WATER AGE IN RESIDENTIAL PREMISE PLUMBING

by

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A Thesis Submitted to the Faculty of the

DEPARTMENT OF CIVIL AND ARCHITECTURAL ENGINEERING AND MECHANICS

In Partial Fulfillment of the Requirements

For the Degree of

MASTER OF SCIENCE

In the Graduate College

THE UNIVERSITY OF ARIZONA

2018

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ACKNOWLEDGMENT AND DEDICATION

Dedicated to my wife, Valeska, and my parents, Patricia and Andreas, for their unconditional support. Without you, nothing would have been possible.

Also, to deeply thank Dr. Lansey, for being an awesome advisor, teacher and friend. I feel very fortunate to know you.

Lastly, to thank all my friends for being present, even remotely, during tough times. A smile is sometimes all you need to keep fighting adversity.

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ABSTRACT

In most countries around the world, water is treated physically and chemically to a quality that is safe for human consumption. In spite of these efforts, every year people die as a consequence of drinking water-associated disease outbreaks. Legionella is arguably the deadliest pathogen in drinking water in the US and efforts are underway to reduce the likelihood of infecting potable water consumers.

One of the primary factors to measure water quality degradation is water age. Water quality degrades with the time that the water sits in pipes. Over time, the residual disinfectant decays, disinfectant by products are created and the water becomes more susceptible to pathogen regrowth. This concern is not limited in the distribution systems but carries over to residential premise plumbing system. A key factor affecting water age in the premises is fixtures' idle times. As a result, poorly designed plumbing layouts and intermittent usage patterns may lead to high residence times.

In the present study, a methodology was developed to numerically quantify water age in residential premise plumbing systems. The scheme is composed of a hydraulic solver, EPANET with modifications, a demand stochastic simulator, SIMDEUM-UA, and a plumbing layout generator based on CAD models. This method was used to determine layout design practices that contribute to lower water ages. The layout is shown to have a significant impact on water age. Modified layouts reduced the water age metrics of absolute maximum age, mean maximum and mean water by up to 76%, 66% and 58%, respectively. A best practice is to connect the water closets at the end of the premise distribution branches.

The effect of water heater types on residence times was also assessed. It was found that instant or on demand heater helps reduce water age across all layouts for all the metrics, at both the outlet and the point of connection of the fixture to the distribution system. To further decrease water age, auto-flushers were installed on certain nodes, as the USEPA (2016) recommends flushing the system at regular intervals, and further if combined with a flush of hot water at a temperature of at least 60 °C (140 °F), it would help sterilize the hot system between the heater and the flusher as recommended by the WHO (2007). Proposed methods to implement these so-called hot super-flushing were discussed for future research. However, none of the hydraulic approaches proposed here impact the "last foot" of pipe connecting plumbing fixtures with the premise distribution pipes.

Lastly, when comparing the resulting pressures using the simulated demands against the peak demand estimates with flows from the plumbing code, code pressures are always lower than the simulated ones. This may indicate that the design method conservatively overestimates demands. Nonetheless, oversized pipes are detrimental for water age and should be avoided, as greater demands are required to flush the system.

CHAPTER 1 - INTRODUCTION AND PROBLEM STATEMENT

In most countries around the world, water is treated physically and chemically to be safe for human consumption. In spite of these efforts, the Center for Disease Control and Prevention (CDC) in the United States reported 42 drinking water-associated outbreaks in 2013-2014, accounting for at least 1,006 cases of illness, 124 hospitalizations, and 13 deaths. Legionella bacteria was implicated in 24 (57%) outbreaks, 130 (13%) cases, 109 (88%) hospitalizations, and all 13 deaths (Benedict et al., 2017). Consequently, Legionella is arguably the deadliest pathogen in drinking water in the US and efforts are underway to reduce the likelihood of infecting potable water consumers.

To that end, the scientific community and governmental organizations agree that the time between water treatment and consumption, known as the water age, is a primary factor in degraded water quality for several reasons. Over time, the residual disinfectant in the water decays as it reacts with organic materials in the water and on pipe walls. These reactions also create so-called disinfection byproducts (DBP) that are potentially carcinogenic. Due to DBP formation and taste and odor issues, increasing chlorine concentrations to inhibit microbial growth of Legionella and other bacteria is not always a viable solution. Other consequences of aging water are: more corrosion, increased water temperature, sediment deposition, and biofilm formation. All these factors contribute to a better environment for pathogen regrowth, especially Legionella.

