumbing flow within the building.

Next, the model was detailed and examined to identify any interference or collision problems between the piping and the fixtures. Any corrections were made to ensure smooth integration between all elements of the plumbing system. To complete the system, details such as valves, fittings, and other accessories needed to ensure proper operation and maintenance of the system over time were added.

4.3.2.1 URL association

To facilitate the data access and sharing to the BIM models developed and update the database with the results of the analyses periodically carried out, each sampling point was linked to a URL address containing the corresponding documents by implementing a URL type parameter.

Before associating URLs, a key step is organizing and structuring directories and subdirectories in the external cloud. The cloud storage might be of any type. In this case study, it was elected to use OneDrive (Microsoft) which was structured and arranged folders to store data for microbiological and chemical results, temperature values, and ordinary maintenance information, such as flushing.

The integration of the URL type parameter was then achieved by using the Autodesk® Revit® 2024 software capability to define and manage shared parameters. They are instance or type parameters that can be shared throughout families/projects of different types. These characteristics are important since they allow data to be shared across several files, and their use has become essential for data management, notably in the assignment of classification systems. Following the software-recommended procedure, once the shared parameter has been set, the project parameter is inserted into the individual plumbing fixture families. The type of both parameters was set to URL. For each specific point, a unique URL was then established, connecting it to external storage containing the corresponding document, making possible simple data storage and consultation. Indeed, utilizing an identified URL enabled direct linkage of the sampling point to an external cloud storage area, thereby facilitating easy access to different resources.

4.3.2.2 IFC export

The last important step concerning the development of the 3D models was their export in IFC format, which serves as an open file format enabling exchange and collaboration among projects in Revit® or other CAD systems. Revit® IFC export option supports different versions of IFC and model views. At this point, it is important to make sure to check the import options for shared parameters so that the assigned URLs are included. BIM Vision® 2.26.2 software was used to move virtually through the project in IFC format by interacting and sharing information about each component of the project.

4.3.3 Water sampling

As described in Paragraph 4.1, accessing building information about floor plans can be complex due to security, safety, and data privacy. To overcome this difficulty, this case study is based on fictitious buildings used as models. These buildings were designed by drawing inspiration from features of real buildings monitored in a previous survey campaign (*Zhang, 2021*). Therefore, although the buildings are fictitious, the water sampling campaign and microbiological analysis data are real, having been collected in a previous survey (*Zhang, 2021*). However, in this case study these data are interpreted from the perspective of the integrated approach presented in this thesis.

The study encompassed an 8-week monitoring program aimed at evaluating water quality within two public buildings. More in particular, water samples were collected every week, except for the one week which corresponds with the holiday break, and only for the second building was extra sampling done. For Building 2, after the holiday break, they performed two samplings in the same week (indicated as 6 and 6A). The holiday break was considered a water stagnation period.

A total of 68 samples were analyzed, with four sampling points designated from each building. These sampling points were chosen to cover a significant portion of the building area, including various sinks located at different positions. One of these sampling points involved flushing the faucet for 20 minutes before sampling to collect water representative of the distribution system (*Zhang, 2021*).

The list and distribution of the sampling points are listed in Table 9.

***Table 9**: Sampling points and description.*

	ID Sampling point	Sampling Point
Building 1	1A	Sink in Woman bathroom
	1B	Sink in South Instruction Room
	1C	Sink in the smaller kitchen
	1D	Sink in the smaller kitchen after 20 minutes of flushing to simulate the water circulating in the WDS
Building 2	2A	Sink in North Instruction Room
	2B	Sink in Kitchen Storage Room
	2C	Sink in South Instruction Room
	2D	Sink in the North Instruction Room after 20 minutes of flushing to simulate the water circulating in the WDS

A total of 2.5 L of water was collected from each sampling point to conduct multiple analyses: 1L for filtration for DNA sequencing, 1L for microbiological analysis, 25 mL for chemical analysis, 50 mL for metal analysis, and 10 mL for flow cytometry analysis.

Initially, a 2-liter glass bottle was filled to the brim with the very first flow of tap water, ensuring maximum collection. Following the sampling, the temperature of the water was recorded.

For samples from the distribution system, a tap was left running for 15 to 20 minutes before sampling. Before collecting water from this source, the temperature was measured to ensure stability, as a consistent temperature indicated fresh water directly from the main pipes, unaffected by building temperatures.

4.3.4 Microbiological analysis

All the water samples were analyzed by flow cytometry and for other water quality parameters. Microbial contamination levels in water samples were determined with the flow cytometry by staining with SYBR Green and Propidium Iodide and quantified using the Accuri C6 (BD, Becton, Dickinson, and Company). Briefly, 495 µL of each water sample were added to 5 µL of SYBR Green solution and 6 µL of Propidium Iodide. The 500 µL Eppendorf were vortexed and incubated for 15 minutes at 37 °C. After the incubation time, the samples were placed into the Flow Cytometer rack, and the auto-run display opened. The flow cytometer analysis was performed following the manufacturer's instructions. Flow cytometer outputs are scatter plots that show distinct locations of interest. The total cell count (TCC) can be performed using SYBR Green staining, whereas the intact cell count (ICC) can be assessed using Propidium Iodide. Cells are counted using gated zones of interest on flow cytometer scatter plots. TCC and ICC were measured as cells/mL. The cytometer presents a green fluorescence detector FL1 and a red fluorescence detector FL3. SYBR Green is detected by the FL1 detector and Propidium Iodide by the FL3 detector. Clouds within the gates corresponding to bacteria with low or high nucleic acid content (LNA or HNA) can be individuated.

Quality control is a fundamental step before the flow cytometer runs to reduce deviations during the data acquisition process. According to the manufacturer, in this case, the quality check was performed using purified water, clean solution, decontamination solution, eight peak beads, and six peak beads. The quality control run was performed requiring 15 minutes.

On the other hand, water samples for microbiological parameters were assigned to an external testing laboratory. The microbiological parameters tested for this Case Study are: HPC at 22 °C, Slow-growing bacteria, Enterococci, Coliform bacteria, *E. coli*, *C. perfringes*, Micro fungi, Mold, Yeast, and Actinomycetes. According to the Swedish Food Agency, the reference value for HPC at 22°C is 100 cfu/mL and 5000 cfu/mL, while the other parameters should be absent in 100 mL *(SLVFS 2001:30, 2001*).

4.4 Case Study 2: Results

The following paragraphs detail the results obtained from each phase outlined in Figure 13. The outcome of the BIM approach development for water quality management is then presented through a series of consequential and interconnected results. The fictitious digital models are presented through a series of figures. Then, microbiological data are presented. The microbiological data presented here *(Zhang, 2021*) are, in this context, reexamined through the integrated approach point of view, reevaluating their implications, with a deeper understanding of their significance, remarking on the importance of the holistic nature of the research methodology.

4.4.1 Results from the application of the methodological approach for digitization

4.4.1.1 BIM Model

The outcomes of the BIM simulation detailed in this Case Study provide good evidence of its usefulness for achieving the study purposes. The fictitious models incorporate architectural and water supply system details to provide a complete and realistic representation of everyday situations, bringing the model as close as possible to what is required during environmental monitoring related to water quality evaluation.

Regarding the conceptualization of the Building geometries, the visual representation of the architectural 3D model of the Buildings elaborated in Autodesk® Revit® software is shown in Figure 16.

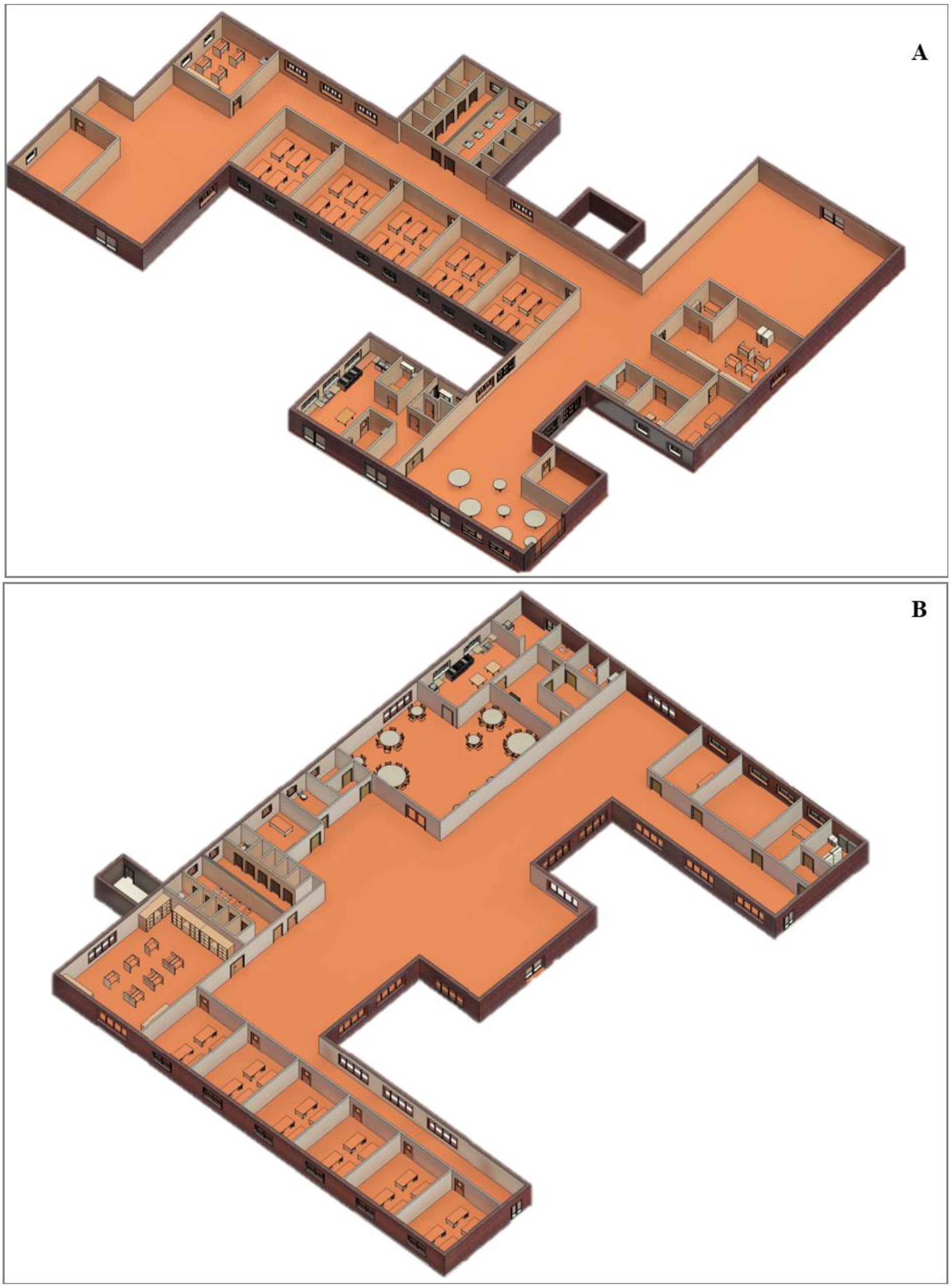


Fig. 16: *Visual representation of the Revit rendering of the architectural components:* ***A)*** *Building 1 and* ***B)*** *Building 2.*

A significant advantage of these models is the interactivity of each component, which, unfortunately, does not completely emerge from the basic static figures. Because of their dynamic character, the models allow us to investigate each component, understand its relationships, and predict how it will interact in various scenarios. This function not only improves the overall understanding of the project but also allows for the identification of potential critical issues and the optimization of solutions in a more effective and timely way.

