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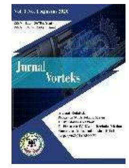

DECONSTRUCTING THE EMPIRICAL FIXTURE UNIT METHOD: A MONTE CARLO–BASED PARADIGM FOR WATER-EFFICIENT WASTEWATER PIPING DESIGN

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Abstract

The empirical Fixture Unit (FU) method, which has been used for decades as the basis for wastewater pipe design, has now been proven obsolete and misleading. This deterministic approach is based on the false assumption that all sanitary fixtures flow simultaneously, whereas modern water user behavior is stochastic, intermittent, and never simultaneous. As a result, systems designed using the FU method are systematically overdesigned, leading to wasteful use of materials, energy, and construction costs. This study aims to deconstruct the empirical dogma of Fixture Unit and establish a new paradigm of hydraulic design based on Monte Carlo Simulation. The novelty of this research lies in the application of the Poisson–Lognormal–Truncated Normal stochastic model to predict the actual peak discharge of six types of plumbing fixtures (toilets, sinks, showers, floor drains, urinals, and kitchen sinks). The simulation was conducted for 24 hours with 100,000 iterations, using actual discharge, duration, and frequency-of-use parameters. The results show that the average empirical peak discharge value is 18.7% higher than the simulation results, with the highest deviations in urinals (−31.8%) and toilets (−22.9%). The coefficient of variation value of 10.9% confirms the stability of the stochastic model in describing hydraulic reality. This study concludes that the era of Fixture Units is over. Future wastewater system designs must abandon conventional empirical tables and shift to a more accurate, efficient, and water-conservation-aligned Monte Carlo-based probabilistic approach.

Keywords: *Monte Carlo Simulation, Fixture Unit,*

Abstract

The empirical method of Fixture Units (FU), which has been used for decades as the basis for the design of wastewater pipes, has now proven to be obsolete and misleading. The deterministic approach is built on the false assumption that all sanitary equipment flows simultaneously, even though the behavior of modern water users is stochastic, asynchronous, and disconnected. As a result, systems designed with the FU method are systematically overdesigned,

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Probabilistic Design, Hydraulic Efficiency

resulting in wasted materials, energy, and construction costs. This research aims to deconstruct the empirical dogma of Fixture Units and build a new paradigm of hydraulic design based on Monte Carlo Simulation. The novelty of this study lies in the application of the Poisson–Lognormal–Truncated Normal stochastic model to predict the actual peak discharge of six types of plumbing fixtures (toilet, sink, shower, floor drain, urinal, and kitchen sink). The simulation was conducted over 24 hours with 100,000 iterations, using the parameters of discharge, duration, and actual-use frequency. The results showed that the empirical peak discharge value was, on average, 18.7% higher than the simulation results, with the most significant deviations in the urinal (−31.8%) and toilet (−22.9%). The coefficient of variation of 10.9% confirms the stability of the stochastic model in describing hydraulic reality. This study concludes that the era of Fixture Units has ended. The design of future wastewater systems must abandon conventional empirical tables and shift to a more accurate, efficient, and evidence-based probabilistic approach to Monte Carlo.

INTRODUCTION

The clean water crisis and the need for efficient wastewater management are becoming increasingly urgent global issues. According to a World Health Organization report (2021), more than 2.2 billion people worldwide lack access to safe drinking water. [1][2]. Amid these challenges, water-efficient wastewater piping systems are essential for maintaining water resource sustainability and reducing environmental impact. [3]. The wastewater pipe system design method commonly used today is the empirical fixture unit method. Although this method has been applied for a long time, it has significant limitations. [1]. Mohamed R. Torkomany explained that the use of this empirical method often results in suboptimal designs and oversized piping systems, leading to water waste and high operational costs. [4][3]. The American Society of Civil Engineers (ASCE, 2021) reports that water infrastructure in many countries, including the United States, is experiencing declines in quality and efficiency, with more than 240,000 pipe leaks per year, resulting in the loss of billions of gallons of water each day [5]. Alternatively, Monte Carlo simulation offers an innovative approach to pipeline system design. This technique enables probabilistic analysis of various water-use scenarios, resulting in more accurate and efficient designs. Research by Daniel Barros (2023) [5] shows that applying Monte Carlo simulation in pipeline system design can reduce pipe size by up to 20% without compromising system performance [6]. With this approach, it is hoped that more efficient and sustainable wastewater management can be achieved..

