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Article

A Digital Integrated Methodology for Semi-Automated Analysis of Water Efficiency in Buildings †

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† This paper is an extended version of our paper published in 2023 Portland International Conference on Management of Engineering and Technology (PICMET), Monterrey, Mexico, 23–27 July 2023, pp. 1–6.

Abstract: Recent developments in the field of digital technologies in construction have led to a renewed interest in the use of building information modeling (BIM) for water efficiency analysis (WEA). BIM has emerged as a powerful platform for performance analysis towards sustainable design. However, there is little available in the literature on WEA using BIM. Extensive research has shown that WEA in buildings focuses on rating systems, 3D modeling, clash detection, and rainwater harvesting analysis. This paper presents a digital integrated methodology with in-depth analysis of three domains: (1) analysis of water usage according to plumbing fixtures and inhabitant demand per day, (2) sizing analysis of hydraulic-plumbing systems using the flowrate calculation method, and (3) analysis of alternative systems using harvested rainwater and treated water. The proposed methodology was applied to a multi-family building in Nuevo León, Mexico. The authors conclude that this methodology can easily be implemented in the short term, and that it may provide a significant improvement in WEA.

Keywords: building performance analysis; building information modeling; water efficiency analysis; hydraulic-plumbing system; water supply system

Citation: Cortez-Lara, P.; Sanchez, B. A Digital Integrated Methodology for Semi-Automated Analysis of Water Efficiency in Buildings. *Buildings* **2023**, *13*, 2911. https://doi.org/10.3390/buildings13122911

Academic Editors: Xuelin Zhang, Asiri Umenga Weerasuriya, Kin Wai Tsang, Yaohan Li and Chi-Chung Lee

Received: 14 October 2023
Revised: 2 November 2023
Accepted: 7 November 2023
Published: 22 November 2023

1. Introduction

A comprehensive analysis of water usage in buildings provides information about water consumption patterns. The domains for water efficiency analysis (WEA) in buildings vary according to the type of building and the regional conditions [1]. To date, several studies in WEA have focused on how to reduce water with the use of rainwater or treated water. However, previous studies have revealed the ineffective use of these domains in regions for which they were not designed [1,2]. This issue has recently been challenged by several studies [2–4] demonstrating the lack of WEA domains due to the use of rating systems. Ratings systems such as Leadership in Energy and Environmental Design (LEED) emerged to facilitate the development of sustainable buildings in many countries [5].

Over the past two decades, major advances in digital technologies have allowed the development of building information modeling (BIM) to improve efficiency in the architecture, engineering and construction (AEC) industry. BIM technology has become an important system for supporting construction processes [6]. This technology can manage precise information with a powerful and highly organized graphical interface. However, much of the literature on BIM-based analysis lacks clarity regarding water efficiency in buildings and is limited [7]. Chang and Hsieh's [8] comprehensive review concluded that BIM-based WEA is still largely unexplored and emphasized its importance for building performance analysis (BPA).

This paper is an extension of work originally presented at the 2023 conference, Portland International Conference for Management of Engineering and Technology (PICMET) [9]. The present research explores a digital integrated semi-automated methodology to fill the gap of WEA using BIM during the project's design and operation phases in a larger scale project. There are two primary aims for this study: 1. to develop a step-by-step methodology for the integration of BIM-based WEA, and 2. to ascertain appropriate domains for WEA.

To accomplish the above objectives, the methodology was validated with a functional demonstration, through the evaluation of a multi-family building based on three main domains: (1) analysis of water usage according to plumbing fixtures and inhabitant demand per day, (2) a sizing analysis of mechanical equipment using the flowrate calculation method, and (3) analysis of alternative systems using harvested rainwater and treated water. The methodology differs from other established approaches in that it analyses the main elements of the hydraulic-plumbing systems and introduces an easier path to exchange information in the operation stage of the project using digital technologies.

2. Literature Review

2.1. BIM as a Performance Analysis Tool

In recent years, there has been an increase in the literature on BIM in the sustainability area as a Building Performance Analysis (BPA) tool. BPA plays a critical role in the analysis of the life cycle of a building. It encompasses three concepts: project phases, green attributes, and BIM. The project phases are concerned with the project life cycle such as the design, construction, operation, and demolition phases. The green attributes concept [8,10,11] includes sustainability parameters that could be addressed by using BIM (e.g., thermal and energy analysis, solar and daylight analysis, etc.). Finally, BIM represents the functions of the building system and its attributes [6]. Recently, considerable evidence has accumulated to show that BIM facilitates collaborative work in digital environments to improve workflow during the design stage in the AEC industry [12–15].

In order to perform BPA using BIM, it is necessary to develop technological tools. A summary of the most widely used BPA software and its area of analysis is presented on Lu et al., [10] comprehensive review.

2.2. The Potential of BIM for Water Efficiency Analysis in Buildings at Various Stages

Most studies in BIM-based WEA in the AEC industry have only been carried out in a small number of areas [16,17] and project stages [8]. Despite this situation, a number of researchers have explored the application of BIM-based WEA at various stages of a project. A summary of those studies of WEA at different building lifecycle stages is presented in Table 1.

Table 1. Previous studies on BIM for WEA in buildings.

Author	Water Domain	Building Project Stage		
		Design	Construction	Operation
(Krygiel and Nies, 2008) [15]	Rainwater harvesting	✓		
(Martins and Monteiro, 2013) [17]	Water distribution systems	✓		
(Bonenberg and Wei, 2015) [18]	Rainwater harvesting	✓		
(Wong and Zhou, 2015) [19]	Rainwater harvesting	✓		

Table 1. *Cont.*

Author	Water Domain	Building Project Stage		
		Design	Construction	Operation
(Lu et al., 2017) [10]	Water consumption	✓		
(Wei et al., 2017) [20]	Water supply, sewage, and rainwater pipes		✓	
(Howell et al., 2017) [21]	Intelligent sensing and cybernetics	✓	✓	✓
(Liu et al., 2019) [22]	Water efficiency	✓		
(Zhao et al., 2019) [23]	Water distribution systems	✓	✓	
(Luo et al., 2022) [24]	Underground pipeline clash detection	✓		
(Wang et al., 2022) [25]	MEP clash detection	✓		

2.2.1. Design Stage

The design stage is considered to be one of the most important stages in the entire life cycle of the project. In this stage, the best solutions to satisfy the owner's requirements are determined. Depending on the circumstances, this stage may consist of a quick review to a large process involving many consultants from various specialties. At this stage, several studies have explored the use of BIM for modeling in 3D and coordinating mechanical, electrical, and plumbing (MEP) systems.