The architectural model served as a foundation for the digital building plumbing development. It has been possible to properly integrate and design the water supply system, assuring a perfect match with the existing buildings.

The visual representation of Building 1 and 2 building plumbing is presented in Figures 17 and 18, respectively. In Figures 17B and 18B is indicated a key aspect that optimizes building plumbing management: the possibility to isolate the building plumbing and visualize its components.

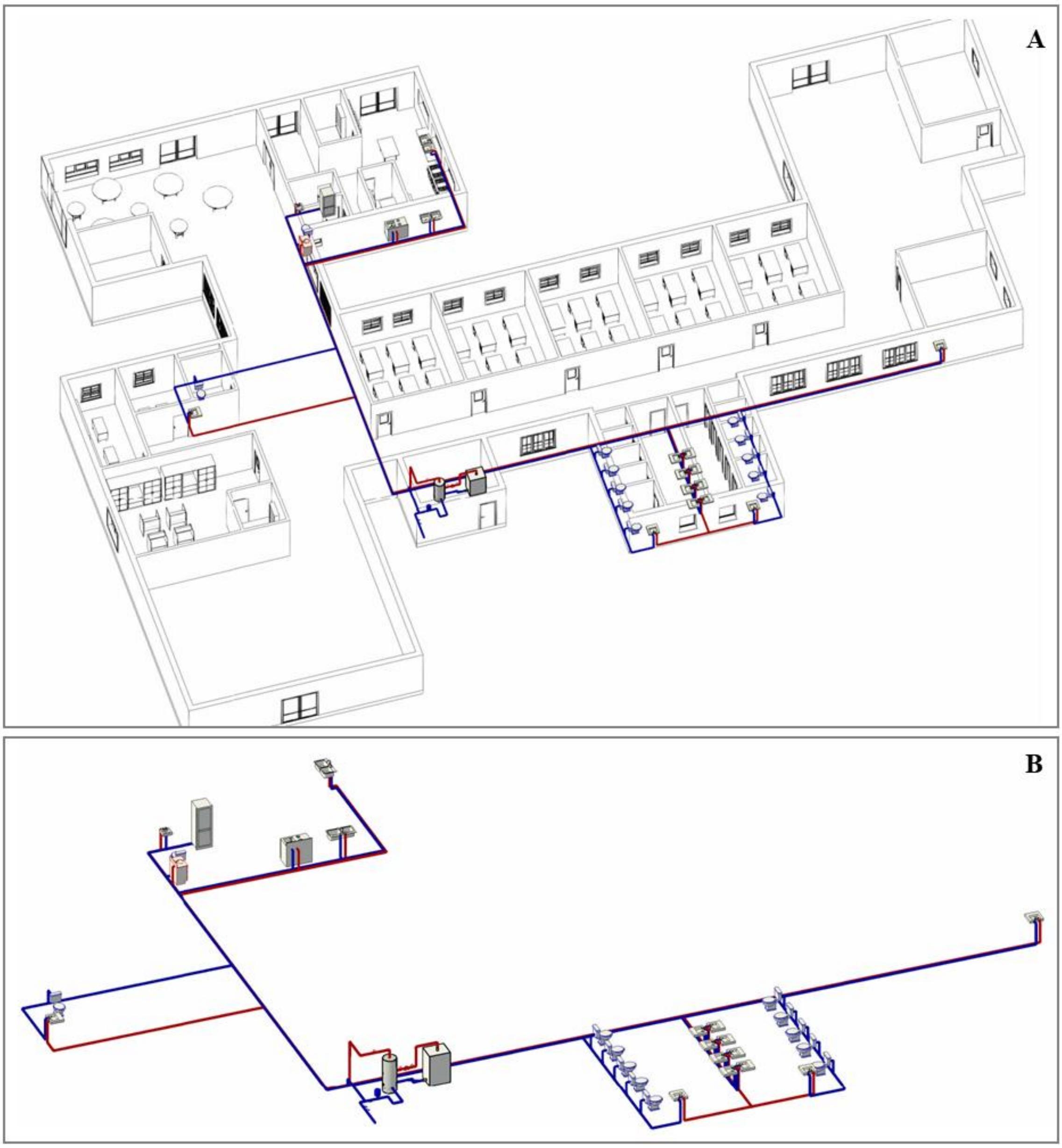


Fig. 17*: Building 1:* ***A)*** *building plumbing linked to the architectural model and* ***B)*** *building plumbing.*

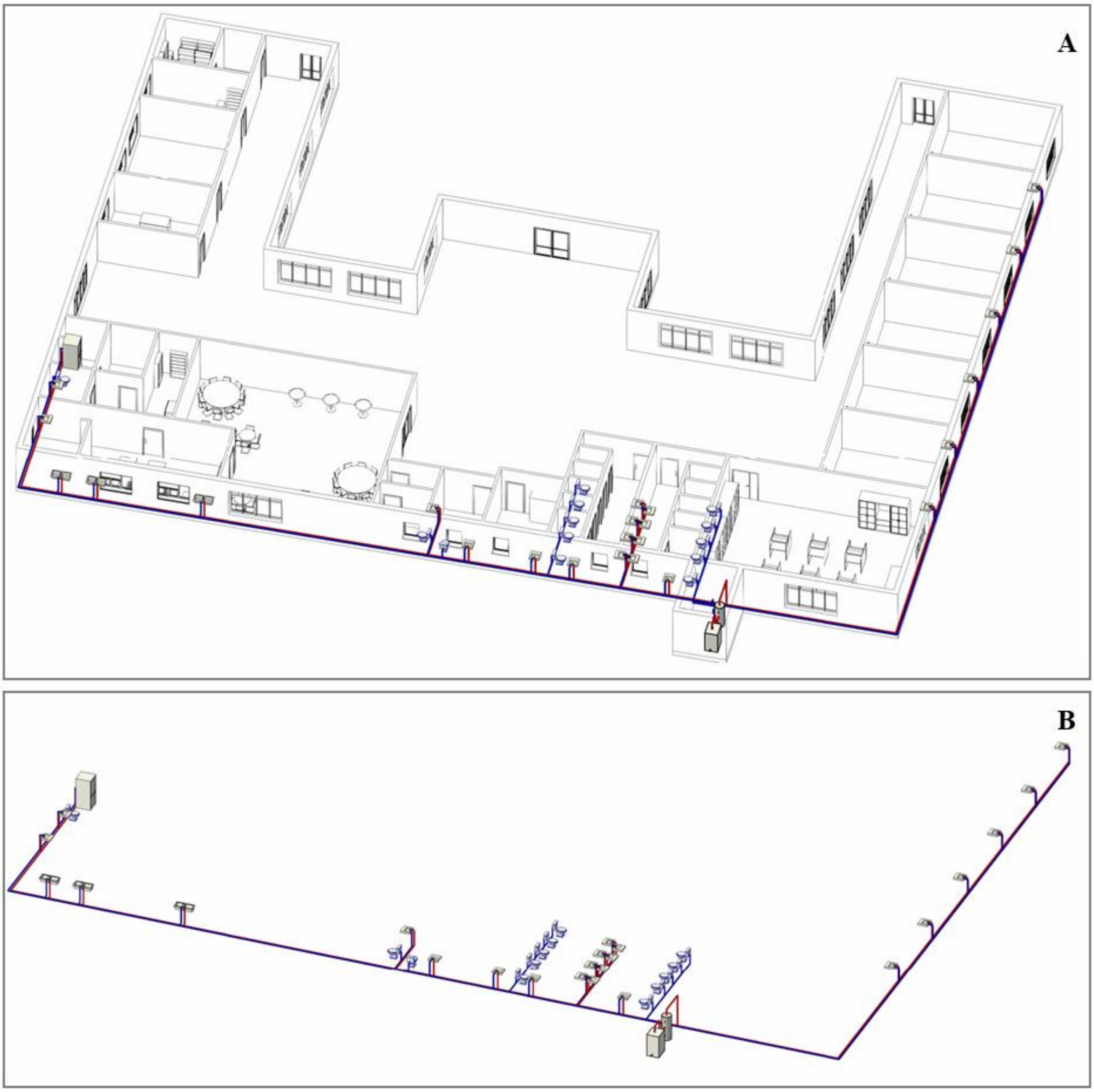
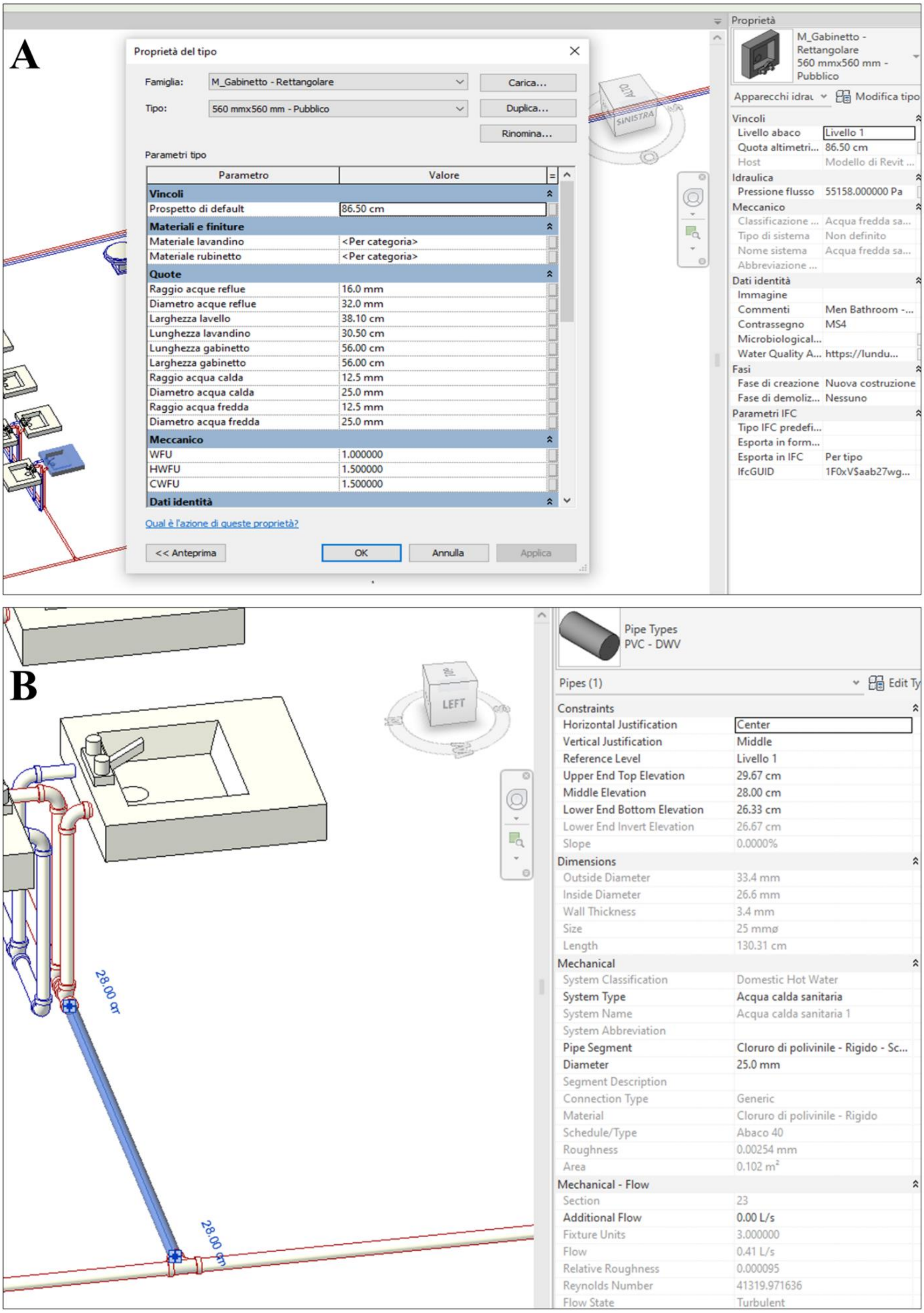


Fig. 18: *Building 1:* ***A)*** *building plumbing linked to the architectural model and* ***B)*** *building plumbing.*

In addition, using Autodesk Revit®, individual plumbing fixtures, such as sinks, or specific sections of pipe can be selected and all relevant information accessed, including size, flow rate, and materials used, as shown in Figure 19.