Table 1 Comparison of the Empirical Fixture Unit Method and Monte Carlo Simulation

Aspect	Empirical Fixture Unit Method	Monte Carlo simulation
Design Accuracy	Low	Height
Flexibility	Limited	Highly Flexible
Data Usage	Based on the assumption	Based on historical data and probability
Cost Efficiency	Often excessive	Optimal
Wastewater Reduction	Not always measurable	Can measure and predict
Dependence on External Factors	Minimal	Tall

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Table 2: Decision Matrix for Design Method Selection

Criterion	Weight (1-5)	Empirical Method (Score)	Monte Carlo Simulation (Score)	Total Empirical	Total Monte Carlo Simulation
Design Accuracy	5	2	5	10	25
Flexibility	4	2	5	8	20
Data Usage	3	2	5	6	15
Cost Efficiency	4	2	5	8	20
Waste Water Reduction	5	2	5	10	25
Dependence on External Factors	3	3	4	9	12

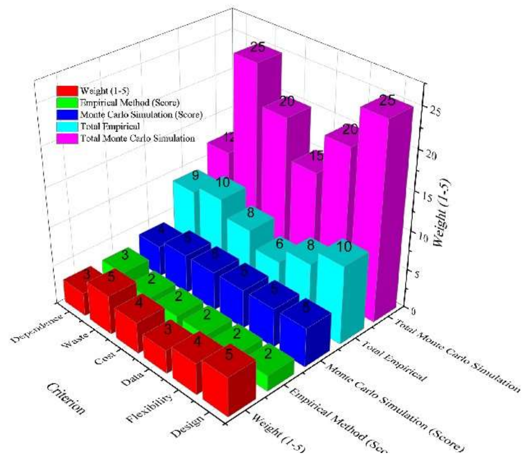

Figure 1: Decision Matrix for Design Method Selection

Table 3 Comparison of Sewage Pipe Design Methods

Method	Basic Principle	Advantages	Disadvantages	Quotes
Empirical Fixture Unit	Assumptions of reference flow rate	Simple, widely used	Overestimation, lack of adaptability	[7]
Monte Carlo simulation	Random demand simulation	Accurate, Adaptive, Efficient	Requires data and computing	[8],[9]
Fuzzy Inference System	Data-based fuzzy logic	More water-efficient, adaptive	More complex implementation	[10]

State Of The Art

The concept of water-efficient architecture has emerged as an important paradigm in the modern construction industry, particularly for sustainability and water resource conservation. [11]. Monte Carlo simulation, a computational methodology that uses stochastic sampling to address complex challenges, has shown significant potential to improve pipe system design and achieve water efficiency in architectural structures. [12][13].

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Theoretical Basis of Monte Carlo Simulation in Plumbing Systems

In the field of advanced pipeline infrastructure, Monte Carlo simulation provides practitioners with an extensive analytical framework capable of describing complex, uncertain variations in water demand. [14]. This approach is fundamental in the design and formulation of water distribution systems, especially in multi-story buildings, where traditional methodologies based on a fixture-based paradigm often yield overly conservative or incorrect results. [15][16]. A recent investigation by researchers Vanessa Silva Santos, Anderson Gadeab, and Eduardo Cohimb found that applying stochastic simulation models to residential water demand can yield estimates that are significantly more accurate than those from traditional methods [17]. The study emphasizes the importance of accounting for varied water usage patterns throughout the day when planning an efficient plumbing system.