In previous studies on WEA, different analyses were related to rainwater harvesting, project checking, and project management. In 2008, Krygiel and Nies [15] calculated the amount of harvested rainwater to reuse in plumbing fixtures. The study was developed using Autodesk Revit, and Microsoft Excel. In 2013, Martins and Monteiro [17] developed a method for the automated code-checking of a building network design in Portugal. In their study, they reported the main principles behind BIM-based automated code-checking and highlighted the IFC (Industry Foundation Classes) role as an exchange format. In 2015, Bonenberg and Wei [18] used BIM tools to simulate rainwater harvesting and water circulation systems, making it possible to reduce waste and improve construction quality. By drawing on the same area of analyzing rainwater harvesting, in 2015 Wong and Zhou [19] investigated the potential for water catchment to reduce water demand for buildings. Following this period, Lu et al. [10] performed a review to provide a holistic understanding on the nexus between BIM and green buildings. They listed three areas of analysis: (1) the application of BIM in different building life cycle stages, (2) the use of BIM as a green building analysis tool (e.g., water usage analysis, energy performance and solar radiation), and (3) BIM as a platform to develop Green Building Assessment (GBA).

In recent years, there has been an increase in the amount of research on the application of mixed digital technologies and frameworks to perform WEA in budlings. Liu et al. [22] performed the first research on the potential of BIM for water efficiency in buildings using a mixed method in 2019. Their research provided a framework for the use of BIM for water conservation in the building design and construction stages. However, the proposed framework has limitations because it has not been tested in a case study and requires more technical information. In a large-scale longitudinal study, Zhao et al. [23], combined BIM and Geographic Information Systems (GIS) to a water distribution system. The study incorporated digital modeling for the planning process of water distribution by applying geospatial information and semantic maps. A recent study by Lou et al. [24], described a

BIM-based multidisciplinary framework for underground pipeline clash detection. The proposed framework integrated clash modules such as clash rule definition, BIM clash detection, irrelevant clash filtration, and clash coordination.

2.2.2. Construction and Operation Stages

Beyond the importance of the construction and operation stages, the application of BIM on WEA has received less attention. The reasons for this lack of study are still unclear. Yet, there are studies that identify the causes that restrict the use of BIM in the AEC industry [26–28].

The studies of BIM in WEA that have been conducted to date in the construction and operation stages are mostly frameworks and strategies for systems analysis. By drawing on a systematical theoretical guide through the entire life cycle of the building, Wei et al. [20], applied BIM to check the water and sewage pipeline infrastructure during construction stages. Following this period, Howell et al. [21], combined BIM, smart appliances, intelligent sensing, and cybernetics to save costs and water resources through various building life cycle stages. The presented research by Howell et al., described a novel cloud-edge solution by unifying domestic socio-technical water systems at an urban scale in a semantic knowledge management service path. A recent study by Wang et al. [25], developed a framework for MEP rule checking using subgraph matching technology to detect logical relationship in MEP systems with BIM.

Overall, all the studies reviewed suggest that BIM-based WEA is a critical and urgent topic to keep developing. Evidence in the literature review highlights the need to explore how to apply and ascertain domains for BIM-based WEA in multiple stages of a construction project to maximize water efficiency and project benefits.

3. Materials and Methods

3.1. Description of the Case Study

The case study is a multi-family building, located in Nuevo León, in Mexico. It is located in the municipality of Santa Catarina and geographically situated at 25.67° N and 100.44° W. The municipality has a total area of 917.61 km^2 with an estimated population of 306,322 inhabitants and a density of 334 inhabitant/km^2 [29]. Santa Catarina was one of the most affected municipalities during the drought of 2022. A combination of the effects of the COVID-19 pandemic and an increase in ambient temperatures for several months, let to the declaration of a water emergency in August 2022.

Due to the building owner's privacy policies, it is not possible to disclose the name or photographs of the project. The built area is 5900 m^2 distributed in two towers. Tower I has six levels. Tower II has 14 levels with amenity spaces, shared facilities, and three basement levels for underground parking. The ground level of both towers consists of an area dedicated to retail and parking. On the above-ground floors of each tower are apartments. The present study utilizes Tower I for the evaluation of the methodology. Tower I has two types of apartments: Type I and Type II. Apartment type I has 1 bedroom, 1 full bathroom, 1 half-bathroom, a living room, utility room, dining room, and kitchen. Apartment type II has 2 bedrooms, 2 full bathrooms, 1 half bathroom, a living room, utility room, dining room, and kitchen.

3.2. Methodology

The presented study proposes a methodology based on three main domains by adapting the conceptual framework previously reported by Liu et al. [22]. The three domains presented in this study are: (1) analysis of water usage according to plumbing fixtures and inhabitant demand per day, (2) sizing analysis of the hydraulic-plumbing system using the flowrate calculation method, and (3) analysis of alternative systems using harvested rainwater and treated water. The results of the evaluation of each domain are later sorted and filtered to compare the calculated data of the design stage to the operation stage. In this study, further data collection is required to determine exactly the differences between the design and operation stages. The limited information meant that it was not possible to evaluate the operation stage.

The entire methodology (Figure 1) is divided into three modules: the identification module, the Blue Project Template (BPT) module, and the output module. The project template method is based on [30] methodology and is adjusted for the domains proposed in this study.

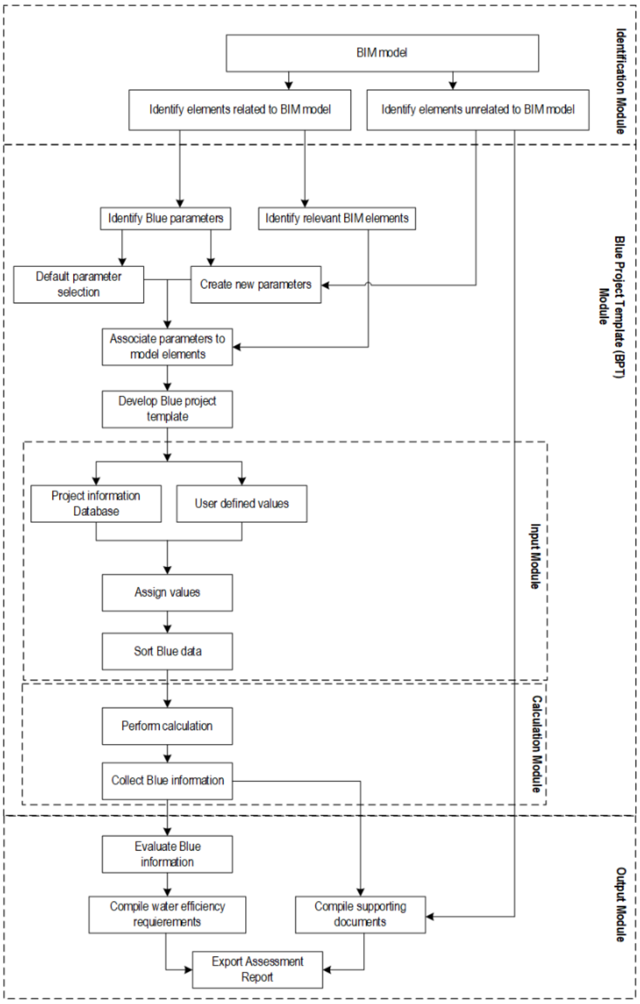


Figure 1. Global methodology workflow.