Famiglia: M_Gabinetto - Rettangolare
Tipo: 560 mmx560 mm - Pubblico

Parametri tipo

Parametro	Valore
Vincoli	
Prospetto di default	86.50 cm
Materiali e finiture	
Materiale lavandino	<Per categoria>
Materiale rubinetto	<Per categoria>
Quote	
Raggio acque reflue	16.0 mm
Diametro acque reflue	32.0 mm
Larghezza lavello	38.10 cm
Lunghezza lavandino	30.50 cm
Lunghezza gabinetto	56.00 cm
Larghezza gabinetto	56.00 cm
Raggio acqua calda	12.5 mm
Diametro acqua calda	25.0 mm
Raggio acqua fredda	12.5 mm
Diametro acqua fredda	25.0 mm
Meccanico	
WFU	1.000000
HWFU	1.500000
CWFU	1.500000
Dati identità	

M_Gabinetto - Rettangolare 560 mmx560 mm - Pubblico

Apparecchi idrau

Vincoli	
Livello abaco	Livello 1
Quota altimetri...	86.50 cm
Host	Modello di Revit ...
Idraulica	
Pressione flusso	55158.000000 Pa
Meccanico	
Classificazione ...	Acqua fredda sa...
Tipo di sistema	Non definito
Nome sistema	Acqua fredda sa...
Abbreviazione ...	
Dati identità	
Immagine	
Commenti	Men Bathroom -...
Contrassegno	MS4
Microbiological...	
Water Quality A...	https://lundu...
Fasi	
Fase di creazione	Nuova costruzione
Fase di demoliz...	Nessuno
Parametri IFC	
Tipo IFC predefi...	
Esporta in form...	
Esporta in IFC	Per tipo
IfcGUID	1F0xV$aab27wg...

Pipe Types
PVC - DWV

Pipes (1)

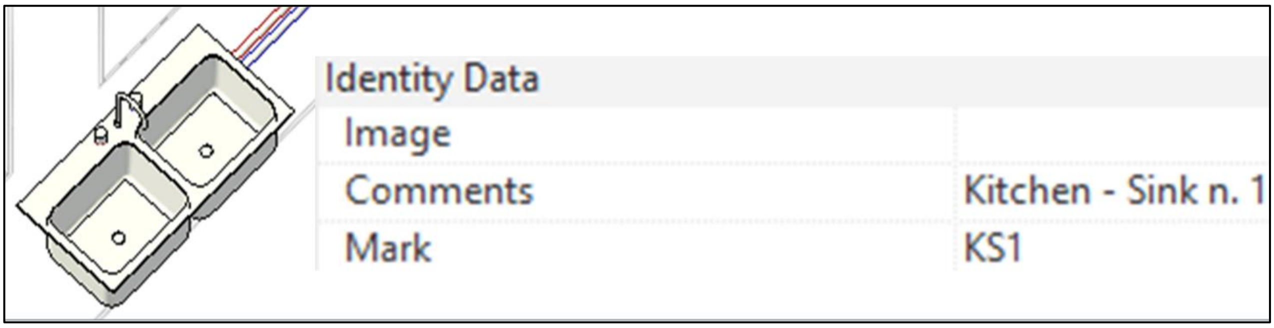
Constraints	
Horizontal Justification	Center
Vertical Justification	Middle
Reference Level	Livello 1
Upper End Top Elevation	29.67 cm
Middle Elevation	28.00 cm
Lower End Bottom Elevation	26.33 cm
Lower End Invert Elevation	26.67 cm
Slope	0.0000%
Dimensions	
Outside Diameter	33.4 mm
Inside Diameter	26.6 mm
Wall Thickness	3.4 mm
Size	25 mmø
Length	130.31 cm
Mechanical	
System Classification	Domestic Hot Water
System Type	Acqua calda sanitaria
System Name	Acqua calda sanitaria 1
System Abbreviation	
Pipe Segment	Cloruro di polivinile - Rigido - Sc...
Diameter	25.0 mm
Segment Description	
Connection Type	Generic
Material	Cloruro di polivinile - Rigido
Schedule/Type	Abaco 40
Roughness	0.00254 mm
Area	0.102 m²
Mechanical - Flow	
Section	23
Additional Flow	0.00 L/s
Fixture Units	3.000000
Flow	0.41 L/s
Relative Roughness	0.000095
Reynolds Number	41319.971636
Flow State	Turbulent

Fig. 19*: Illustration of the functionality of selecting and displaying detailed information about plumbing fixtures and piping using Revit software:* ***A)*** *Hydraulic device and* ***B)*** *Pipes.*

In this operational context, each hydraulic device (sinks and showers), representing a sampling point, has been categorized by assigning a unique code and a detailed description (Table 10). This information is easily accessible in the properties panel of each point, as reported in Figure 20.

***Table 10**: Sampling points and descriptions in each Building.*

Sampling Points - Building 1		**Sampling Points - Building 2**	
ID	**Description**	**ID**	**Description**
WS1	Female Bathroom - Sink n. 1	WS1	Female Bathroom - Sink n. 1
WS2	Female Bathroom - Sink n. 2	WS2	Female Bathroom - Sink n. 2
WS3	Female Bathroom - Sink n. 3	WS3	Female Bathroom - Sink n. 3
WS4	Female Bathroom - Sink n. 4	WS4	Female Bathroom - Sink n. 4
WHS5	Female Bathroom Handicap - Sink n. 5	WHS5	Female Bathroom Handicap - Sink n. 5
MS1	Male Bathroom - Sink n. 1	MS1	Male Bathroom - Sink n. 1
MS2	Male Bathroom - Sink n. 2	MS2	Male Bathroom - Sink n. 2
MS3	Male Bathroom - Sink n. 3	MS3	Male Bathroom - Sink n. 3
MS4	Male Bathroom - Sink n. 4	MS4	Male Bathroom - Sink n. 4
MHS5	Male Bathroom Handicap - Sink n. 5	MHS5	Male Bathroom Handicap - Sink n. 5
SKS1	Teacher Kitchen – Sink n.1	NS1	Infirmary
KS1	Kitchen – Sink n.1	CS1	Instruction Room - Sink n.1
KS2	Kitchen – Sink n.2	CS2	Instruction Room - Sink n.2
SDS1	Staff Locker Room – Sink n.1	CS3	Instruction Room - Sink n.3
SDS2	Staff Locker Room – Sink n.2	CS4	Instruction Room - Sink n.4
SDSh1	Staff Locker Room – Shower	CS5	Instruction Room - Sink n.5
OBS1	Office Bathroom – Sink n.1	CS6	Instruction Room - Sink n.6
RS6	Instruction Room n.1 – Sink n.1	HBS1	Handicap Bathroom – Sink n.1
		SS1	Staff Bathroom – Sink n.1
		KS1	Kitchen – Sink n.1
		KS2	Kitchen – Sink n.2
		KS3	Kitchen – Sink n.3
		STS1	Storage Room – Sink n. 1
		SDS1	Staff Locker Room – Sink n.1
		SDSh1	Staff Locker Room – Shower



Identity Data

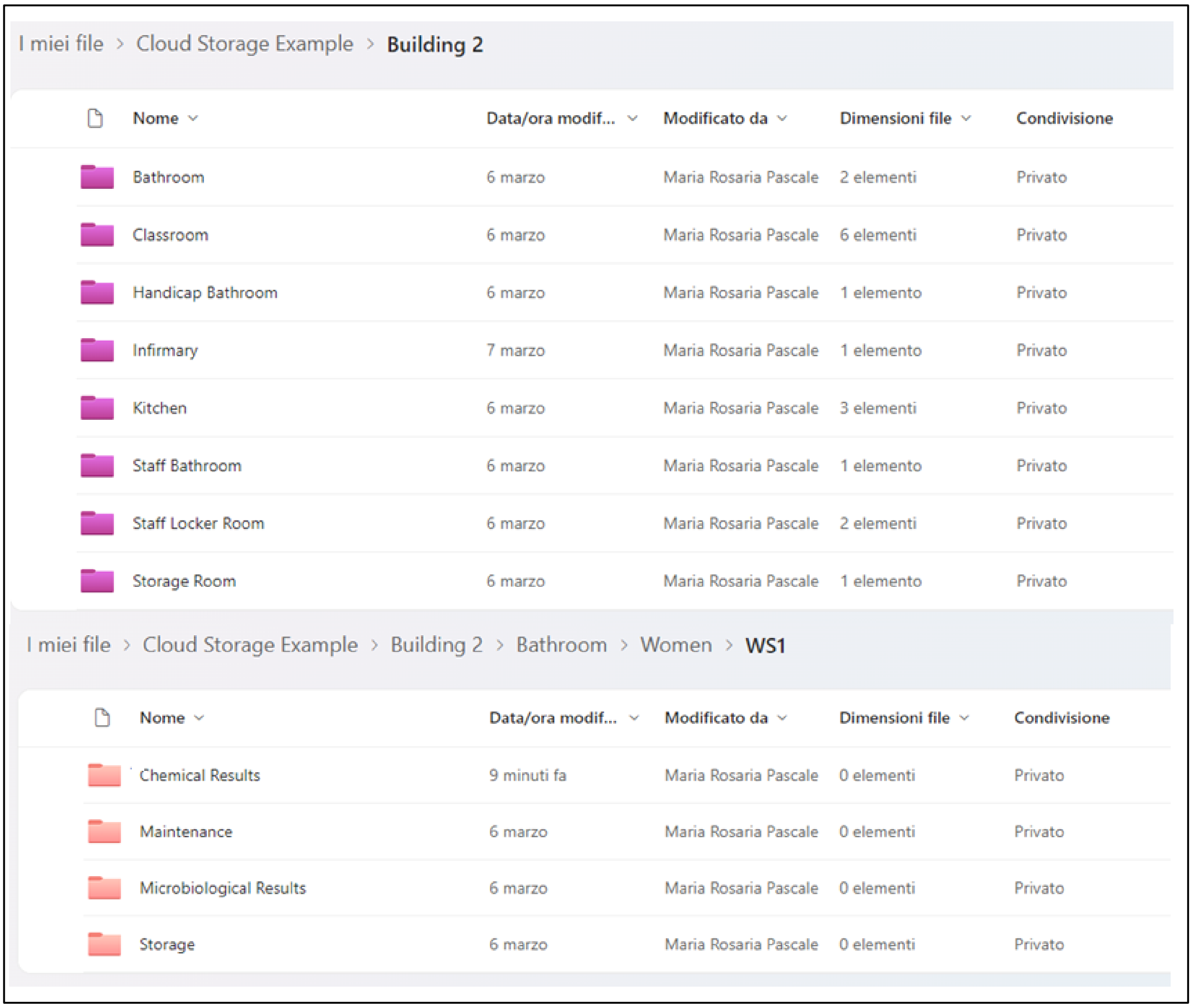
Image

Comments Kitchen - Sink n. 1

Mark KS1

***Fig. 20:** Sample ID and description related to a sampling point in the properties panel in Revit.*

Simultaneously a OneDrive folder structure was set up intuitively and conveniently, as reported in Figure 21. More specifically, for each Building, dedicated folders have been made relating to certain rooms, such as bathrooms. Within each of these folders, subfolders labeled with the name of each sampling point have been developed and, in each of them, all files relevant to microbiological results or storage data specific to that sampling point have been systematically grouped.