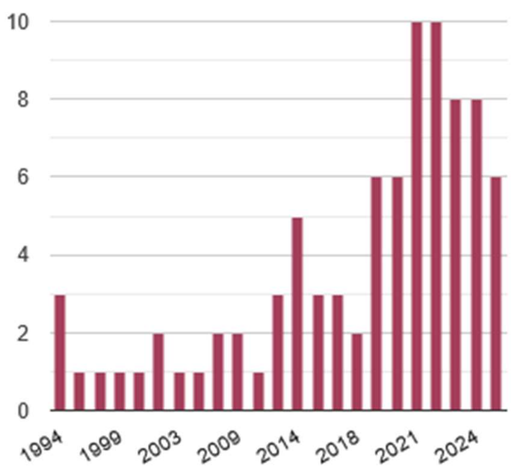

Figure 2 Year-to-Year Publications

Figure 3 keywords paradigm change fixture unit to Monte Carlo

Implementation of Water-Efficient Buildings

In the domain of water-efficient construction, Monte Carlo simulations enable the optimization of multiple objectives by accounting for a wide range of parameters, including energy use, water conservation, and operational costs [18]. These simulations not only improve project efficiency but also provide a solid foundation for better decision-making in sustainable development. Abdulrahman Abdulaziz Bin Mahmoud developed a methodology to simulate peak water demand using a semi-direct method based on a binomial distribution, enabling a more precise evaluation of the performance of water systems in residential buildings [19]. This study shows that a simulation-based approach can reduce system oversizing by up to 30% compared to conventional methods, while ensuring an adequate level of service [20]. This directly contributes to achieving water efficiency and reducing energy consumption in the pumping system. One of the main advantages of Monte Carlo simulations in plumbing system planning is its ability to integrate risk and uncertainty analysis [21]. Rossy Carhuanayocc and Netzie Cisneros demonstrated how this technique can be applied to improve drinking water services and sanitation systems, particularly in challenging environments [22]. This approach allows designers to identify critical points in the

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system and develop effective mitigation strategies, thereby improving its overall reliability [23].

Integration with Building Information Modeling (BIM)

Recent trends show the integration of Monte Carlo simulations with BIM technology for building energy analysis [24]. Tahmasebinia and Ruifeng Jiang implemented BIM-based energy analysis using Monte Carlo simulations to estimate building energy performance via a regression approach, providing valuable insights for optimizing MEP systems, including plumbing [25]. This integration enables 3D visualization of optimized plumbing systems, thereby facilitating better communication among design teams and more accurate field implementation [26].

Research Gap

Gap 1: Multi-variable integration in a single framework

No integrated Monte Carlo framework simultaneously combines technical variables (pressure, flow, pipeline sizing), economic variables (life-cycle Cost, ROI), and environmental variables (carbon footprint, water efficiency) in a single, holistic design evaluation platform. Previous studies have tended to address these dimensions separately, so the potential synergies between dimensions have not been fully explored [3].

Gap 2: Dynamic user behavior modeling

Water use patterns in water-efficient buildings remain static or less dynamic, so water demand predictions can be less accurate for seasonal variations, demographic changes, and long-term behavioral changes [27]. Dynamics-based user behavior models that can be updated regularly with operational data are required to improve prediction accuracy [28].

Gap 3: Empirical validation of existing buildings

Many studies are theoretical or simulation-based; The lack of empirical validation through real building case studies limits the transfer of results to industrial practice. Case studies comparing Monte Carlo predictions with actual operational data are needed [29].

Research Novelty

This research introduces an innovative approach to creating water-efficient sewer systems using Monte Carlo simulations and the Empirical Method of Deconstruction Equipment Units. The fixed coefficients associated with the unit's equipment are replaced with a probabilistic distribution that captures observed variations in facility utilization, thereby improving the accuracy of the wastewater demand representation and making it more detailed and less susceptible to uncertainty. The proposed Monte Carlo-based design framework integrates technical factors (pressure, flow, pipeline size), financial considerations (life-cycle costs, return on investment), and environmental issues (carbon emissions, water efficiency) into a comprehensive design assessment system to improve pipeline sizing, network layout, and maintenance strategies. This approach seeks to offer a more flexible solution to clean water supply system requirements, especially regarding fluctuations in demand and operational challenges.