Collaboration of professionals from multiple fields such as architects, plumbing engineers, and landscape designers is essential for the entire process at the operation stage. Autodesk Revit was selected as the software to develop the prototype system using this methodology because widely used around the world [7].

3.2.1. ISO-46001.2019—Water Efficiency Management Systems: Requirements and Guidance for Use

In this study, ISO-46001.2019 [31] was chosen as the base standard for water efficiency evaluation due to the lack of standards for WEA in the study region. The ISO-46001.2019 standard specifies water efficiency management system requirements and contains guidance for their use. The core of this standard addresses three lines of development called the 3 Rs: (1) reduce, (2) reuse, and (3) replace. ISO (the International Organization for Standardization) is a worldwide federation of national standards and is widely accepted around the world [31].

3.2.2. Identification Module

This module identifies the elements that are linked to each of the domains according to the building type. There are two subcategories of information according to their source: (1) related to the BIM model and automatically collected, such as, plumbing fixtures, and piping material; and (2) unrelated to BIM model and manually collected, such as operation and maintenance (O&M) data, number of occupants, construction work schedule, and per capita water consumption. The identified elements are then transmitted to the BPT module to sort the parameters according to the three domains: (1) analysis of water usage according to plumbing fixtures and inhabitant demand per day, (2) sizing analysis of hydraulic-plumbing system using the flowrate calculation method, and (3) analysis of alternative systems using harvested rainwater and treated water. Figure 2 shows the data process developed in the subcategory identification module according to their source.

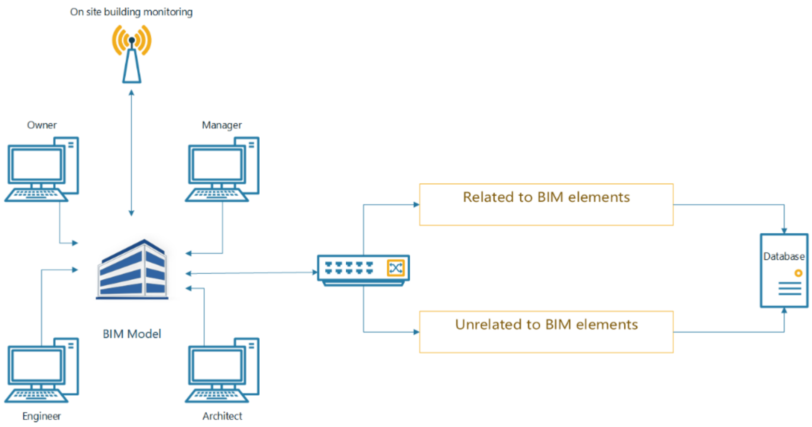
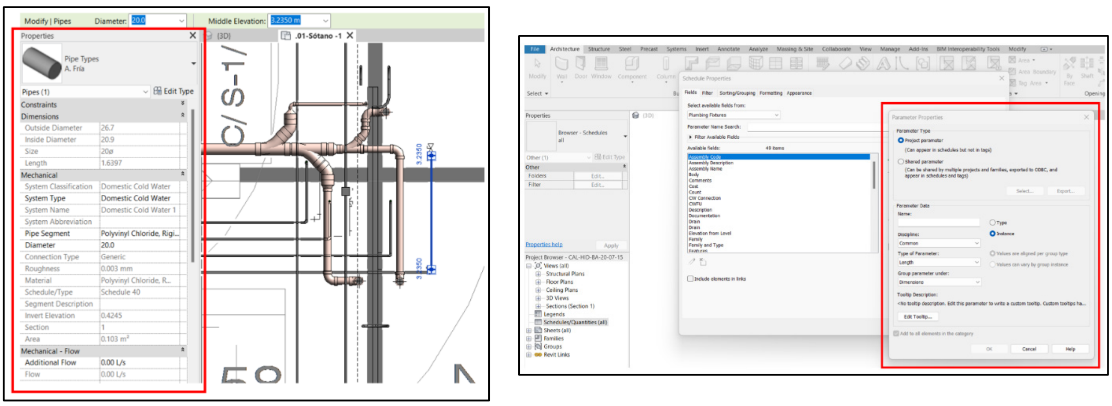


Figure 2. Identification module and data integration.

3.2.3. Blue Project Template (BPT)

The use of Revit for water efficiency analysis requires two main features: (1) default parameters for the model compatible with WEA requirements, and (2) custom project parameters referred as the Blue Project Template (BPT). The default parameters consider standardized data and calculation values of the elements that integrate water supply systems such as piping material, inlet and outlet connections, and type of plumbing fixtures. The customized parameters allow the user to manually enter specific values for equipment or system elements such as recovery water for heating, ventilation, and air conditioning (HVAC) equipment (Figure 3). Figure 4 illustrates the process of creating the BPT.



(**a**) (**b**)

Figure 3. Blue Project Template parameters. (**a**) Default parameters; (**b**) customized parameters.

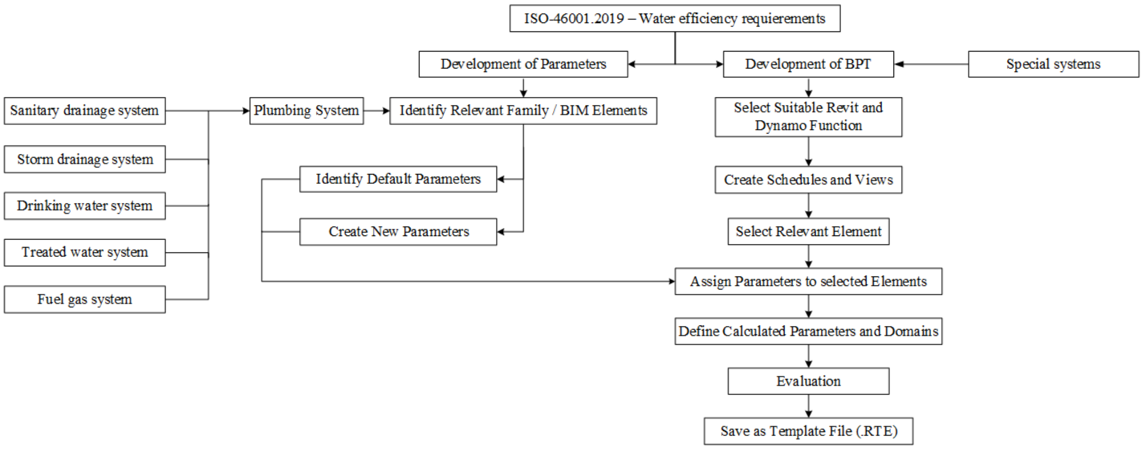
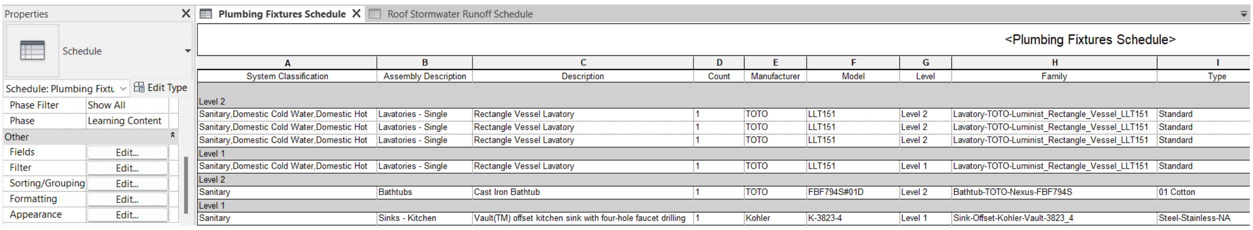