I miei file > Cloud Storage Example > **Building 2**

Nome	Data/ora modif...	Modificato da	Dimensioni file	Condivisione
Bathroom	6 marzo	Maria Rosaria Pascale	2 elementi	Privato
Classroom	6 marzo	Maria Rosaria Pascale	6 elementi	Privato
Handicap Bathroom	6 marzo	Maria Rosaria Pascale	1 elemento	Privato
Infirmary	7 marzo	Maria Rosaria Pascale	1 elemento	Privato
Kitchen	6 marzo	Maria Rosaria Pascale	3 elementi	Privato
Staff Bathroom	6 marzo	Maria Rosaria Pascale	1 elemento	Privato
Staff Locker Room	6 marzo	Maria Rosaria Pascale	2 elementi	Privato
Storage Room	6 marzo	Maria Rosaria Pascale	1 elemento	Privato

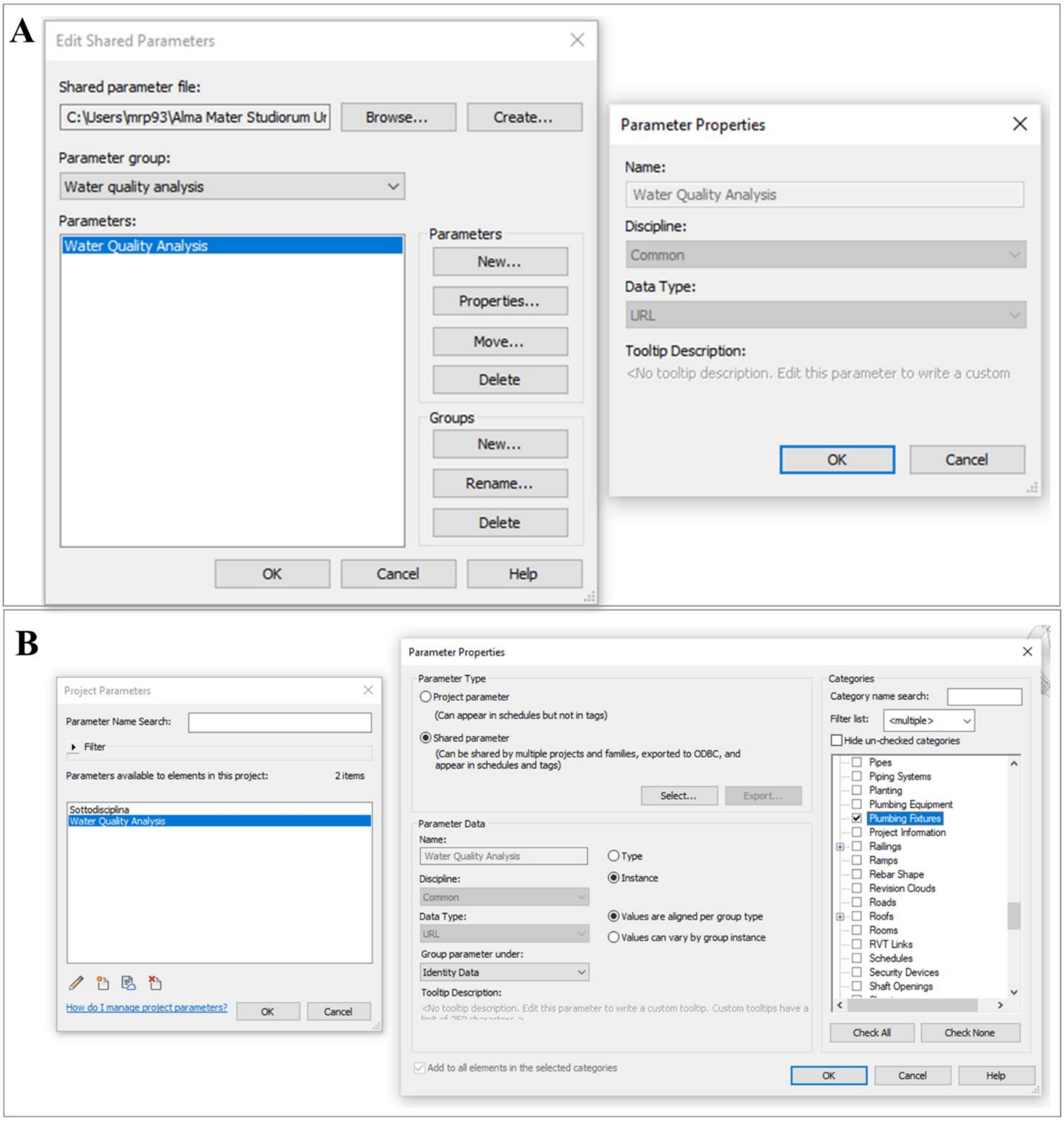
I miei file > Cloud Storage Example > Building 2 > Bathroom > Women > **WS1**

Nome	Data/ora modif...	Modificato da	Dimensioni file	Condivisione
Chemical Results	9 minuti fa	Maria Rosaria Pascale	0 elementi	Privato
Maintenance	6 marzo	Maria Rosaria Pascale	0 elementi	Privato
Microbiological Results	6 marzo	Maria Rosaria Pascale	0 elementi	Privato
Storage	6 marzo	Maria Rosaria Pascale	0 elementi	Privato

***Fig. 21**: Example of storage folder associated with the individual sampling points and the relative files.*

4.4.1.2 URL linking

The plumbing devices in the model were linked to folders on OneDrive using URL association. The first step in this assignment was to create a shared parameter within the project. Following the program instructions, a common parameter entitled "water quality analysis" was created, with URL as the data type to be controlled (Figure 22). The project parameter was then built from the common parameter, assigned to instances, and linked to the plumbing fixture categories as indicated in Figure 22.



Shared parameter file: C:\Users\mrp93\Alma Mater Studiorum Ur

Parameter group: Water quality analysis

Parameters: Water Quality Analysis

Name: Water Quality Analysis

Discipline: Common

Data Type: URL

Tooltip Description: <No tooltip description. Edit this parameter to write a custom

Parameter Name Search:

Parameters available to elements in this project: 2 items

Sottodisciplina
Water Quality Analysis

Parameter Type
○ Project parameter
(Can appear in schedules but not in tags)
● Shared parameter
(Can be shared by multiple projects and families, exported to ODBC, and appear in schedules and tags)

Parameter Data
Name: Water Quality Analysis
○ Type
● Instance
Discipline: Common
Data Type: URL
● Values are aligned per group type
○ Values can vary by group instance
Group parameter under: Identity Data
Tooltip Description: <No tooltip description. Edit this parameter to write a custom tooltip. Custom tooltips have a

Categories
Category name search:
Filter list: <multiple>
☐ Hide un-checked categories
☐ Pipes
☐ Piping Systems
☐ Planting
☐ Plumbing Equipment
☑ Plumbing Fixtures
☐ Project Information
☐ Railings
☐ Ramps
☐ Rebar Shape
☐ Revision Clouds
☐ Roads
☐ Roofs
☐ Rooms
☐ RVT Links
☐ Schedules
☐ Security Devices
☐ Shaft Openings

☑ Add to all elements in the selected categories

Fig. 22: *Setting URLs as parameters: A) creating shared parameters and B) assigning project parameters.*

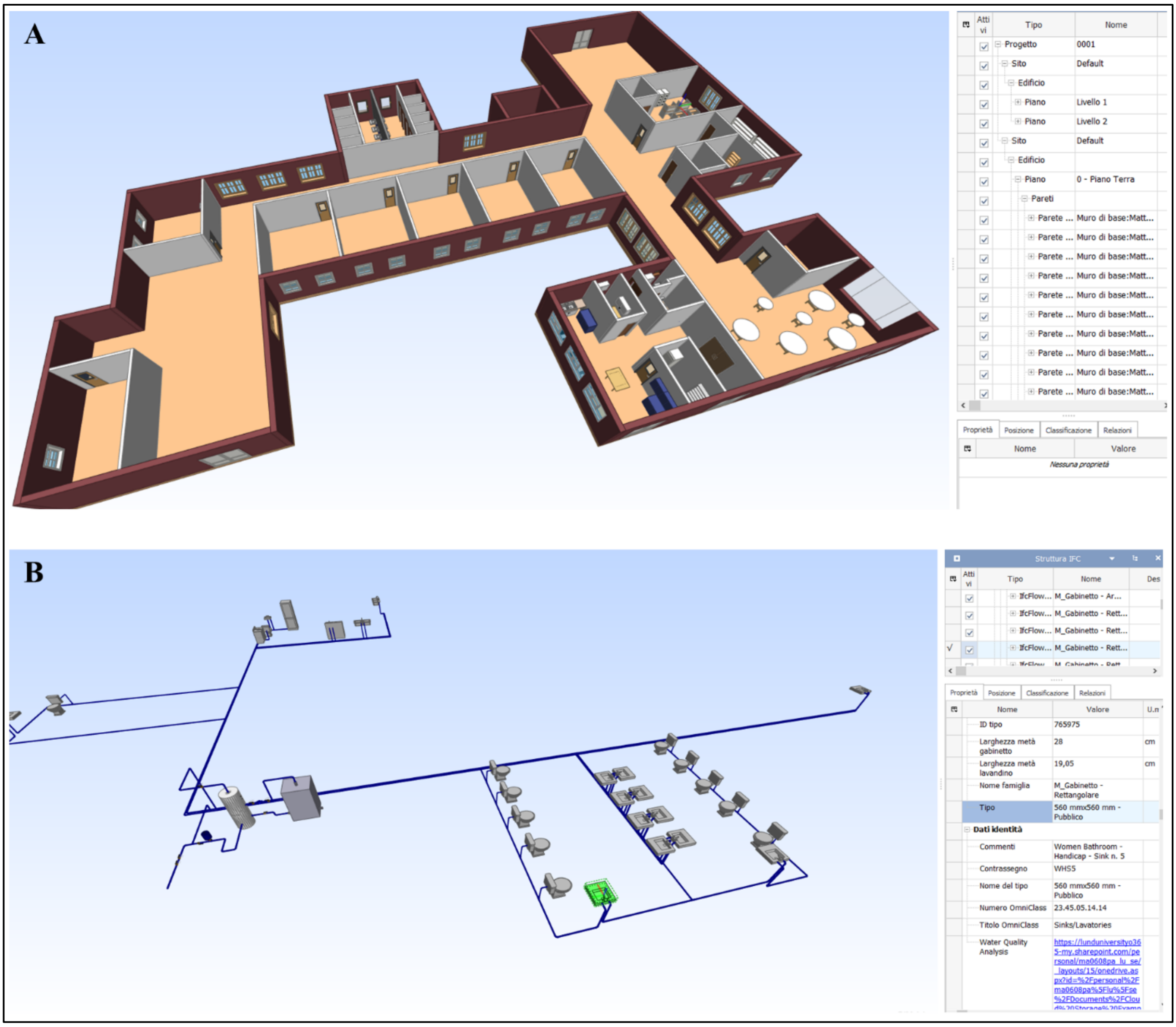
Once the URL parameter is assigned, it will display in the properties panel associated with a specific sample point by clicking on it, as shown in Figure 23.