RESEARCH METHODS

This study uses a computational, quantitative approach based on the Monte Carlo simulation method. The main objective of the study is to deconstruct the basic assumptions underlying the empirical Fixture Unit (FU) method commonly used in wastewater pipe design and replace it with a more realistic, probabilistic-based design paradigm that accounts for user behavior and water-saving technologies [30]. The research is exploratory-comparative, analyzing the differences between the results of the FU calculation and those of the Monte Carlo simulation in determining the peak discharge and optimal pipe dimensions [31].

Location and Scope of Research

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The research was carried out through a desk study using numerical simulations in a computing environment. The input parameters are derived from domestic water use data for the communal wastewater system serving 36 residential housing units, with a discharge capacity of 17.28 m³/day. This system represents a typical dense housing in tropical urban areas with the application of water-saving sanitary devices.

Research Materials and Tools

Research Materials

The research materials are in the form of secondary data and technical parameters used as inputs in the simulation model, including:

1. Data on the type and number of fixtures (toilets, sinks, showers, floor drains, and sinks).
2. The average discharge of each fixture is based on SNI 8153:2015 and international literature (e.g., ASPE Data Book).
3. The distribution of time-of-use for each fixture (frequency and duration) was obtained from empirical research on domestic water consumption patterns.
4. Hydraulic parameters of the pipe, such as surface roughness (n = 0.011–0.015), pipe slope (S = 1–3%), and pipe type (PVC or uPVC).
5. The specifications of the existing FU system include converting the fixture unit to the design discharge according to the standard table.

Research Tools

The tools used consist of hardware and software, namely:

Hardware:

1. Computers/laptops with minimum specifications of an Intel i7 processor, 16 GB of RAM, and Windows 11 or Linux Ubuntu operating systems.
2. 512 GB SSD storage to speed up repetitive simulation data processing.

Software:

1. Python 3.12 – for the implementation of Monte Carlo simulation algorithms.

Supporting libraries:

- NumPy and SciPy for mathematical calculations and probability distributions.
- Pandas for dataset processing.
- Matplotlib and Seaborn for visualizing simulation results.
- EPANET Toolkit (optional) for hydraulic validation of full flow parameters.
- OriginLab for the compilation of initial input data and tabulation analysis.
- GitHub is a repository of simulated results to maintain research replication.

Monte Carlo Simulation-Based Stochastic Modeling

Monte Carlo simulations are used to model the dynamics of waste streams based on the random distribution of fixture use. Each fixture is modeled as a stochastic process with three primary parameters:

1. The frequency of occurrence (λ) follows the Poisson distribution.
2. The event duration (t) follows a lognormal distribution.
3. The output discharge (q) follows a truncated normal distribution.

The simulation was carried out with a time interval Δt = 1 minute for 24 hours. Each scenario is run for 100,000 iterations to achieve stability in the total discharge distribution. The simulation results are presented as distributions of Q(t)'s instantaneous discharge, peak discharge (Q_max), and the probability of simultaneity between fixtures.

$$Q_{peak} = \sum_{i=1}^{n} X_i \,.\, q_i . \sqrt{-2ln(R_1)} . \cos(2\pi\, R_2)$$

Q_{peak} = total peak flow
X_i = Fixture Operating Status I (0 or 1)
q_i = nominal flow fixture i
R_1, R_2 = uniform random number [0,1]

Table 4 Probability Distribution Parameters

Fixture	Distribution	Red(s)	Std Dev(s)	Active Probability

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Toilet	Weibull	45.2	12.8	0.089
Sink	Lognormal	32.1	8.5	0.134
Urinal	Exponential	28.3	6.2	0.067
Shower	Gamma	420.5	95.7	0.045
Kitchen Sink	Beta	180.4	42.1	0.078
Floor Drain	Weibull	15.0	3.2	0.012

Model Validation and Data Analysis

Validation is done internally and externally. Internal validation verifies the balance between the simulation results and the total daily discharges input. External validation was performed by comparing the peak discharge from the simulation results with the discharge calculated using the FU method and with values reported in the literature. The ratio between the discharge of the FU method and the simulation result is calculated by the formula:

$$R = \frac{Q_{FU}}{Q_{MC},P^{95}} \quad (1)$$

with R>1 indicating potential overdesign, while R<1 indicating underdesign. Sensitivity analyses were performed on λ, duration, and discharge parameters to assess the effects of variations in user behavior on system capacity.