Figure 4. Blue Project Template steps diagram.

When the BPT configuration is completed, the elements processed in the identification module are automatically sorted according to the parameters set in the BPT module. Each of the elements are extracted from the BIM model (Figure 5) and grouped in line with four subcategories of the water supply system.



A	B	C	D	E	F	G	H	I
System Classification	Assembly Description	Description	Count	Manufacturer	Model	Level	Family	Type
Level 2								
Sanitary,Domestic Cold Water,Domestic Hot	Lavatories - Single	Rectangle Vessel Lavatory	1	TOTO	LLT151	Level 2	Lavatory-TOTO-Luminist_Rectangle_Vessel_LLT151	Standard
Sanitary,Domestic Cold Water,Domestic Hot	Lavatories - Single	Rectangle Vessel Lavatory	1	TOTO	LLT151	Level 2	Lavatory-TOTO-Luminist_Rectangle_Vessel_LLT151	Standard
Sanitary,Domestic Cold Water,Domestic Hot	Lavatories - Single	Rectangle Vessel Lavatory	1	TOTO	LLT151	Level 2	Lavatory-TOTO-Luminist_Rectangle_Vessel_LLT151	Standard
Level 1								
Sanitary,Domestic Cold Water,Domestic Hot	Lavatories - Single	Rectangle Vessel Lavatory	1	TOTO	LLT151	Level 1	Lavatory-TOTO-Luminist_Rectangle_Vessel_LLT151	Standard
Level 2								
Sanitary	Bathtubs	Cast Iron Bathtub	1	TOTO	FBF794S#01D	Level 2	Bathtub-TOTO-Nexus-FBF794S	01 Cotton
Level 1								
Sanitary	Sinks - Kitchen	Vault(TM) offset kitchen sink with four-hole faucet drilling	1	Kohler	K-3823-4	Level 1	Sink-Offset-Kohler-Vault-3823_4	Steel-Stainless-NA

Figure 5. Plumbing fixture schedule for BPT project development.

The four subcategories are identified as plumbing fixtures, mechanical equipment, runoff areas, and special equipment, as is shown in Table 2. The special equipment subcategory is associated with the new parameters set by the user in the BPT module. This last subcategory mainly focuses on the equipment or elements of other systems that use water for their operation such as the heating, ventilation, and air conditioning (HVAC) and fire protection (FP) systems.

Table 2. Subsystem water supply elements.

Plumbing Fixtures	Mechanical Equipment	Runoff Areas	Special Equipment
Toilet	Potable water pump	Garden	Other
Dual-flush toilet	Hot water circulation pump	Terrace	
Flushometer valve toilet	Treater water pump	Rooftop	
Urinals	Irrigation pump		
Lavatories	Water heater		
Kitchen sink	Boiler		
Service sink			
Laundry tray			
Faucet			

Table 2. *Cont.*

Plumbing Fixtures	Mechanical Equipment	Runoff Areas	Special Equipment
Drinking fountains			
Showers			
Bathtubs			
Bidet			

The calculation module (Figure 6) is based on a multi-source element assessment to integrate data and evaluate the overall design and operation stages of the building's water supply system through three domains: (1) analysis of water usage according to plumbing fixtures and inhabitant demand per day, (2) a sizing analysis of mechanical equipment using the flowrate calculation method, and (3) analysis of alternative systems using harvested rainwater and treated water.

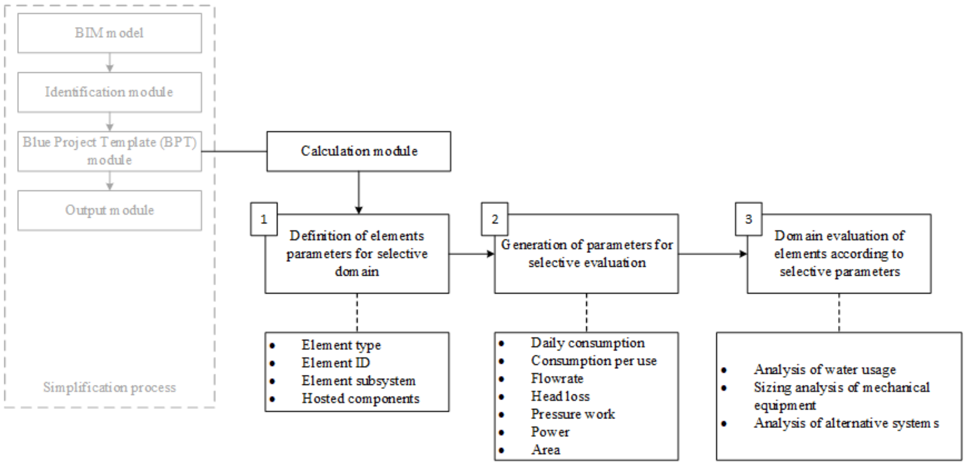


Figure 6. Calculation structure model.

Analysis of Water Usage According to Plumbing Fixtures and Inhabitant Demand

Recent evidence suggests that a detailed study of water use in buildings provides information about consumption patterns. Several lines of evidence have identified factors that are related to water consumption such as, circadian rhythms, work schedules, daily habits, and family structure [32–39].

This domain analyzes the information obtained from the model to perform calculations based on the scenarios that can be presented in a building. It also evaluates alternatives generated from base consumption established in the guidelines to determine the feasibility of alternative water sources.

Sizing Analysis of Hydraulic-Plumbing Systems Using the Flowrate Calculation

Over the past century, the models used to estimate peak water demand have been based on adaptations and modifications of the fixture unit (FU) model developed by Hunter in the 1940s [40]. This method applies binomial probability theory to estimate the number of services operating simultaneously in a period a time [40]. This, in turn, has led to unnecessarily oversized water supply systems in buildings [41,42].