Identity Data	
Image	
Comments	Kitchen - Sink n. 1
Mark	KS1
Water Quality Analysis	https://l

Fig. 23: *Sink with the shared parameter Water Quality Analysis and the respective URL to the external cloud Storage*

4.4.1.3 IFC File

The final important step in this framework is to export the project to IFC format. During this process, in the export dialog window, adjust options such that URL parameters are included in the export. Figures 24 and 25 report the IFC file format of Building 1 and 2, respectively of the architectural part (Panel A) and only the pipes (Panel B), along with their corresponding URLs.



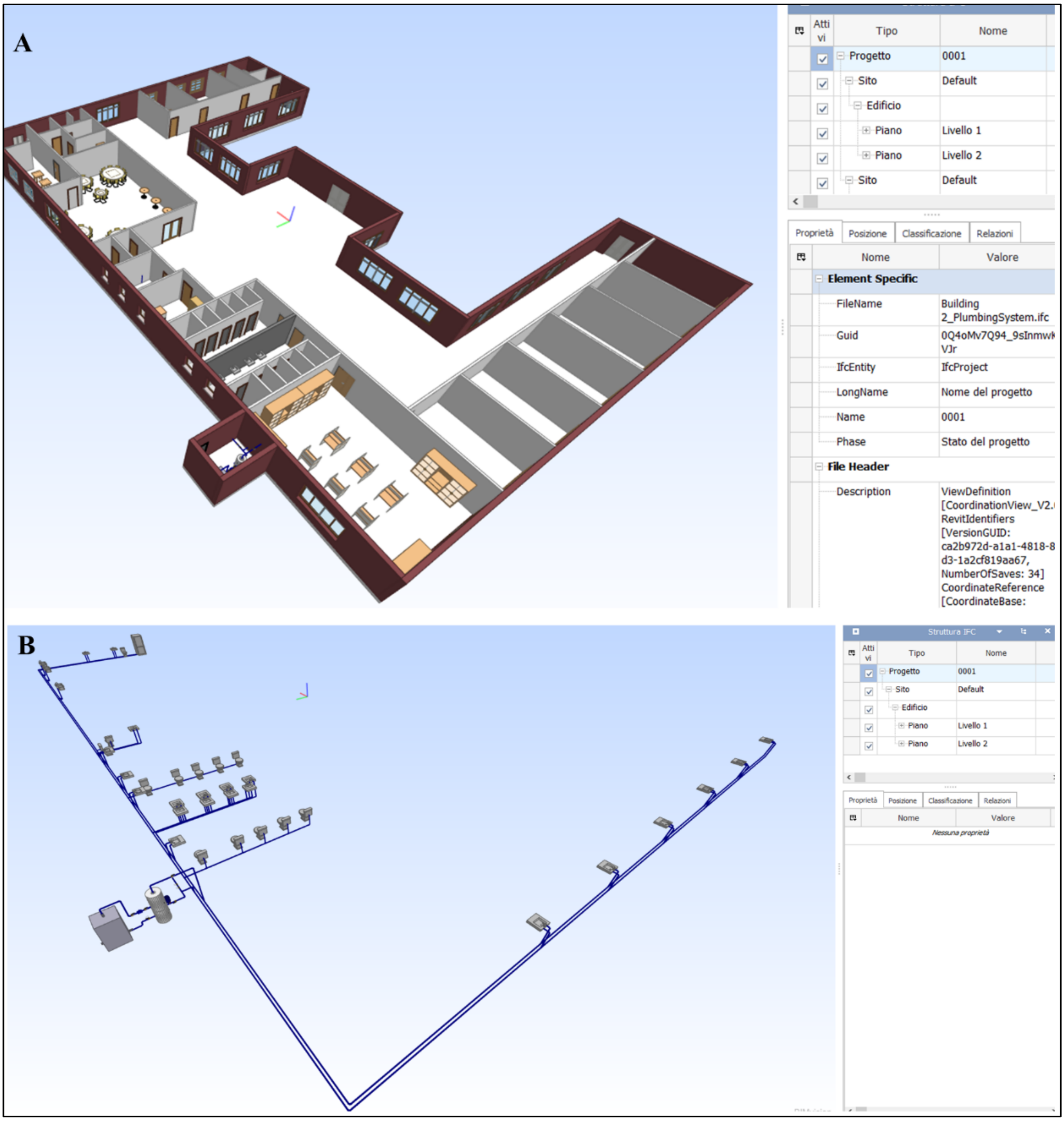
Attivi	Tipo	Nome
☑	Progetto	0001
☑	Sito	Default
☑	Edificio	
☑	Piano	Livello 1
☑	Piano	Livello 2
☑	Sito	Default
☑	Edificio	
☑	Piano	0 - Piano Terra
☑	Pareti	
☑	Parete ...	Muro di base:Matt...
☑	Parete ...	Muro di base:Matt...
☑	Parete ...	Muro di base:Matt...
☑	Parete ...	Muro di base:Matt...
☑	Parete ...	Muro di base:Matt...
☑	Parete ...	Muro di base:Matt...
☑	Parete ...	Muro di base:Matt...
☑	Parete ...	Muro di base:Matt...
☑	Parete ...	Muro di base:Matt...
☑	Parete ...	Muro di base:Matt...

Nome	Valore
Nessuna proprietà	

	Attivi	Tipo	Nome	Des
	☑	IfcFlow...	M_Gabinetto - Ar...	
	☑	IfcFlow...	M_Gabinetto - Rett...	
	☑	IfcFlow...	M_Gabinetto - Rett...	
√	☑	IfcFlow...	M_Gabinetto - Rett...	

Nome	Valore	U.m
ID tipo	765975	
Larghezza metà gabinetto	28	cm
Larghezza metà lavandino	19,05	cm
Nome famiglia	M_Gabinetto - Rettangolare	
Tipo	560 mmx560 mm - Pubblico	
Dati identità		
Commenti	Women Bathroom - Handicap - Sink n. 5	
Contrassegno	WHS5	
Nome del tipo	560 mmx560 mm - Pubblico	
Numero OmniClass	23.45.05.14.14	
Titolo OmniClass	Sinks/Lavatories	
Water Quality Analysis	https://lunduniversityo365-my.sharepoint.com/personal/ma0608pa_lu_se/_layouts/15/onedrive.aspx?id=%2Fpersonal%2Fma0608pa%5Flu%5Fse%2FDocuments%2FCloud%20Storage%20Examp	

Fig. 24: *Building 1: IFC format and visualization on BIM Vision® software of the shared model: A) Architectural component and B) Plumbing system.*



Attivi	Tipo	Nome
☑	Progetto	0001
☑	Sito	Default
☑	Edificio	
☑	Piano	Livello 1
☑	Piano	Livello 2
☑	Sito	Default

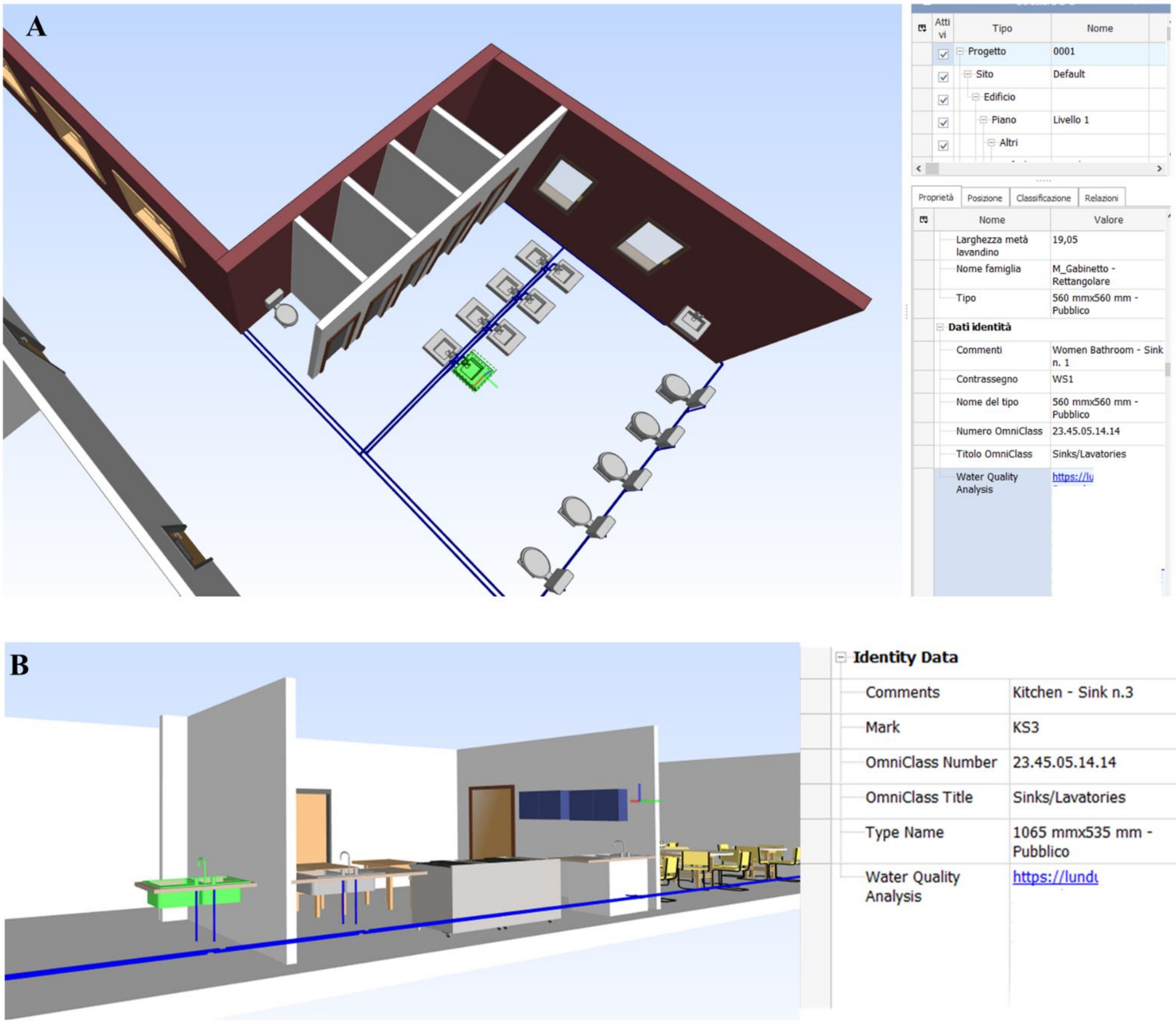
Nome	Valore
Element Specific	
FileName	Building 2_PlumbingSystem.ifc
Guid	0Q4oMv7Q94_9sInmw VJr
IfcEntity	IfcProject
LongName	Nome del progetto
Name	0001
Phase	Stato del progetto
File Header	
Description	ViewDefinition [CoordinationView_V2. RevitIdentifiers [VersionGUID: ca2b972d-a1a1-4818-8 d3-1a2cf819aa67, NumberOfSaves: 34] CoordinateReference [CoordinateBase:

Attivi	Tipo	Nome
☑	Progetto	0001
☑	Sito	Default
☑	Edificio	
☑	Piano	Livello 1
☑	Piano	Livello 2

Nome	Valore
Nessuna proprietà	

Fig. 25: *Building 2: IFC format and visualization on BIM Vision® software of the shared model:* ***A)*** *Architectural component and* ***B)*** *Plumbing system.*

The exported IFC file then presented the URL parameter through which the database containing this information can be accessed, according to an external server-based data structure. This made it possible to access the same folders associated with individual sampling points and consequently to view the contained file, which was updated to the last tap operation performed. In Figure 26 a specific sampling point along the building plumbing is highlighted, displaying the corresponding information and its associated URL upon clicking.