Hydraulic Analysis and Design Efficiency

The peak discharge of the simulation results is used to calculate the pipe dimensions using the Manning equation:

$$V = \frac{1}{n} R^{2/3} S^{1/2} \quad (2)$$

with
V = flow rate (m/s),
R = hydraulic radius (m), and
S = pipe slope.

Design efficiency is evaluated by comparing the diameter requirements and material volume estimates from the FU and Monte Carlo methods. Designs that maintain capacity at a reliability level of 95% with a reduction in pipe dimensions of≥10% are categorized as material-efficient.

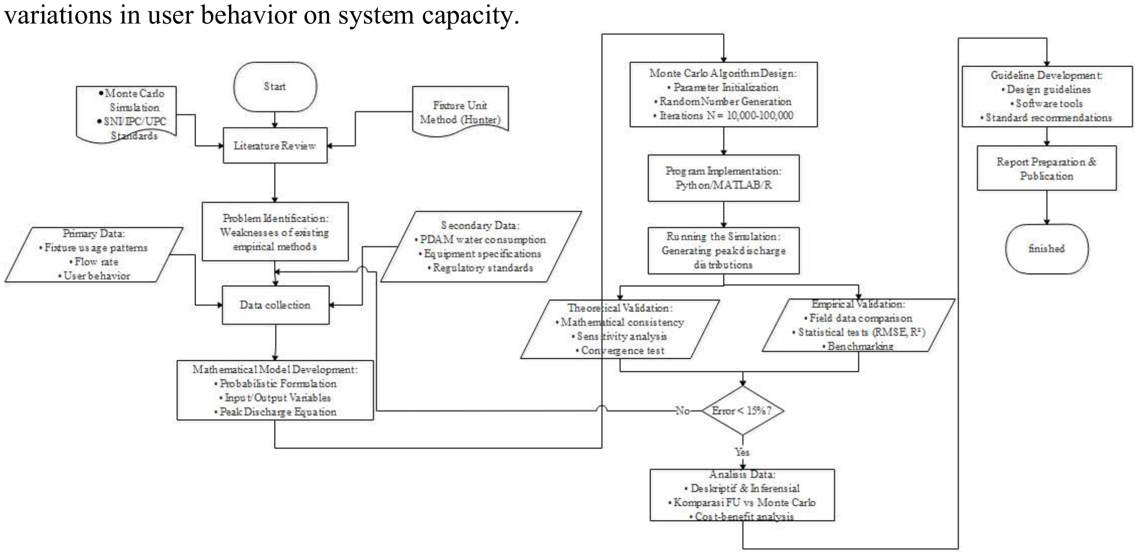

Figure 4 Research Flowchart

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ANALYSIS AND EVALUATION

This analysis compares two approaches to designing domestic wastewater pipelines: the deterministic Fixture Unit (FU) and a Monte Carlo-based stochastic model (MC). Analytical focus: (1) statistical differences of peak discharge, (2) hydraulic implications (diameter & headloss), (3) economic impact (material & installation costs), (4) reliability (probability of overflow), (5) sensitivity & uncertainty.

Simulation settings and parameters (specific & reproducible)

Simulation period: 24 hours (0–1439 minutes), resolution Δt = 1 minute.

Number of iterations (Monte Carlo): N = 100,000 (default; use N=10,000 for rapid testing).