In order to achieve an efficient design this domain evaluates several methods to calculate the peak water demand in the building. Peak water demand calculation is a key issue in the design of water supply systems. It allows the sizing of plumbing elements to achieve an efficient distribution of water to all end-point services [9,43].

Analysis of Alternative Systems Using Harvest Rainwater and Treated Water

Water efficiency can be achieved through the application of several methods. In that context, the implementation of technical (equipment and physical appliances) and non-technical (behavior and users' awareness of water use) methods are suitable alternatives to improve water efficiency [38]. The main benefits of these methods are the reduction in the amount of potable water required to complete an activity in a building, improved functionality of systems during a dry season, and decreasing water leaks [43]. According to Dziegielewski, some of the technical solutions at building scale are the implementation of reduced flow showerheads, low pressure supply appliances, dual flush toilets, and rainwater harvesting [44].

In this last domain, alternative systems are evaluated in order to reduce the strain on traditional water systems and to increase their resilience. Alternatives systems include rainwater harvesting and graywater reuse systems. A net zero water building (NZWB) is an example of alternative systems that were introduced by the International Living Future Institute. In a NZWB, the total annual water used is equal to the sum of alternative water use and the total water returned to the original source, such as surface water, groundwater, and others [45]. However, alternative systems should be analyzed from the cost–benefit perspective. Analysis of the first two domains proposed in this paper allows us to determine the feasibility of applying alternative systems from a cost–benefit perspective.

3.2.4. Output Module

The output module integrates key information to visualize data. Visual outputs can be presented in traditional views (floors, sections, and 3D views) and dynamic views supporting 2D and 3D perspectives, due to the ease of visualizing data in BIM. When the data analysis was completed, a Microsoft Excel sheet was created to assist designers and professionals in decision-making.

3.3. Framework to Integrate the Methodolgy Using Digital Technologies

The integration of BIM is divided into three modules, namely the water data development module (WDDM), the design of water use data module (DWUDM), and the water efficiency assessment module (WEAM). The whole procedure is shown in Figure 7.

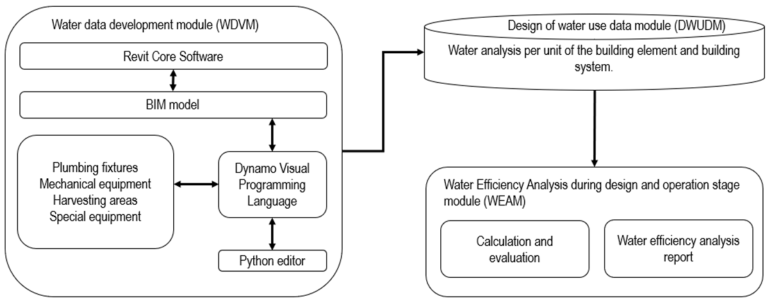


Figure 7. Framework to integrate digital technologies.

The WDDM corresponds to data collection for all the elements that form the water supply system contained in the digital model by applying visual programming using Dynamo, Revit, Microsoft Excel, and the Python programming language. The Dynamo open programming interface allows the customization of the flow of information contained in a digital model in Revit. Its visual programming process permits the definition of relationships and sequences that compose customized algorithms. The DWUDM corresponds to the storage and management of all the information obtained from the BIM model using Python and Microsoft Excel. The WEAM is the last module and corresponds to the evaluation, calculation, and analysis of the elements then used to generate the Microsoft Excel spreadsheet report. The organization of the framework used to integrate digital technologies and the steps of the process are shown in Figure 8.

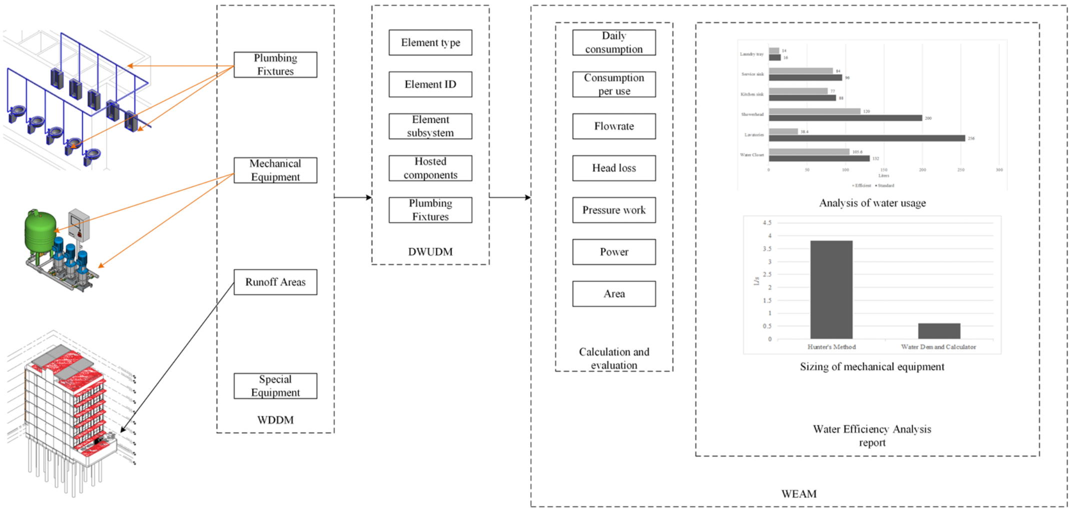


Figure 8. Organization of the framework used to integrate digital technologies and the module sequence.

4. Results and Discussions

This section presents the results using the proposed methodology in this study for the BIM-based WEA. To compare the difference between the current state-of-the-art methodologies and the presented proposal, a comparative table (Table A1) was produced with the domain of each methodology evaluated. All the analysis processes were carried out on a Windows 11 Home 64-bits OS, Intel i5 CPU 2.7 GHz processor and 8.00 GB RAM personal computer.

The first step of the methodology examined the elements related and unrelated to the BIM model under the identification module, as is shown in Table 3. All the plumbing fixtures, mechanical equipment, and planting details were extracted and sorted from the BIM model under the piping and architecture filters and areas (Gross Building), mechanical equipment, piping systems, and plumbing fixtures categories. The special equipment domain does not apply to this project because there are no systems with this attribute.

Table 3. Water supply system evaluation.

Water Supply System								
Plumbing Fixture			**Mechanical Equipment**			**Runoff Area**		
Toilet	210	units	Potable water pump	3	Units	Terrace	1170	m^2
Lavatories	210	units	Hot water circulation pump	1	Units			
Shower	132	units						
Kitchen sink	78	units						
Service sink	78	units						

The next stage of the proposed methodology is the BPT module to evaluate the subcategories presented in Table 3 under the three domains mentioned in Section 3 of this paper. The criteria and design guidelines of the hydraulic-plumbing system are described the Mexican Standards [46–48] and Guidelines of Plumbing Systems [49].