Attivi	Tipo	Nome
☑	Progetto	0001
☑	Sito	Default
☑	Edificio	
☑	Piano	Livello 1
☑	Altri	

Proprietà | Posizione | Classificazione | Relazioni

Nome	Valore
Larghezza metà lavandino	19,05
Nome famiglia	M_Gabinetto - Rettangolare
Tipo	560 mmx560 mm - Pubblico
Dati identità	
Commenti	Women Bathroom - Sink n. 1
Contrassegno	WS1
Nome del tipo	560 mmx560 mm - Pubblico
Numero OmniClass	23.45.05.14.14
Titolo OmniClass	Sinks/Lavatories
Water Quality Analysis	https://lu

Identity Data

Comments	Kitchen - Sink n.3
Mark	KS3
OmniClass Number	23.45.05.14.14
OmniClass Title	Sinks/Lavatories
Type Name	1065 mmx535 mm - Pubblico
Water Quality Analysis	https://lundı

Fig. 26: *IFC format and visualization on BIM Vision® software of the shared model: by clicking on a sampling point, its information can be accessed and linked to storage folders*

4.3.2 Microbiological results

Part of the microbiological analysis results described in this section have been already described in a previous study (*Zhang, 2021*). The resulting raw data was used for additional investigation in this thesis. Once the sampling points were identified and labeled on the template, the results of microbiological analysis were linked to the new labeling. So, the sampling points associated with the previously collected samples are listed in Table 11.

Table 11: *Sampling points along the fictitious BIM Models developed*

	ID Sampling point	**ID on BIM Models**
Building 1	1A	WS1
	1B	RS6
	1C	SKS1
	1D	SKS1*
Building 2	2A	CS1
	2B	STS1
	2C	CS6
	2D	CS1*

4.3.2.1 TCC and ICC results

Variations in TCC and ICC results observed in Building 1 and Building 2 are presented in Figure 27 and Figure 28, respectively.

In both the Figures the sampling intervals are indicated. In particular, Week 5 is not reported because it corresponds to the holiday break. Consequently, this week is considered as stagnation because taps were not resulting in a reduced flow within the building plumbing. Thus, Weeks 1-4 represent the period before stagnation, whereas weeks 6A-9 represent the period after stagnation.

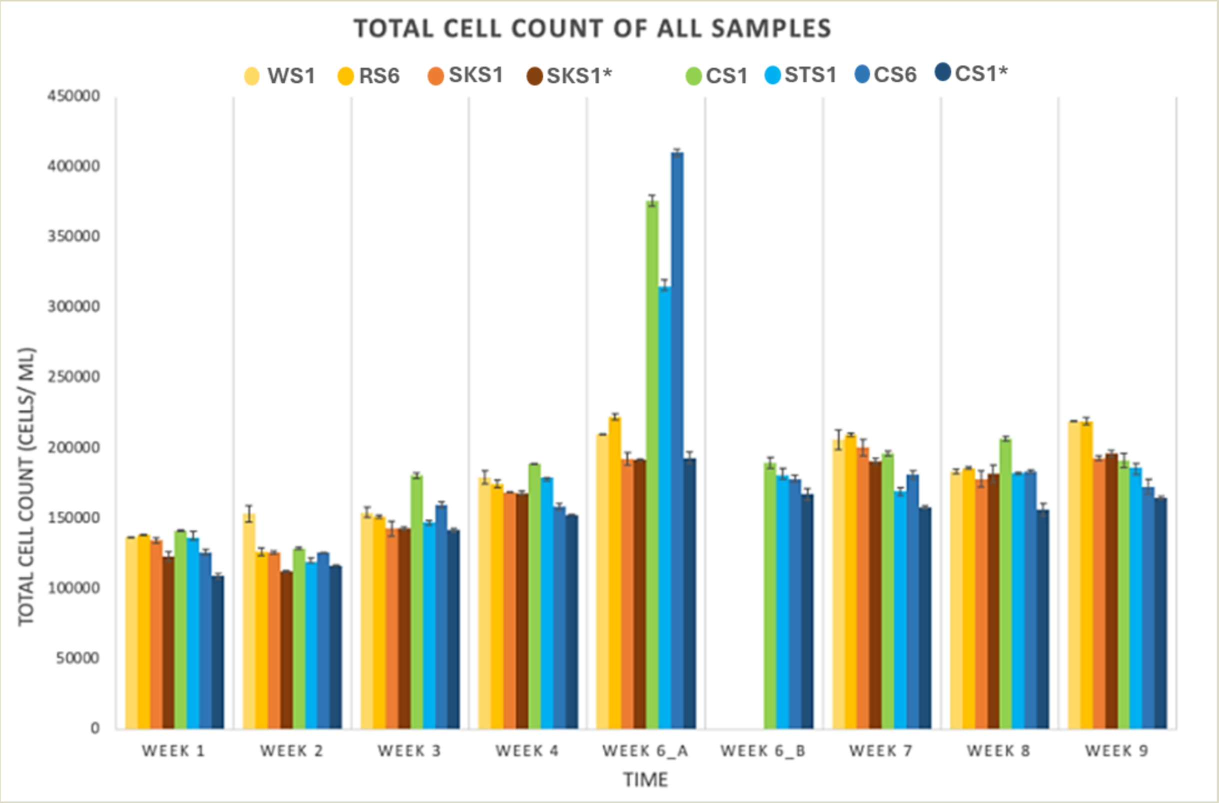


***Fig. 27**: TCC of all the samples. Shades of yellow refer to Building 1 while shades of blue refer to Building 2 (Zhang, 2021).*

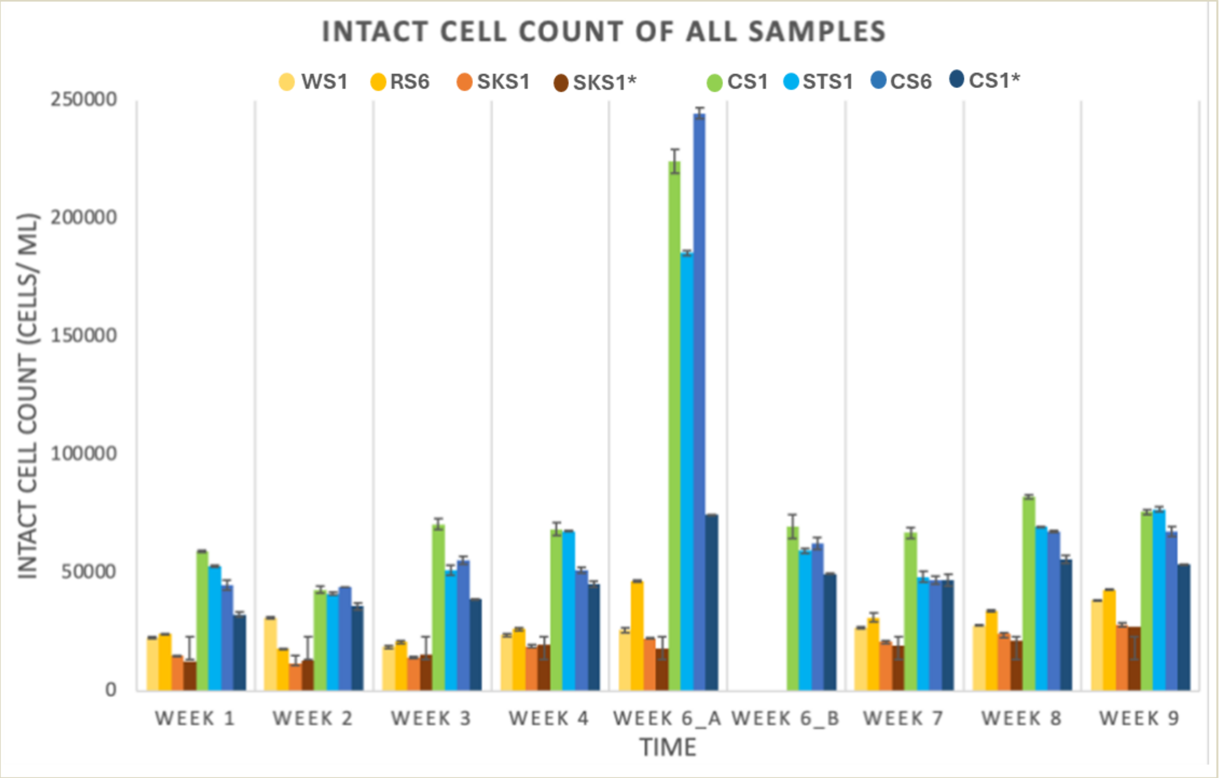


***Fig. 28**: ICC of all the samples. Shades of yellow refer to Building 1 while shades of blue refer to Building 2 (Zhang, 2021).*

As indicated in the Figures, significant fluctuations in TCC and ICC were observed after stagnation, which tends to decrease to lower values in the subsequent weeks of tap use. To be more specific, the increase in the counts was more evident in Building 2, rather than Building 1.

4.3.2.2 Microbiological water quality parameter analysis results

The microbiological parameters researched were analyzed by an analytical laboratory outside the University, and all parameters researched were following Swedish Food Agency regulations for drinking water quality (*SLVFS 2001:30, 2001*). The following Tables will show the values and parameters that do not comply with the regulations, specifically Table 12 refers to Building 1, and Table 13 to Building 2.

According to the Swedish Food Agency, the reference value for HPC at 22°C is 100 cfu/mL and 5000 cfu/mL. In general, for Building 1, it can be noted that the HPC at 22°C values were all below the permitted limit, except for sample WS1 in week 4, where there were 410 cfu/mL. For all weeks, Sample WS1 showed the highest level of HPC compared to the other samples. Sample SKS1*, which represents the water inside the WDS, revealed no HPC at 22°C values.

Regarding slow-growing bacteria, all samples were below the reference level. Sample WS1 presented was always higher values in week 4, with 810 cfu/mL. Again, the SKS1* sample shows no substantial slow-growing bacteria values. Regarding the other indicators, the WS1 sample exhibits the most contamination over weeks. Molds and micro-molds, on the other hand, are found in all samples.