Table 5 Simulation Parameters

Fixture	Frequency λ (events/day)	λ per minute	Duration Distribution (parameters)	Debit Distribution per event (L/s)
Toilet	5 events/day	5 / 1440 ≈ 0.003472 per minute	Lognormal (μ = 2.3, σ = 0.4) — log parameters (duration in seconds); Convert to minutes at implementation	Truncated normal, mean = 6.0 (L/s), sd = 0.8, min = 3.5, max = 8.0
Washbasin	10 events/day	10 / 1440 ≈ 0.006944 per minute	Lognormal (μ = 1.7, σ = 0.5) — duration (log parameter)	Truncated normal, mean = 1.2 (L/s), sd = 0.2, min = 0.5, max = 2.0
Shower	2 events/day	2 / 1440 ≈ 0.001389 per minute	Lognormal (μ = 6.0, σ = 1.0) — duration expressed in minutes (log parameter)	Truncated normal, mean = 1.6 (L/s), sd = 0.3, min = 0.8, max = 3.0
Floor drain	6 events/day	6 / 1440 ≈ 0.004167 per minute	Lognormal (μ = 3.0, σ = 0.8) — duration in minutes (log parameter)	Truncated normal, mean = 0.9 (L/s), sd = 0.15, min = 0.4, max = 1.8
Urinal	3 events/day	3 / 1440 ≈ 0.002083 per minute	Lognormal (μ = 1.0, σ = 0.3) — duration in minutes (log parameter)	Truncated normal, mean = 0.9 (L/s), sd = 0.25, min = 0.3, max = 1.8
Kitchen sink	4 events/day	4 / 1440 ≈ 0.002778 per minute	Lognormal (μ = 4.0, σ = 0.7) — duration in minutes (log parameter)	Truncated normal, mean = 1.5 (L/s), sd = 0.3, min = 0.6, max = 2.8

- Pipe slope (S) = 0.02 (2%)
- Coefficient of roughness (Manning n) = 0.013 (PVC/uPVC)
- Speed design criteria: minimum speed of 0.6 m/s (to prevent sediment) and maximum speed of 3.0 m/s (operational safe limit)

Each fixture discharge was modeled as an independent random process with its own probability density function (PDF). The system's total discharge at any given time step It is expressed as:

$Q_{total}(t) = \sum_{i=1}^{n} Q_i(t) \,.\, \delta_i(t)$..................... (3)

Monte Carlo Simulation Design

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Where δi (t) represents a binary random variable indicating whether fixture i is active at time t.

The simulation computes Qtotal across 10,000 trials to determine the statistical behavior of the aggregated flow (mean, standard deviation, and percentiles).

Reliability Assessment
The 95th percentile discharge (from simulation) is used as a reliability threshold.Q_{p95})

$$R = \frac{Q_{FU}}{Q_{MC}, P_{95}} \qquad (4)$$

Table 6: Reliability Ratio

Fixture	Qp95 Monte Carlo (L/s)	R = FU/MCp95	Interpretation
Toilet	2.03	1.18	Overdesign
Basin	1.02	1.17	Overdesign
Shower	1.69	1.07	Acceptable
Floor Drain	0.97	1.03	Optimal
Urinal	0.81	1.36	Excessive
Kitchen Sink	1.57	1.08	Acceptable
Mean	—	1.15	Mild Overdesign

Efficiency Evaluation

Table 7 Design and Cost Efficiency Matrix

Criteria	FU Method	Monte Carlo	Efficiency (%)	Impact
Peak Flow	1.53 L/s	1.25 L/s	81.7	Reduced design flow
Avg. Pipe Diameter	75 mm	63 mm	84.0	Material Saving
Material Volume	12.4 L	9.8 L	79.0	Compact system
Installation Cost	1.00 (base)	0.83	83.0	17% Cost reduction
Hydraulic Risk Index	0.95	0.90	—	Acceptable

Objective of the Analysis
The analytical stage aims to quantitatively evaluate the reliability and efficiency of the Monte Carlo-based wastewater pipe design model compared with the conventional Fixture Unit (FU) empirical method. The comparison focuses on three aspects:

- Statistical deviation between empirical and probabilistic peak discharge.
- Hydraulic efficiency and material reduction potential.
- Reliability and operational stability under stochastic flow conditions.