Not surprisingly, several studies have identified premise plumbing systems as a source of Legionella infection. The underlying premise here is that building and household plumbing layouts and water usage patterns are prime contributors to high residence times and promote conditions that are prone to pathogen proliferation. The WHO recommends that the control of Legionella should begin during water system design; with a primary goal of identifying and eliminating conditions that can lead to an increased residence times, such as dead ends (WHO, 2007).

The main objective of this study is to contribute to those efforts by quantitatively assessing water age in alternative premise plumbing layouts. If alternatives can prove significant for specific systems, layout design guidelines will be posed to lower water age while meeting plumbing code specifications. The impact of heater type will be assessed through a comparison of residence times of hot water in premises with traditional tank and instant water heaters. Modeling a temporal sequence of demands is necessary to assess premise water quality. A concurrent analysis of water pressures is completed comparing plumbing code demand and pressure conditions with those from simulated time series to assess the level of conservatism in the plumbing codes.

1.1. Hypotheses

Based on the above discussion, the following hypothesis are formulated for residential premise plumbing:

(1) The impact of the plumbing layout significantly affects water age; a good design can reduce maximum age relative to a poor/traditional design; even when both have no dead ends.

(2) Connecting a high volumetric demand whose age is not critical, e.g., water closets, at the end of each branch is a good design practice and lowers the overall cold-water age throughout the residence. Since the volume within domestic pipes is

small, a high-volume demand will flush and replace water in a branch refreshing water in the nodes upstream of the fixture.

(3) Pipes that connect fixtures with the distribution pipes inside the premise, described as stubs, act as dead ends. Water may remain in stubs for long time periods when the downstream fixture is not activated.

(4) Replacing the traditional tank water heater with an instant (tankless) one can reduce the hot water residence time.

1.2. Scope

This study quantifies the impact of premise plumbing layout design on the potable water residence time in individual residences. To that end, a numerical model, EPANET, is solved for varying distribution pipe layouts to provide connection points to fixtures. Residence time is determined with this mathematical model that represents water movement in the premise plumbing system. As the time water spends in the pipes heavily depends on the demand, a stochastic demand generation model estimates the water use for each fixture on a minute-by-minute basis. The same demand patterns are applied to each premise plumbing layout and the effects on water age are examined for the hot and cold water systems.

Prior to testing, each layout's pipes are sized to meet the pressure and flowrate specifications defined in the International Plumbing Code 2012 (ICC, 2012). The peak demand in each branch is estimated using the q_1+q_3 method (Buchberger et al., 2017), and the head losses are computed using the Darcy-Weisbach equation considering the flow's

Reynolds' number. As the peak demand differs from simulated ones, the resulting pressures are compared to obtain clues if the design methods are too conservative.

Lastly, conclusions are drawn from the improved designs for different layouts with respect to water age. The conclusions should lead to establishing design practice guidelines that minimize residence times while meeting the code pressure specifications.

CHAPTER 2 - LITERATURE REVIEW

This chapter presents a review of the main findings and concepts on the impact of water age on water quality; beginning with the general effects of aging water followed by a focus on premise plumbing. Methods to compute water age are presented including a technique to simulate residential demand.

The chapter is structured as follows. First, the effects of water age on water quality in distribution systems are described. Section two describes the relation between chlorine decay and water temperature that is important when analyzing the effects of the water heater type.

As water ages, the conditions are more favorable for regrowth of some pathogens and potentially colonization of pipe systems. The main bacteria of concern are Legionella. The third section describes the importance of Legionella on water quality and human health and the premise plumbing factors that affect its presence. The next section is a brief review of studies that have concluded that green buildings are exacerbating the water age problem.

To assess water age in a building or a distribution system, either a tracer method or a mathematical model is required. Section five presents a mathematical model for computing water age. To represent conditions at the premise level, detailed demands are required. Section six presents a stochastic model that simulates the demand in small time steps for each fixture in a residence. This model is based on statistical parameters including flow use in each fixture and the number and time of use per resident. To account for the trend toward low water use appliances, the model parameters can be modified to reflect water efficient fixtures. Section seven presents fixture water use data, for old (inefficient), present (regular), and water conserving (efficient) appliances that can be examined in future research.