***Table 12**: Microbiological parameters analysis results for Building 1.*

Sampling points	**Weeks**	**Microbiological parameters**					
		HPC at 22 °C cfu/mL	Slow growing bacteria cfu/mL	Fecal coliforms cfu/100 mL	*Yeast* cfu/100 mL	Mold cfu/100 mL	Micro mold cfu/100 mL
WS1	1	48	290				
	2		184				
	3	30	236	2			
	4	410	810		1		1
	6	2	65				
	7	10	89				
	8	15	53	8		2	2
	9	45	215	21	11		11
RS6	1	1	11			40	40
	2		1				
	3	1	25				
	4		31				
	6	1	120				
	7	2	24				
	8		11				
	9	1	25				
SKS1	1	5	11				
	2	1	7			7	
	3	2	3				7
	4	9	21			1	
	6		5				1
	7		5				
	8	11	24				
	9	7	16				
SKS1*	1	1	6			50	50
	2		4			3	
	3		3				3
	4	1	5				
	6		2				
	7	1	15				
	8		5				
	9		5				

Building 2 does not, however, exhibit considerable contamination. It is worth noting that sample CS1 presents high values of HPC at 22°C and slow-growing bacteria compared to the other samples. Again, sample CS1*, which receives water from the WDS, exhibits values that fall within the standards.

***Table 13**: Microbiological parameters analysis results for the Building 2.*

Sampling points	**Weeks**	Microbiological parameters					
		HPC at 22 °C cfu/mL	Slow growing bacteria cfu/mL	*Yeast* cfu/100 mL	Actinomycetes cfu/100 mL	Mold cfu/100 mL	Micromold cfu/100 mL
CS1	1	5	80				
	2	18	61	1			1
	3	13	143				
	4	67	550				
	6	1	49				
	6A	70	390				
	7	16	207				
	8	9	111				
	9	33	194				
STS1	1	7	8				
	2	3	5		2		
	3	7	16				
	4	2	24				
	6	7	26				
	6A	1	31				
	7	2	25		1	1	1
	8	4	25				
	9	5	47				
CS6	1	5	11				
	2	13	105				
	3	5	20				
	4	1	23				
	6	1	115		1		
	6A	1	49				
	7	16	78				
	8	6	18		2		
	9	1	15				
CS1*	1	1	12				
	2	1	3			1	1
	3	2	13				
	4	5	12				
	6	5	6		1		
	6A	2	14				
	7	1	10				
	8	1	10		1		
	9	1	5				

4.4 Case Study 2: Final Considerations

This section discusses the application findings and the effectiveness of the proposed methodology in Case Study 2, answering the initial research question: improve data management strategies in water quality assessment. The effective method and relevance in accomplishing the primary goal of the research will be evaluated. This discussion evaluates the practical implications and importance of the results, as well as describes the conclusions, and provides relevant insights for potential improvements or future enhancements of the proposed approach.

4.4.1 Discussion

The presence of microorganisms in water needs to be addressed throughout the building life cycle, from design to everyday maintenance, especially for sensitive buildings such as healthcare facilities and hospitals (*De Giglio et al., 2021*). Building plumbing presents a series of components, including materials and maintenance practices implemented, that may affect water quality *(Yao et al., 2023*). Therefore, daily decisions on building plumbing could have a significant impact on microorganism growth and spread. However, as illustrated in the background of the thesis, some limitations can compromise successful management of water quality and building plumbing.

Based on practical experiences, professionals involved in water quality surveillance and monitoring recognize the difficulties of establishing a direct correlation between microbiological contamination and building plumbing characteristics. These difficulties originate mostly from a lack of detailed and updated water system layouts as well as a shortage of representative data sampling and data related to the containment measures undertaken. In addition, some failures are sometimes caused by missing or unclear communication among various system management professionals.

Therefore, the research questions that guided this study intended to identify a strategy for filling gaps in current water quality monitoring management practices by identifying BIM models as potential tools and evaluating advantages and disadvantages.

To address the research inquiries, two fictitious building plumbing were implemented, based on a pre-existing water assessment monitoring plan (*Zhang, 2021*). These systems were designed specifically to evaluate the suitability of the proposed methodological approach, presenting all the features of the water supply system in their simplest form, simulating as much as possible real scenarios, to encourage innovative management.

The proposed methodological approach aims to: (i) digitize the Buildings and their plumbing system using the BIM approach, (ii) connect models and external cloud storage, facilitating data collection and accessibility, (iii) use the model as a tool to make maintenance decisions and implement containment measures, (iv) evaluate the microbiological results within the context of the building, in relation with the plumbing system. This approach focuses on studying the influence of building plumbing on microbial communities, providing a more comprehensive understanding.

Thus, the BIM models' development is one of the critical points of this case study. In the architectural and construction field, BIM advantages related to coordination and communication are widely recognized (*Azhar, 2011; Aziz et al., 2024*). However, this is the first time that the potential of BIM has been utilized to address challenges related to building plumbing and water quality assessment, previous studies focused mostly on improving water efficiency *(Liu et al., 2019; Khoshdelnezamiha et al., 2020*); as of the time of writing this thesis, to the best of my knowledge, no proposal has been made to combine the concept of integrating BIM, building plumbing studies and microbiological water quality, especially emphasizing the support of BIM for management purposes.

The primary advantage of building digitization lies in its ability to address the issue of outdated layouts, both for the architectural part and the water supply system. Having access to accurate and up-to-date layouts facilitates the preliminary maintenance procedures, settling at an early stage remotely, without the need for physical site visits. In addition, the virtual model enables in-depth investigations of both the building and the plumbing system, leading to an understanding of their dynamics. This facilitates the maintenance methodologies development based on the actual building design. In fact, for the Buildings, by enhancing maintenance efficiency, this approach could strengthen the long-term safety and functionality of the facilities. A similar aim was applied to other contexts of facility management, fire safety engineering, and acoustic and historical heritage restoration (*Apollonio et al., 2018; Girelli et al., 2019, 2020; de la Hoz-Torres et al., 2022; Yakhou et al., 2023*). Each of these studies concludes by highlighting the benefits of integrating BIM models to improve workflow and utilize them for a range of applications.

By integrating the two Buildings' architectural details and plumbing specifics within the models, it was possible to create a comprehensive and dynamic digital representation of the buildings and their respective water systems. These models not only enabled detailed visualization of the structures and their components, including the exact locations of each sampling point, but also provided quick and intuitive access to crucial building plumbing-related information. This advantage is fundamental for the WSP, ensuring precision in sampling strategies.

The idea of assigning unique URLs to each sampling point in Buildings 1 and 2 and connecting them to external cloud storage accessed only through a password is both simple and extremely innovative in its context. The results obtained demonstrate the ease of creating the URL as shared parameters using Autodesk® Revit® software, and the benefit of this method is to minimize the flow of information among stakeholders thus mitigating the risk of losing critical data related to contamination or maintenance issues over the time. Everyone with access to the model can consult information particular to each sampling point, such as microbiology, plumbing, maintenance, and data storage details. This information remains readily available and can be updated or modified as needed, preventing data loss within the multidisciplinary team information exchange process. The use of cloud storage to properly arrange data into folders and subfolders ensures that project-related information is better managed, facilitating team communication and data sharing. This approach substantially facilitates the consultation and updating of key information for building plumbing management, enabling faster responses to maintenance needs, microbiological contamination control, and building optimization.

Another important aspect pertains to the BIM and IFC data exchange format. These advancements are changing the way of collaboration, visualization, and documentation in facility planning, construction, and management (*Yu et al., 2023*). As a result, exporting models in IFC format has made it easier to share and interoperate BIM data with other platforms and software, enhancing collaboration and communication among the various stakeholders engaged in building management and maintenance. The IFC language is an interoperable, acknowledged, interdisciplinary language, as well as an open data format that is not controlled by a single operator and allows information to be exchanged without loss or distortion (*Gerbino et al., 2021*).

Unfortunately, the true complexity and effectiveness of BIM models do not fully emerge from written texts or static figures alone. The real power of BIM models lies in their dynamism and interactivity, aspects that are best experienced through videos or direct interaction with the model itself. The space within the Buildings can be virtually explored, allowing the user to manipulate components and observe interactions in real-time. By virtually manipulating these elements, users can simulate different scenarios and observe how changes impact the overall functionality and performance of the building. Such an approach provides a deeper understanding of the relationships between various design elements and system dynamics, which can be critical for accurate evaluation and effective communication of complex technical concepts. The direct interaction with the model can facilitate stakeholder involvement and foster closer collaboration during all phases of the project, thereby improving the overall quality of the result.

BIM in water quality monitoring offers numerous advantages. However, it is critical to recognize some limitations, especially when working with older buildings or sensitive buildings for which there is difficulty in finding and sharing floor plans, given the sensitivity of the associated data. As a consequence, for existing Buildings, there are some challenges including restricted data availability, variations in building configurations, and the need for specialized skills for effective BIM implementation. In conclusion, the absence of available data on Buildings could represent a significant limitation for this case study: at the same time, this restriction represented the main obstacles in this case study but also its basic premise, highlighting the importance of actively addressing this issue to ensure the overall success of the project.

To maximize the potential of BIM, it is essential to address these challenges with a proactive approach, implementing strong data protection measures and hiring highly experienced personnel to manage the software appropriately.

As part of this study, data previously collected on the microbiological quality of water have been linked to their respective sampling points, transitioning from traditional paper reports to dynamic digital management within the model, resulting in a "living" model that evolves in real-time.

The microbiological results were examined with a particular emphasis on the relationship between water stagnation, system flushing, and the establishment of point source contamination. This approach enables a comprehensive assessment of the quantitative microbiological risk within the Buildings, as well as the implementation of a regular maintenance plan aimed at maintaining and controlling high water quality to contain contamination while also ensuring that water quality standards are consistently met over time. This assessment and planning process laid the basis for the creation of a simple WSP, which provided a complete framework of preventative and corrective procedures required to effectively manage microbiological risk in building environments.

As previously mentioned, the sampling campaign included a week-long break due to the closure of both buildings. This break period corresponds to a stagnation phase in the water system, as there was no water flow or usage in the buildings during that time, and stagnation in the Building water system is commonly used to describe a lack of water flow.

In this study, it was aimed to address how stagnation contributes to microbiological contamination. The findings derived from the flow cytometry analysis provided clear evidence of a significant increase in TCC and ICC within both Buildings after the stagnation phase, with Building 2 exhibiting a higher effect. This increase in microbial counts strongly suggests that during the period of unused tap water, the water within the building water system had prolonged contact with the material and the biofilm in the pipelines. As a consequence, this contact facilitated the proliferation and spread of microbial growth throughout the system. Furthermore, the dynamics of microbial growth were evident in the TCC and ICC data after the week of stagnation, illustrating a notable decrease after the resumption of tap water usage. This decline can be attributed to the flushing action of water flow, effectively removing stagnant water along with microbial contamination. The decrease in cell counts following the flushing underscores the efficacy of water flow in mitigating microbial contamination within the system. Overall, this aspect highlights the critical role of stagnation periods in exacerbating microbial contamination within the building water system. Despite being well aware of its significant impact on water quality, monitoring water quality after periods of inactivity is generally not conducted

(*Bédard et al., 2018*). Understanding the impact of stagnation on microbial contamination is critical for the development and implementation of an effective WSP. Incorporating this knowledge into the WSP allows for the identification of potential risks associated with stagnant water and the formulation of target strategies to mitigate these risks. By recognizing the increased microbial growth during stagnation periods, preventive measures such as regular flushing of water systems and implementing appropriate maintenance protocols can be incorporated into the plan. In this case, water quality monitoring of before and after periods of inactivity could be integrated into routine WSP procedures ensuring timely detection of any microbial contamination and prompt corrective actions. Overall, addressing the effects of stagnation on water quality within the WSP enhances the overall safety and integrity of the water supply system, safeguarding public health.

On the other hand, the results of the analysis of microbiological parameters conducted did not reveal any microbiological contamination of special significance, as all values found were following the limits set by current regulations.