4.1. Analysis of Water Usage According to Plumbing Fixtures and Inhabitant Demand per Day

The results, as shown in Figure 9, indicate a positive impact from the perspective of water savings. By applying the plumbing fixture type criteria and modifying the plumbing fixtures from non-efficient to efficient, there was a global saving of 43% percent. This percentage can be reduced if we consider the savings achieved by using treated water. Further analysis shows that a reduction in potable water due to the use of treated water, using a standard configuration of the plumbing fixtures, is up to 23% less potable water, and up to 32% with an efficient configuration of the plumbing fixtures. If we turn to the analysis of filtered stormwater, results demonstrated no significant increase in water savings due to the rainfall intensity in Santa Catarina. However, with a successive increase in the rainfall intensity and rainfall duration, a significant increase in water savings could be achieved. Yet, rainfall intensity and duration of rainfall are random variables and are technically challenging to measure because of external factors.

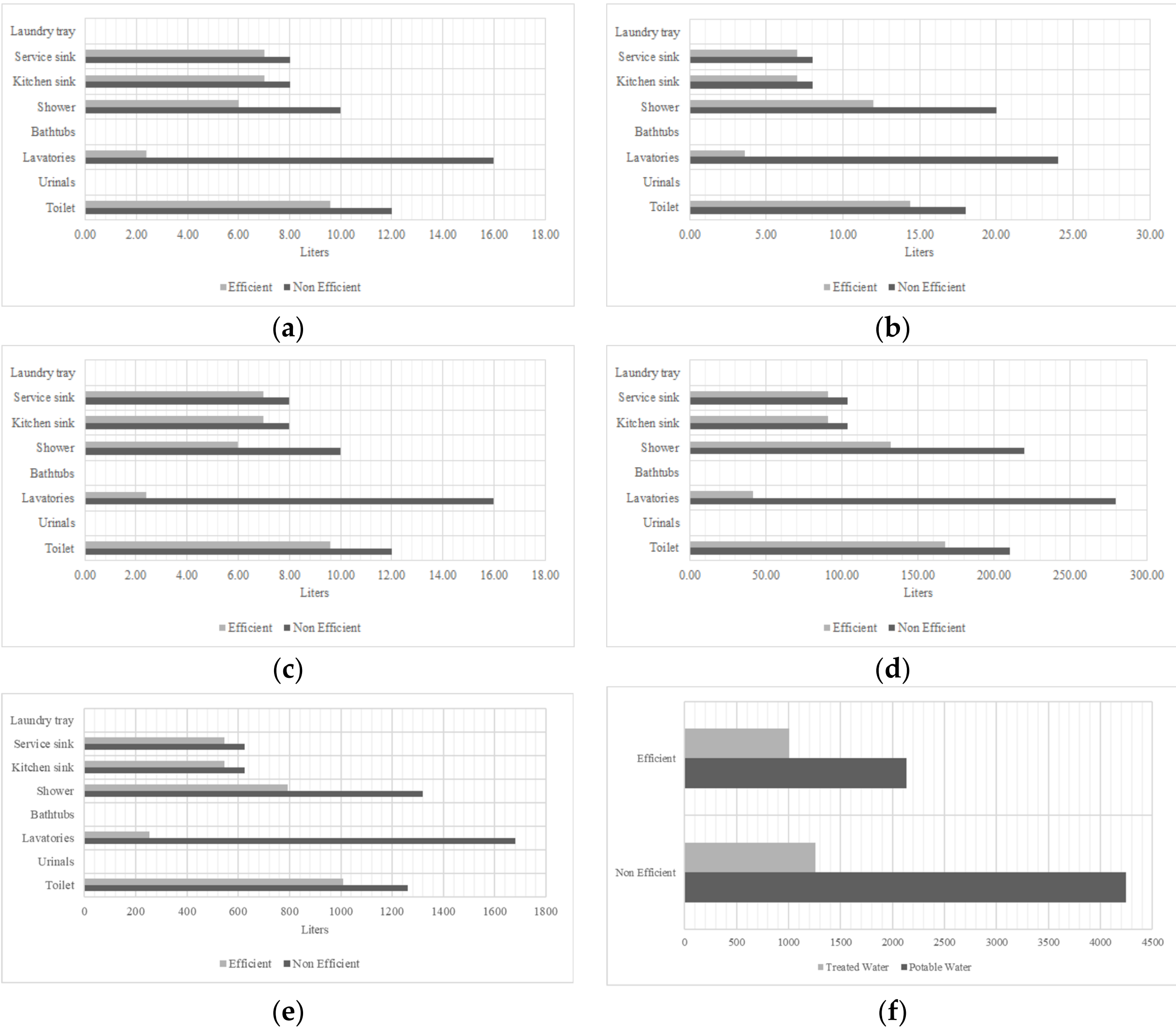


Figure 9. Water consumption comparison of using efficient and non-efficient plumbing fixtures. (**a**) Comparative design flowrate; (**b**) water consumption in apartment Type I; (**c**) water consumption in apartment Type II; (**d**) water consumption by level; (**e**) total water consumption in the tower; and (**f**) comparative water consumption using treated water and potable water.

The next section of this domain was concerned with water usage according to inhabitant demand per day according to local standards. The Table 4 illustrates the consumption of water per level, room, and the total water usage.

Table 4. Global inhabitant water demand per day.

Level	Total Apartments	Apartment Type I		Apartment Type II		Inhabitants per Bedroom	Daily Water Consume	
		Count	Bedrooms	Count	Bedrooms		Liters/Inhabitant/Day	Liters/Day
1st Floor	13	4	1	9	2	2	200	8800
2nd Floor	13	4	1	9	2	2	200	8800
3rd Floor	13	4	1	9	2	2	200	8800
4th Floor	13	4	1	9	2	2	200	8800
5th Floor	13	4	1	9	2	2	200	8800
6th Floor	13	4	1	9	2	2	200	8800
TOTAL	78	24	6	54	12	N/A	N/A	52,800

4.2. Sizing Analysis of Hydraulic-Plumbing System Using the Flowrate Calculation Method

The sizing analysis of hydraulic-plumbing system due to the flowrate calculation method domain revealed the importance of accurate methods to calculate the flowrate. In this case study, two methods were used to calculate peak water demand: (1) Hunter's method and (2) the water demand calculator (WDC). The first method is the standard for calculating peak water demand in Mexico [49]. The WDC was developed in 2020 as part of a research project founded by the International Association of Plumbing and Mechanical Officials (IAPMO), the American Society of Plumbing Engineers (ASPE), and the Water Quality Association (WQA). It predicts peak water demand by applying exhaustive enumeration, the Wistort method and the modified Wistort method algorithms [50].