In addition to water age, the plumbing system design must meet the requirements established in plumbing codes. The final section in this chapter summarizes relevant design criteria of a widely employed plumbing code.

2.1. Effects of water age in water quality

Increasing water age can cause or worsen several water quality problems. Those problems can be classified into three categories; chemical, biological, and physical issues (US EPA, 2002a).

2.1.1. Chemical issues

Chemical concerns include Disinfection By-Product (DBP) formation, disinfectant decay, and reduction of the corrosion control effectiveness. DBPs are a family of chemicals formed when disinfectants react with naturally occurring organic matter and inorganic substances in the water and on the pipe wall. DBPs include haloacetic acids (HAA) and trihalomethanes (THM) (California Environmental Health Tracking Program, 2018). The main adverse health effects of long-term DBP exposure are increased cancer risks, and liver, kidneys, and central nervous system problems (US EPA, 2018a). In the Unites States, the Stages 1 and 2 of the Disinfectants and Disinfection Byproducts Rules are regulations established by the EPA whose specific objective is to reduce drinking water exposure to disinfection byproducts (US EPA, 2018b).

As water ages, residual chlorine decays. These reactions occur with substances in the water, known as bulk decay, and with interactions on the pipe wall, described as wall reactions. EPANET (Rossman, 2000) represents both mechanisms in modeling chlorine decay in water distribution networks. In some situations, the separation into two mechanisms is not valid (Clark and Haught, 2005). Although many other models have been proposed, chlorine decay is still frequently represented as a simple exponential reduction with time (Fisher et al., 2011). For more details refer to section 2.2.

Another chemical issue related with water age is the reduction in corrosion control, due to the lower effectiveness of phosphate inhibitors and pH management in poorly-buffered waters (USEPA, 2002a).

2.1.2. Biological issues

Nitrification and microbial growth are the main biological problems associated with aging water. Nitrification is a microbial process in which reduced nitrogen compounds, like ammonia or ammonium, are oxidized to nitrite and then to nitrate. Nitrifying bacteria are slow growing organisms. Consequently, nitrification problems usually occur in large reservoirs or low-flow sections of the distribution system (US EPA, 2002a). The problem is greatest when temperatures are warm and water usage is low. These conditions occurred during the nitrification episodes in Texas water systems during the rainy summers of 2007 and 2015 (Texas Commission on Environmental Quality, 2018). Therefore, the Texas Commission on Environmental Quality (2018) directs that reducing water age is a key point to prevent nitrification.

The other primary biological problem related with age is microbial regrowth. Regrowth refers to the recovery and growth of environmentally or disinfectant stressed microbes, as well as the growth of non-injured microbes (USEPA, 2002b). Two main mechanisms relate aging water to microbial growth. The first is the loss of residual disinfectant (secondary disinfection). The purposes of the residual disinfectant are (1) to protect the water from pathogens entering through line breaks or from contaminated equipment used in distribution system maintenance, and (2) to suppress bacterial growth and biofilm formation in static water areas (Geldreich, 1996; Trussell, 1999). Secondary disinfection also protects against reinoculation of the flowing water by microbes trapped in biofilm on pipe walls that can occur during biofilm erosion (Haas, 1999). The second mechanism relating microbial growth with aging water is biofilm formation on pipe walls that is enhanced in low velocity or stagnant water. Thus, long resident times and, consequently, a lack of residual disinfectant can adversely affect water quality. The situation worsens as organisms attached to biofilms are more resistant to disinfection than those in the water (Berger et al., 1993; Crozes and Cushing, 2000). Furthermore, some researchers have found that chlorine residual may not control biofilms (LeChevallier 1990; Wierenga, 1985; Nagy and Olson, 1986; Characklis, 1988).

2.1.3. Physical issues

Physical water quality problems associated with water age are temperature increases, sediment deposition, and water color (USEPA, 2002a). Although those issues may not have a direct potential to impact public health, they may result in improved conditions for the microbial growth.