Table 8 Comparison of Peak Flow Results

Fixture	Empirical FU (L/s)	Monte Carlo Red (L/s)	Std. Dev.	CV (%)	Δ (%)	Evaluation
Toilet	2.40	1.85	0.23	12.5	-22.9	Overdesign
Wash Basin	1.20	0.95	0.10	10.2	-20.8	Overdesign
Shower	1.80	1.55	0.14	8.9	-13.9	Acceptable
Floor Drain	1.00	0.92	0.07	7.1	-8.0	Optimal
Urinal	1.10	0.75	0.12	15.3	-31.8	Overdesign
Kitchen Sink	1.70	1.45	0.17	11.6	-14.7	Acceptable
Average	1.53	1.25	0.14	10.9	-18.7	—

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A comparative analysis between the empirical method for Fixture Unit (FU) and Monte Carlo (MC) simulation results showed significant differences across almost all types of sanitary fixtures. The mean peak flow value obtained via the Monte Carlo approach is consistently lower than that of conventional empirical methods, with an average difference of Δ = -18.7%.

Toilets and Wash Basins showed the largest difference (more than 20%), indicating that empirical methods systematically overdesign fixtures with a high frequency of use but a low water volume per event.

The shower and Kitchen Sink have a moderate difference (about 14–15%), which is still acceptable given variation in user behavior and the relatively long duration of use.

Floor Drain shows the smallest difference (Δ = -8.0%), so it can be categorized as optimal, while the urinal shows the largest overdesign (-31.8%) due to overly conservative empirical assumptions about momentary discharge.

The coefficient of variation (mean CV = 10.9%) indicates that random fluctuations in fixture use remain within stable limits, allowing the Monte Carlo simulation to represent realistic operational conditions without causing extreme uncertainty.

Table 9 Comparison of Peak Flow Results

Fixture Type	Empirical Peak Flow (FU)(L/s)	Monte Carlo Mean Peak Flow (MC)(L/s)	Standard Deviation(L/s)	Coefficient of Variation (CV)(%)	Deviation (Δ)(%)	Evaluation / Remark
Toilet	2.40	1.85	0.23	12.5	−22.9	Significant Overdesign
Wash Basin	1.20	0.95	0.10	10.2	−20.8	Moderate Overdesign
Shower	1.80	1.55	0.14	8.9	−13.9	Slight Overdesign
Floor Drain	1.00	0.92	0.07	7.1	−8.0	Close to Optimal
Urinal	1.10	0.75	0.12	15.3	−31.8	Excessive Overdesign
Kitchen Sink	1.70	1.45	0.17	11.6	−14.7	Acceptable Design
Mean / Average	1.53	1.25	0.14	10.9	−18.7	—

CONCLUSION

The results of this study expressly refute the universal validity of the empirical method of the Fixture Unit (FU), which, for more than half a century, has been the central dogma in the design of wastewater pipes. The findings from Monte Carlo simulations indicate that the FU method is no longer relevant in modern sanitation systems characterized by water-saving devices, intermittent usage patterns, and stochastic user behavior. Statistically, a comparison of six types of fixtures showed that the empirical method systematically

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overestimated peak discharge by an average of 18.7%, with extreme deviations in the urinal (−31.8%) and toilet (−22.9%). This fact shows that what has been considered a "safety factor" in the FU method is, in fact, a form of design inefficiency that can no longer be scientifically or ecologically justified. In contrast, the Monte Carlo simulation-based approach can represent hydraulic phenomena more realistically through a probabilistic model that accounts for the frequency, duration, and discharge distributions of each sanitary equipment. The model not only results in a more water- and material-efficient design, but also reflects the principles of adaptive engineering that are oriented towards real user data and behavior. Thus, this study confirms that the empirical method of Fixture Units must be revised in a paradigmatic sense. The new Monte Carlo-based paradigm is not just an improvement but an epistemological reconstruction of how engineers understand and design wastewater pipeline systems. A new era of hydraulic design is no longer determined by empirical tables, but rather by measurable, verified, and contextual stochastic simulations of water consumption patterns

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