Certainly, it is indeed noteworthy that there were no significantly elevated contamination values in any of the samples, both before and after the stagnation period. This suggests that there may not be a substantial difference in contamination levels before and after stagnation. These results are completely in contrast to the findings from the flow cytometry analysis. Culturable cell counts provide insights to identify microorganisms that can increase in plumbing systems and, culture-based methods can detect viable but not culturable cells in distribution systems (*Bédard et al., 2018*). These considerations could explain the differences between microbiological parameters and flow cytometry results. Flow cytometry provides insights into the total microbial cell population, regardless of their cultivability, offering a representation of microbial abundance in water systems (*Robinson et al., 2023*). Therefore, the difference observed could be attributed to the ability of flow cytometry to capture a broader spectrum of microbial activity.

Culture-based methods play a critical role in identifying culturable microorganisms.

The results in this study revealed that the overall water quality was good in both the Buildings. The exception was in Building 1 with the sampling point WS1 exhibiting higher contamination compared to the others over all the weeks of analysis. This elevated contamination was evident across various parameters, including general microbial contamination as indicated by the HPC at 22°C, as well as the presence of slow-growing bacteria and fecal coliforms. This suggests a localized microbial contamination that could be removed by cleaning and flushing the tap.

Moving beyond the mere detection of contaminants in microbiological analysis is a fundamental step. It is essential to contextualize this data by examining the specifics of the building plumbing in analysis.

In our case, if microbiological concentration at point WS1 consistently persists over time despite the application of various containment measures, this could be related to a problem with the configuration of the building plumbing rather than being the result of localized external contamination. This means analyzing the structural characteristics of the building, the dynamics of water flow, and the maintenance practices employed. Only through this detailed assessment it can be possible a complete and accurate view of the risk of microbiological contamination by identifying where corrective action is needed and to take appropriate measures to ensure water quality safety.

As a consequence, a WSP was implemented identifying potential risks associated with stagnation, including microbial growth and contamination. People who occupy the Buildings, infrastructure materials, and maintenance factors were factors considered to determine the mitigation strategies.

Develop and implement regular flushing protocols to minimize stagnation and maintain water flow, conduct periodic inspections and maintenance of plumbing systems to identify and address potential sources of contamination, and ensure proper disinfection procedures are in place to control microbial growth and maintain water quality were all included in the plan.

For the monitoring and surveillance, a monitoring program to assess water quality before and after periods of inactivity was established and a key role of this program was represented by the documentation and review of the data.

Maintain thorough documentation of all WSP activities, including monitoring results, corrective actions taken, and changes to protocols or procedures to improve the maintenance of WDS and water quality. Regularly review and update the WSP as needed to reflect changes in building usage, infrastructure, or regulations.

In conclusion, with the application of this methodology approach for evaluating water quality, it was possible to address the initial research questions. BIM emerges as a promising solution to fill the existing gap in data sharing, management, and communication, offering a comprehensive approach to data management and sharing, and facilitating better communication between professionals involved in risk assessment. It highlights the potential of BIM in improving the understanding and management of complex architectural and construction projects.

This study lays down the fundamental groundwork for leveraging BIM technology in a novel domain, establishing a workflow that can be potentially applied to other reconstructions, representing a significant departure from conventional methodologies. An interesting future advancement could involve the creation of simulation and prediction tools designed to evaluate expected water quality under different water safety management strategies. These tools could utilize advanced modeling techniques and real-time data integration to simulate outcomes, highlighting the potential impact of interventions or changes in infrastructure. Integrating these within BIM models, decision-makers could visualize and assess the interplay between structural design and water safety measures.

4.4.2 Case study 2: Conclusions

The methodological approach proposed with this Case Study provides a simple and effective method for developing an intuitive and efficient data management model, encouraging improved stakeholders' involvement, other than the better management of water quality monitoring. Moreover, a detailed understanding of microbial contamination dynamics within the building plumbing is essential for developing effective monitoring and control strategies. Integrating this knowledge enables the adoption of proper and timely control measures to prevent and manage water contamination, thereby reducing risks to public health and enhancing overall water quality as well as the proper system operation.

Several points can be considered as benefits resulting from the application of the proposed approach:

- Effectively address the issue of data sharing and availability.
- Establish a streamlined data flow, ensuring clear and consistent communication channels.
- Promote collaboration and coordination between professionals involved in building plumbing management and monitoring, with a clear delineation of responsibilities.
- Conduct comprehensive evaluations of building plumbing to enhance its functionalities.
- Provide a thorough understanding of risk assessment and management concerning water quality.
- Implement a holistic approach to evaluate microbiological water quality.
- Safeguard public health by assuring safer drinking water.
- Ensure the proper building plumbing operation and functionality over time.

Chapter 5

This chapter briefly provides a summary of the findings derived from both experimental works carried out in this thesis by providing discussion on the research questions that motivated this study. Moreover, it offers some considerations on water quality evaluation and recommendations for potential future research.

Conclusions

The main aim of this PhD thesis was to develop a novel and innovative approach to assessing microbiological water quality. It discusses the importance of considering water quality within WDS and building plumbing, rather than considering it as a separate part influenced only by biological communities. Integrating the knowledge that microbial communities are strongly influenced by the WDS structure and its hydraulic parameters, such as water pressure and flow rate, is fundamental. The consequent critical aspect is that awareness needs to be integrated into standard environmental monitoring practices, ensuring that all stakeholders, from technicians to management professionals, consistently give priority and integrate this awareness into their daily routines and decision-making process.

The proposed methodology holds significant importance as it aims to address gaps in water quality data sharing and communication among management stakeholders. This is achieved by using the potential of BIM technology to optimize WDS management practices. Through this innovative approach, the research tried to address critical deficiencies in current methodologies and contribute to enhance the comprehension and management of water quality in buildings.

In particular, two case studies were presented. Case Study 1, involving an important monument, served as the foundation for the approach development. Case Study 1 has proven to be extremely useful in delineating the integrated approach to address some challenges related to water quality evaluation. The integrated approach proposed for monitoring water quality suggests that by integrating and studying microbiological contamination concerning specific hydraulic parameters, water quality is improved as microbiological contamination is reduced and prevented. By carefully adjusting fundamental hydraulic parameters and addressing engineering interventions on pipelines, this approach has significantly improved water quality, without the need for complicated treatments using thermal or chemical shocks. These kinds of measures are not so common in standard environmental surveillance practices. The identification of crucial areas in the distribution and treatment processes for water has been made possible by this integrated approach, which has also established a strong basis for continual operation optimization. It has also made prompt problem-solving possible, allowing for proactive water quality management.

This holistic approach is then concluded with the support of BIM. The use of BIM has played a crucial role in this context, providing essential support through efficient management and analysis of information. Thanks to BIM, it has been possible to integrate detailed data regarding hydraulic systems and microbiological processes, allowing for a comprehensive and accurate view of the system. The practical purpose was the implementation of a tool that goes beyond simply creating virtual models: it is not just about designing virtual buildings, but understanding how these projects can translate into concrete operations improving efficiency.

As illustrated in Chapter 3, despite the encouraging results obtained, Case Study 1 concerns a WDS characterized by sophisticated functionalities for a fountain but limited in size and lacking hydraulic fixtures such as sinks, showers, or other rooms. Essentially, it is a closed circuit, rather small in scale. At this level, the question was: Is it possible to extend the application of this innovative approach to managing larger WDS within buildings? To address this, it was delved into Case Study 2.

While Case Study 1 initiated the development of the integrated approach, Case Study 2 aimed to refine a more robust and resilient approach for water and WDS management practices.

With this approach, it has been shown the potentiality of the 3D model to represent a support and a core of a solid database in which the different information could be stored, managed, shared, and combined to guarantee good water quality and optimize the study, visualization, and interaction with the WDS. The availability of an interactive digital model has enabled more efficient and targeted management of monitoring activities. This has been crucial because it allows every relevant aspect of management to be kept under control, ensuring a timely response to any changes or anomalies.

Overall, Case Study 2 highlighted how the use of an interactive digital model can significantly improve water quality management.

This is the first time that the potential of BIM is being applied in the context of environmental monitoring plans for water quality evaluation, representing an application quite simple as it is innovative. Traditionally associated with the building and architecture sector, the use of BIM in this context opens promising scenarios. The adaptation of the BIM model to the context of environmental monitoring plans for water quality represents a significant step towards smarter and more responsible management of WDS, combining innovative technologies with a holistic vision. Obviously, this work has laid the foundation and is only the beginning of a broader, more precise, and defined development of the application of BIM in the water quality monitoring field.

This PhD thesis aims to challenge the current worldview by identifying the shortcomings of the current approach, which relies, for instance, on traditional paper-based communication. Instead, it presents an innovative and robust framework and strategy. This framework considers the diverse needs of stakeholders of buildings and specific requirements, while also offering benefits.

The component that is intended to stand out in the project outcomes is how the interaction between microbiological expertise and hydraulic engineering experience is an appropriate way to prevent and contain microbiological contamination, assuring the proper and functional activities of the system other than preserving the public health, considering water not focusing on a single analysis but in a holistic way.

The insights highlighted in this thesis serve as a foundation for further potential improvements for future research. It is not possible to define a strategy that reduces the risk associated with the plumbing system to zero, but there is a need to further investigate the integrated approach between different disciplines to increase the cooperation and awareness of microbial communities about the pipes allowing risk mitigation. Other improvements should be made to better adapt the sophisticated BIM software options to the field of plumbing industry to microbial proliferation. The development of such an aspect would mark a substantial advancement in public health safety.

This thesis was fundamentally based on a multidisciplinary approach, which has become crucial in various fields. Technological innovation, public health, and resource management are just a few areas that require an integrated vision capable of combining different perspectives, knowledge, and skills. This not only leads to more innovative and comprehensive solutions but also helps to address difficult problems that cannot be solved by a single discipline. However, multidisciplinary collaboration is not without its challenges. Difficulties often arise in communication, where different specialist languages can lead to misunderstandings, and in coordination, which requires the alignment of different working methodologies, timelines, and goals. These challenges were also addressed in the course of this thesis work, demonstrating how complex but at the same time fundamental and innovative it is to combine skills and knowledge from different fields. The results obtained, however, represent an important starting point for raising awareness of the integrated approach. In particular, in the context of water management and quality, which is still too sectoral and fragmented, this approach proves to be the only possible way to achieve significant improvements. Indeed, water management and quality require not only technical and engineering expertise but also an in-depth understanding of microbiological communities, biofilms, and the interactions between them. Therefore, it is only through multidisciplinary collaboration that sustainable and effective solutions can be developed, and above all, lasting over time. The results obtained in this thesis underline how the integration of different disciplines can lead to a more comprehensive view and more effective solutions, stimulating a new awareness and a paradigm shift in traditional sectoral fields. As a consequence, future investigations and improvements should be applied in the context of collaboration and communication.

The last core message that this thesis aims to convey is that considering water as a whole system is the key to truly safeguarding public health. While much attention in the microbiological fields is often directed towards the importance of the clinical field, it is crucial to recognize the equally crucial role of bacteria living in the environment. Before pathogenic bacteria reach humans, they live and grow in the environment. Understanding that our health is linked to the risk arising from interactions between microorganisms and the environment is fundamental. In the context of WSP and ensuring good water quality, WDS is central to this message. Understanding how bacteria move and interact within a WDS and addressing current gaps are the starting points for implementing risk management and preserving health.

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