LeChavallier (1990) found that water temperature affects the microbial growth rate, disinfection efficiency, pipe corrosion rates, and biofilm development. Microbes generally grow more rapidly in warmer temperatures (Donlan and Pipes, 1988; LeChevallier et al., 1996). Further, several authors have observed that bulk chlorine decay rates also increase with temperature (Powell et al., 2000; Fisher et al., 2011; Feben and Taras, 1951). Those findings are in line with the Arrhenius equation, that states that chemical reaction rates increase with temperature (section 2.2.).

The organic and inorganic sediments that may accumulate in the low-flow areas of the distribution system, can enhance microbial activity by providing protection and nutrients (USEPA, 1992). Moreover, biofilms may lead to sediment accumulation and the proliferation of some microorganisms (van der Kooij, 2000).

2.2. Chlorine decay

As noted, disinfectant decay is related to water age and temperature. The temperature effect is important in a premise system given the amount of time water spends in traditional residential tank heaters at relatively high temperature (but not high enough to disinfect it). Although other models have been proposed, Fisher et al. (2011) note that chlorine decay is frequently represented as a simple exponential reduction with time or:

$$C = C_0 \cdot e^{-k \cdot t}$$

where:

C	Chlorine concentration at time t [mg/L]
C_0	Initial chlorine concentration [mg/L]
k	First order chlorine decay constant [L/hr]

A simple method to separate the bulk decay and wall reactions is to define the overall decay constant (k) as the sum of a bulk and wall decay constants (k_b and k_w, respectively). However, decay coefficients in the literature range from 0.02 to 0.74 [L/hr], suggesting that factors affecting the decay rate are not accounted for in a first order model (Powell et al., 2000). Explanatory factors include temperature variations and the total organic carbon concentration (TOC, a measure of organic content).

A number of author have observed that bulk chlorine decay rates increase with temperature (Powell et al., 2000; Fisher et al., 2011; Feben and Taras, 1951). The Arrhenius equation describes temperature dependence on reaction rates:

$$k_t = F \cdot e^{\frac{-E}{R(T+273)}}$$

where:

k_t	Specific reaction rate constant (unit depends on order of reaction)
F	Pre-exponential factor (a constant for each chemical reaction)
E	Activation energy [J/mol]
R	Ideal gas constant (8.31 J mol^{-1} $°C^{-1}$)
T	Temperature [°C]

The ratio of activation energy to the universal gas constant, *E/R*, defines the sensitivity of a reactions to temperature (Fisher et al., 2011). To assess temperature effects, Powell at al. (2000) set the ratio to 7300°C, its average optimal value. Fisher and Kastl (1996) assumed that the temperature dependence for all reaction coefficients was described by a single value of the activation energy in a modified Arrhenius equation:

$$k_t = k_{20} \cdot e^{\frac{-E(20-T)}{R(T+273)(20+273)}}$$

The growth or decay of a substance, like chlorine, is related to the reactions with other constituents in the system, such as organic compounds. The future of water distribution system water quality modeling is to simultaneously represent multiple components (Lansey and Boulos, 2005). Powell et al. (2000) and other authors have proposed different relationships to account for the multiple components, but the parameters and equations are still being subject of debate in the scientific community.

2.3. Legionella in premise plumbing

The emphasis of the present study is on premise plumbing systems. In section 2.1., cited literature suggests that current premise plumbing designs may enhance pathogen growth within the water system due to lack of consideration of water age. The bacteria of primary concern at the residence and building scales is Legionella as it has been implicated in the majority of the drinking water-associated outbreaks demonstrating that it can colonize premise plumbing systems and cause lethal illness.

2.3.1. What is Legionella?

The genus Legionella refers to a group of gram-negative rod-shaped bacteria, that includes at least 50 bacterial species. Those bacteria are found in aquatic environments, and thrive in warm water and warm damp places, such as cooling towers (WHO, 2007). Legionellosis is a generic term referring to bacterial infections associated to Legionella, that can range in severity from a mild, febrile illness (Pontiac fever) to a rapid and potentially fatal pneumonia (Legionnaires' disease) (WHO, 2007). The major mode of transmission is inhalation of contaminated aerosols (WHO, 2007), as opposed to ingestion of contaminated water (US EPA, 2016). Legionella does not transmit from animals to humans (Cunha, 2006), and only one probable person-to-person transmission has been reported (Correia et al., 2016).