From the data in Figure 10, the greatest demand by far is calculated using Hunter's method. Of interest here is the fact that the use of these values for peak water demand increases the size of the plumbing system elements such as water pumps, expansion tanks, piping, valves, and water heaters. Closer inspection of the two method's results shows that by applying WDC there was a substantial reduction in the sizing of the plumbing system due to the lower values of the flowrates. This situation represents a positive impact on the construction industry since it makes it possible to reduce construction costs within the design parameters of the standards.

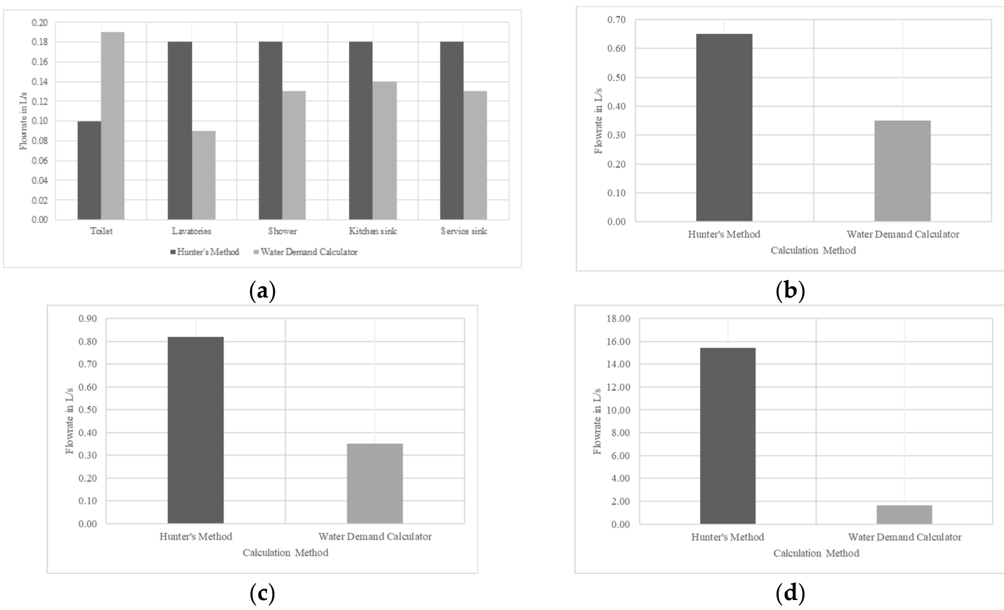
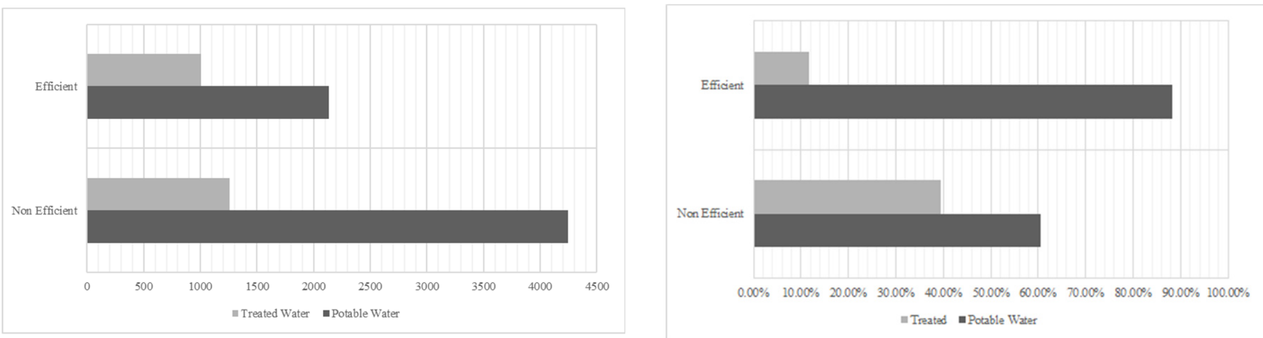


Figure 10. Plumbing fixture flowrate calculation method comparison. (**a**) Plumbing fixture flowrate; (**b**) total flowrate of apartment Type I; (**c**) total flowrate of apartment Type II and (**d**) total building flowrate calculation method comparison.

4.3. Analysis of Alternative Systems Using Harvested Rainwater and Treated Water

In the final part of the BPT, the analysis of alternative systems using harvested rainwater and treated water was evaluated. The combination of the results obtained in the first and second domain were used to analyze the benefits of using harvested rainwater and treated water. This first prototype for WEA evaluates the most critical conditions obtained from the BIM model. Under these criteria, the usage of water according to plumbing fixtures and inhabitant demand per day, and the highest peak water demand value with the maximum value of simultaneous probability were evaluated.

The data presented in Figure 11 are quite revealing in several ways. First, counterintuitively, the use of efficient plumbing fixtures was not the best option to improve water efficiency in mixed systems. Comparing the two results in Figure 11b, when the specifications of the plumbing system were efficient, the amount of wastewater generated was only 12% of the total water consumption. This result is somewhat counterintuitive to implementing a water treatment plant. On the contrary, when the specification was non-efficient, the amount of wastewater produced was up to 40% of the total water consumption. Further analysis of inhabitant demand per day revealed the feasibility of using a mixed water system as is shown in Table 5.



(**a**) (**b**)

Figure 11. Alternative system evaluation. (**a**) Comparative water consumption using treated water and potable water in plumbing fixtures and (**b**) usage percentage of a mixed system of potable water and treated water with efficient and non-efficient plumbing fixtures.

Table 5. Alternative system evaluation in liters per day: 60% potable water and 40% treated water.

Level	Full Potable Water	Mixed-Water System	
		Potable Water	Treated Water
1st Floor	8800	5280	3520
2nd Floor	8800	5280	3520
3rd Floor	8800	5280	3520
4th Floor	8800	5280	3520
5th Floor	8800	5280	3520
6th Floor	8800	5280	3520
TOTAL	52,800	31,680	21,120

In the final part of the third domain, an analysis of peak water demand was performed as is presented in Figure 12. This analysis was performed at a global scale considering all the plumbing fixtures using Hunter's method and WDC. The single most striking observation to emerge from Hunter's method was that the mixed water system significantly increases the flowrate up to 33% by using treated water. If we now turn to the WDC analysis, no numerically significant difference between a full potable water system and a mixed water system was found using WDC. What stands out in this is the similarity between the flowrate calculated between both systems using WDC.