An important characteristic of Legionella is that it can persist in varied environmental conditions such as in low or high temperatures and in the presence of disinfectants, low pH, low nutrients and high salinity (USEPA, 2016, referring to other authors). It is able to withstand temperatures of 50 °C (122 °F) for several hours (WHO, 2007), and it can also survive at temperatures below freezing (Borella et al., 2005). The mechanism that allows Legionella to persist in adverse conditions is its association with biofilms (WHO, 2007) and their symbiotic and parasitic interactions with other microorganisms (USEPA, 2016). The association with biofilms appears to increase Legionella's resistance to disinfectants (Falkinham et al., 2015).

2.3.2. Why is Legionella important?

The latest report of the US Center for Disease Control and Prevention (CDC) indicates that during the 2013 – 2014 period, 42 drinking water-associated outbreaks were reported, accounting for at least 1,006 cases of illness, 124 hospitalizations, and 13 deaths. Legionella was implicated in 24 (57%) outbreaks, 130 (13%) cases, 109 (88%) hospitalizations, and all 13 deaths (Benedict et al., 2017). This situation is not new. Between 2009 and 2012 Legionella accounted for 40 of the 65 drinking water-related waterborne disease outbreaks in the United States causing 72 illnesses and 8 deaths. The CDC identified environmental conditions within premise plumbing systems as the deficiency that caused 32 of the 40 Legionella outbreaks (Beer et al., 2015; CDC, 2013).

Furthermore, between 3,000 and 4,000 cases of Legionellosis are reported to the CDC each year (CDC, 2012); however, the actual number of hospitalized cases in the United States is estimated to be between 8,000 and 18,000 annually (Marston et al., 1997). The reason for the under-reporting is that many cases of pneumonia are treated with antibiotics and never tested for Legionella (CDC, 2011).

Most relevant to this study is that premise plumbing systems have been identified as a source of Legionella infection (Stout et al., 1992a). This is particularly important in the case of hospitals and health-care facilities in general (Lin et al., 2011; Sabrià & Yu, 2002), but also in domestic plumbing systems (Arnow et al., 1985; Stout et al., 1992b). In the study conducted by Lu et al. (2016), with samples collected between 2012 and 2013, Legionella was found in finished water from water treatment plants, but it persists and grows in biofilms of municipal water distribution systems.

The USEPA (2016) summarized peer-reviewed scientific literature regarding Legionella growth in premise plumbing of large buildings and concluded: "*Premise plumbing systems can be colonized with Legionella and transmit the bacteria through aerosols generated from showers, humidifiers and spas associated with hot water distribution systems, as well as from respiratory therapy devices…*". In houses, inhalation of Legionella can occur from aerosols that are generated by showers and by tap diffusers aimed at reducing water use (WHO, 2007).

2.3.3. Factors affecting Legionella in premise plumbing

The World Health Organization (WHO, 2007) has identified numerous risk factors associated with Legionella in-building distribution systems:

- Water quality and treatment: Legionella requires nutrients for sustained growth. Hence, water without proper treatment may allow Legionella to proliferate within the piping system (WHO, 2007).
- Temperature: Legionella can survive and multiply in water at temperatures of 25 - 45 °C, with an optimal range of 32 - 42 °C (Yee and Wadowsky, 1982).
- Stagnation: "*Proliferation of legionellae is promoted by stagnation, which occurs, for example, in the dead-ends of distribution system pipework, and in storage tanks and systems that are not frequently used.*" (WHO, 2007).
- Construction materials: Natural materials (like hemp and natural rubber), synthetic materials, and corrosion may encourage biofilm formation (WHO, 2007).

- Presence of biofilms: Legionella can withstand adverse conditions (WHO, 2007) and disinfectant (Falkinham et al., 2015) in these “protected” environments.
- Disinfection: Low residuals.

2.3.4. Technologies for controlling Legionella in existing premise plumbing systems

The USEPA (2016) identified several technologies for controlling Legionella in existing premise plumbing systems. However, “*the effectiveness of a particular technology is dependent upon building-specific characteristics such as pipe material, age and condition; water usage rates and water age; and water quality parameters (e.g., pH, hardness, organic contaminants, inorganic contaminants, types of waterborne pathogens) …”* (USEPA, 2016). Furthermore, they recognized that long-term eradication has not been consistently demonstrated with any of the reviewed technologies, especially on complex buildings and in the presence of biofilm.

Nevertheless, the WHO (2007) presents various approaches to control Legionella in piped water systems. The main one, and that is of particular interest in this study, is that the control of Legionella should begin at the design stage of the water system. Good design practices imply that pipes should be as short as possible, dead-ends should be avoided both during design and construction phases, material selection should minimize bacterial growth, and disinfectant residuals should be maintained (WHO, 2007; USEPA, 2016). Another important hydraulic measure is to flush the pipeline at regular intervals as a primary practice for proper distribution system maintenance (USEPA, 2016). Flushing and pigging can remove the biofilm, sediments (Crozes and Cushing, 2000), and tuberculation, improving the system hydraulics (USEPA, 2016).

In addition, water temperature is critical in Legionella control. It is recommended that the cold water at the tap should not exceed 25 °C (77 °F) and, when possible, it should be below 20 °C (68 °F). On the other hand, hot water that reaches the tap in one minute or less should exceed a temperature of 50 °C (122 °F). Alternatively, the system should be periodically flushed with a temperature of at least 60 °C (140 °F), along with precautions to avoid scalding (WHO, 2007). This temperature ranges are in line with the findings from Arnow et al. (1985), who indicates that it is more likely (42%) to detect Legionella in systems whose maximum temperature was below 60 °C compared with systems whose maximum temperature is above 60 °C (7%).

2.4. Green buildings and elevated water age

Recent studies have found that green building strategies may exacerbate the water age problem, and, consequently, increase the likelihood of pathogens emerging within those buildings. A required category for green building certification on the Leadership in Energy and Environmental Design (LEED) website is water use reduction. For indoor uses, low flow fixtures are common practice (USGBC, 2018). Regardless of fixture type, green buildings must also meet applicable plumbing codes. For example, the 2012 International Plumbing Code (ICC, 2012) establishes design criteria for flowrates and pressures per fixture. Those flowrates are higher than the baseline from which the LEED certification establishes the water use reduction. As a consequence, plumbing piping is oversized in green buildings.

Rhoads et al. (2016) compared samples taken from green buildings with those taken from conventional buildings. Green building waters were significantly older and had lower disinfectant residuals and higher total bacteria levels. As a temporary solution for buildings connected to drinking water mains, they recommend regular flushing to maintain disinfectant residuals, improve corrosion control, and achieve temperature targets. Nonetheless, they concluded that "*the design of green buildings with water conservation features should minimize overall water age, eliminate unnecessary water storage and should give special attention to avoiding conditions conducive to pathogens in premise plumbing…*" (Rhoads et al., 2016).

2.5. Tools to determine water age

Two approaches can be applied to establish the water age within a distribution system. The first is tracer studies that are comprised of injecting a benign tracer (e.g., fluoride, sodium chloride, or calcium chloride) and measuring its distribution in the water distribution system over time. Varying characteristics (hardness or conductivity) or changeovers from chlorination to chloramination during transitional periods in system operation are opportunities for tracer studies (US EPA, 2012a). "*Tracer studies have been performed to calculate water age throughout a distribution system, calibrate water quality and hydraulic models, and to enhance the study of water age in relation to water quality parameters such as chlorine residual or trihalomethanes…*" (US EPA, 2012a).

The second approach for estimating water age is to mathematically model water movement in the distribution system under steady state and dynamic conditions. From a water quality standpoint, a steady state is achieved when water quality at all nodes does not change over time. Males et al. (1985) first modeled these conditions. Their approach was extended by Boulos and Altman (1993) and Chung et al. (2007). However, steady state conditions are rarely reached in a water distribution network due to demand variations. Hence, dynamic simulation is a necessary tool (Lansey and Boulos, 2005).

In that line, two main approaches are applied to simulate advective transport along the pipe; Eulerian and Lagrangian. Eulerian methods consider fixed grids or cells and move water to grid locations or through the cells to represent the movement of a constituent in a pipe (Lansey and Boulos, 2005). Lagrangian methods, on the other hand, track the location of the fronts of discrete water parcels as they move through the network. Those locations are updated at a fixed time step, or when they reach a node (Lansey and Boulos, 2005).