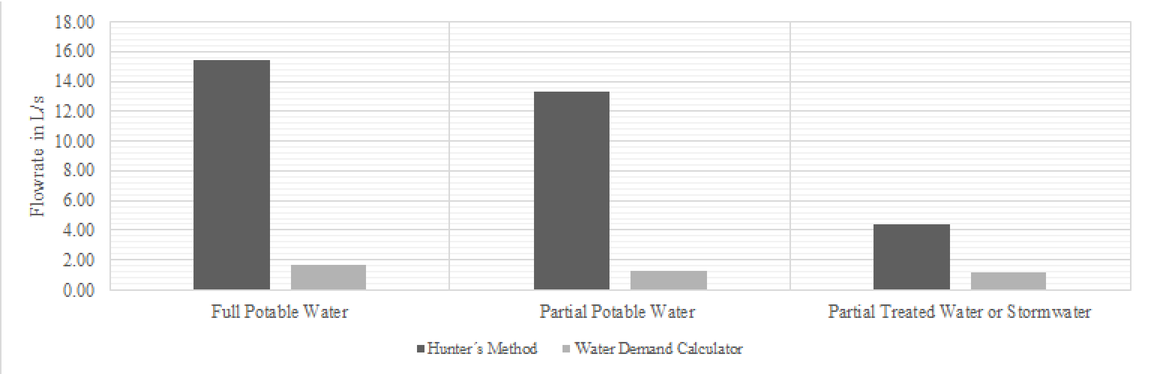


Figure 12. Comparative flowrate using Hunter's method and WDC.

In the overall context of the proposed methodology, the ability to adequately perform the WEA can be highlighted. As mentioned in the literature review for BIM-based WEA, this methodology was developed to fill the current gap in the research. Traditional WEA focuses only on the assessment of one domain, such as rainwater harvesting, clash detection, 3D visualization, and rating systems. Usually, those methodological approaches report the potential and feasibility to develop WEA in digital environments. However, most of the current studies only provide assumptions or partial water simulation analysis. Consequently, there is a gap between the industry and academic research.

The proposed structure of the methodology combines simplicity in design analysis with an integral evaluation of the main domains of the hydraulic plumbing system and related systems such as HVAC or FP. The suggested domains and their customization increase the modularity of the methodology, making it possible to decrease or increase the size of the project with practical applicability. This means that designers and professionals are able to rapidly identify key elements and parameters during the design stage to improve water savings and increase the performance of the system in the following stages of the project. Furthermore, the proposed methodology could be used as a guide for the use of digital technologies in WEA since there are no regulations or standards governing WEA. This lack of standards limits the accuracy of analysis for each region, as is the case with Mexico. However, more data are needed to perform the analysis during the operation stage. Perhaps the most unexpected results were obtained in the third domain with the use of efficient plumbing fixtures in a mixed water system. What is curious about this result is that efficient plumbing fixtures do not contribute to the implementation of treated water systems. These systems could only be feasible in large buildings with several services and with a predominance of toilets and urinals, such as a stadium. This observation may support the hypothesis that non-efficient plumbing fixtures contribute to the implementation of treated water systems due to the high flowrate of water. With further research on different types of building and economic analysis, the potential of the methodology could be enhanced to develop a full picture using this methodology for WEA.

5. Conclusions

This study set out to assess the feasibility of WEA using digital technologies which were applied to a multi-family building in Santa Catarina, Nuevo Leon. Based on the premise of previous studies on the use of BPA, this integrated digital methodology proposed a guide to perform WEA based on three domains and the ISO-49001.2019 [31] standard, due to the lack of existing regulation for WEA. The first domain calculated the viability of using efficient and non-efficient plumbing fixtures. The results confirmed the potential of efficient plumbing fixtures to save water and reduce water usage. However, further research is needed to better understand the users' patterns and the factors that drive the implementation of efficient plumbing fixtures. The second domain performed the calculation of peak water demand by applying different methods. The findings suggest that in general there is an urgent need to develop new calculation methods for water demand. These results provide further support for the hypothesis that current methods tend to oversize plumbing systems. Finally, one of the more significant findings to emerge from this study was developed in the last domain. In contrast with earlier findings, implementation of treated water systems could be affected when the plumbing fixtures are efficient. These findings will be of interest to designers and professionals in the AEC industry because they will be able to modify the project during its life cycle.

The development of this digital integrated methodology provides a guide for further research in WEA. However, future work should be focused on the feasibility of this methodology in different types of buildings. In addition, it will be necessary to evaluate the performance of this methodology over a longer period of time and in different stages such as construction and operation.

Author Contributions: Literature review, P.C.-L.; writing—original draft preparation, P.C.-L.; writing—review and editing P.C.-L. and B.S.; supervision, B.S. All authors have read and agreed to the published version of the manuscript.

Funding: This publication was supported by Consejo Nacional de Humanidades, Ciencia y Tecnología (Conahcyt) of Mexico [grant number 714370]. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the Conahcyt.

Data Availability Statement: The data that support the findings of this study are not available due to commercial restrictions.

Acknowledgments: The authors would like to thank Martin Rogelio Bustamante and Romeo Ballinas Gonzalez from Tecnologico de Monterrey for their constructive feedback during the drafting of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Comparative methodologies domains.

Author	Building Life Stage				Evaluation Domain											
					Rainwater		Treated water				Water Supply					
	Design	Construction	Operation	Case study	Harvesting	Reuse	Reuse	Code checking	Water Consumption	Clash Detection	Plumbing Fixtures	Mechanical Equipment	Grid optimization	Leak Detection	Telemetry	3D Visualization
(Krygiel and Nies, 2008) [15]	✓			✓	✓	✓										✓
(Martins & Monteiro, 2013) [17]	✓			✓				✓								✓
(Bonenberg and Wei, 2015) [18]	✓			✓	✓	✓										✓

Table A1. *Cont.*

Author	Building Life Stage				Evaluation Domain											
					Rainwater		Treated water				Water Supply					
	Design	Construction	Operation	Case study	Harvesting	Reuse	Reuse	Code checking	Water Consumption	Clash Detection	Plumbing Fixtures	Mechanical Equipment	Grid optimization	Leak Detection	Telemetry	3D Visualization
(Wong and Zhou, 2015) [19]	✓				✓	✓	✓									✓
(Lu et al., 2017) [10]	✓															✓
(Wei et al., 2017) [20]		✓											✓			✓
(Howell et al., 2017) [21]	✓	✓	✓	✓					✓		✓	✓	✓	✓	✓	✓
(Z. Liu et al., 2019b) [22]	✓				✓				✓	✓	✓	✓	✓	✓		✓
(Zhao et al., 2019) [23]	✓	✓		✓						✓			✓			✓
(S. Luo et al., 2022) [24]	✓			✓						✓			✓			✓
(Y. Wang et al., 2022) [25]	✓			✓						✓			✓			✓
Proposed Methodology	✓		✓	✓	✓	✓	✓		✓		✓	✓	✓			✓

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