Due to its overall efficiency, EPANET 2 applies the latter approach (Rossman, 2000) using a so-called time-driven transition scheme. This method was first introduced by Liou and Kroon (1987), and generalized by Rossman et al. (1996). Herein, water quality fronts (abrupt changes in water quality) are identified and tracked at discrete time steps. At each time step, the locations of the fronts are updated as well as the water quality (i.e. age or constituent grow or decay). Based on the front locations, the total mass constituent that reaches a node and the total average nodal concentration during the period are computed (Lansey and Boulos, 2005). Segments (volumes of water between fronts) are introduced or destroyed based on parcel volumes, flowrates and the time-step, or if the average nodal concentration differs significantly from the next downstream parcel's concentration (Rossman, 2000). For more information, refer to Lansey and Boulos (2005).

2.6. Stochastic end-use water demand model for households

To model water quality dynamics, water demands must be known as a simulation results precision is determined primarily by the modeled time step. This section describes a simulation model for imposing water demands at each fixture in residential buildings. From a set of field data from a subdivision in Milford Ohio, Buchberger and Wu (1995) characterized residential water demands as rectangular pulses with three variables: intensity, duration, and frequency. They proposed a probabilistic model for residential demand pulse signals (Buchberger and Wu, 1995). The occurrence and time between occurrences of demands of a particular type is based on a Poisson probability distribution. The magnitude is based on field data for the various household uses. To derive the necessary model parameters, the set of water demand measurements from the field site were analyzed (Buchberger and Wells, 1996).

The resulting model was applied in other locations, with probability distributions for intensity and duration were found for locally obtained datasets. The need for local data is a primary drawback of this approach. Further, it is difficult to correlate the parameters retrieved from the measurements with normally available data such as population size, age and installed appliances.

Based on their probabilistic model, a demand generation model can be formulated using an assumed set of parameters. The model develops a time series of uses and demand volumes for each fixture (i.e., the timing of opening the kitchen tap or flushing a toilet and the corresponding withdrawal). At each use occurrence, a rectangular finite pulse is generated with a corresponding intensity. If two or more demands overlap, the total water use at the residence is the sum of the individual intensities from the coincident pulses, as shown in Figure 1.

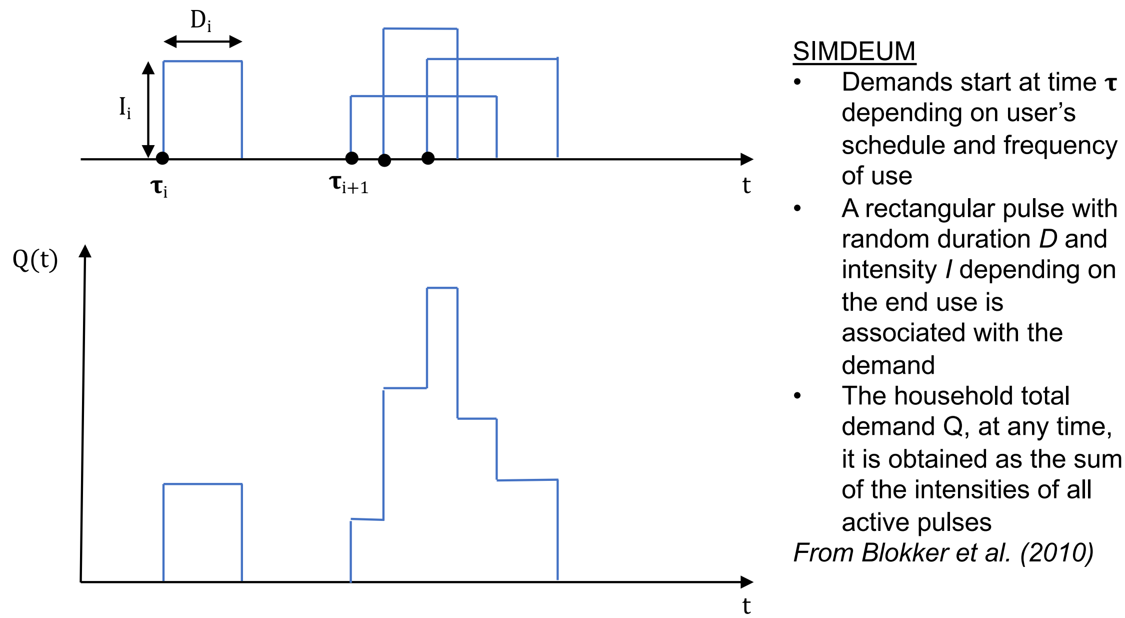

Figure 1: Schematic of residential demand characterization as rectangular pulses

To avoid the need for measurement campaigns, Blokker et al. (2010) developed a stochastic end-use model, in which the intensity, duration and frequency of rectangular demand pulses is represented by a probability density function for each fixture. Furthermore, the likelihood of each fixture use varies throughout the day depending on the residents' schedule. This resulting end-use model, SIMDEUM, acts as a predictive model and can be utilized in the design stage and in existing networks where no household water meters are installed (Blokker et al., 2010). The underlying probabilities model within SIMDEUM was programmed for this study and applied as the demand generator.

Of note, SIMDEUM was developed in the Netherlands, where the fixtures, number of household occupants, and occupants' habits may differ from the United States. Creaco et al. (2017) parametrized SIMDEUM using information from the study in Milford, Ohio. They compared the simulation results with flowrate measurements from 20 households coupled with other rectangular pulses methods. It was concluded that SIMDEUM has a similar performance than the other methods and was more accurate for single family households. Further, SIMDEUM's flexibility allows it to be applied in scenario studies to examine changes in water-using appliances and human behavior (Creaco et al., 2017).

Although SIMDEUM was originally developed to compute maximum demands to design self-cleaning networks, it has been used in other applications (Blokker et al., 2017) including water quality modeling to estimate maximum flow velocities, flow direction reversals and residence time in pipe networks (Blokker, 2010a). Water quality modeling driven by SIMDEUM provides an understanding of water age in the distribution system periphery where high demand variability makes it difficult to calibrate water quality using tracer measurements (Blokker et al., 2010b). SIMDEUM driven water quality has also been used to model water temperature in domestic systems (Moerman et al., 2014) and bacterial growth in distribution systems (Blokker et al., 2014).

2.7. Water use data

As Figure 1 illustrates, the volumetric water demand depends on the frequency, duration and intensity of the water uses. With high water efficient fixtures becoming the norm in green buildings, demand volumes and durations must be modified. To understand the present water-use per capita for each fixture, Buchberger et al. (2017) analyzed water use measurements from over 1000 single-family homes across the Unites States between 1996 and 2011 (Table 1).

Table 1: Frequency and volume of water use per capita in single family homes (Buchberger et al., 2017)

Fixture	Water use events (per capita per day)	Volume (GPCD)
Bathtub	0.08	1.54
Clother washer	0.97	14.31
Dishwasher	0.33	0.77
Faucet	22.74	11.87
Shower	0.76	12.59
Toilet	5.80	15.18
Others	9.74	3.84
Leaks	50.11	11.98
Totals (excluding leaks)	40.44	11.98

Estimated values of per-capita daily water-use and frequency are also given in Vickers (2001) for several fixtures, considering high, regular and low efficiency appliances depending on their manufacturing or installation year. Those values were estimated based on technological or regulation changes (Table 2).

Comparing Tables 1 and 2, the total water-use per capita per day from the two sources is very similar for the average efficiency fixtures (present day). Using Creaco et al. (2017) values for SIMDEUM (Table 8) an estimate of average daily demand is the sum of the products of the mean frequency, mean intensity and mean duration for each end-use. Assuming an average of 2.7 residents per household, the daily demand per capita obtained is shown in Table 3, were the mean values correspond similar to the ones from Tables 1 and Table 2. Further, by adjusting the intensity and duration parameters in SIMDEUM, the more water efficient appliances can be incorporated in the model.

Table 2: Estimates of daily per capita per day water, broken down for different fixtures (data from Vickers, 2001)

Fixture	Category	Type	Frequency (per capita, per day)	Water use [GPD] (Per capita, per day)	Description
Toilet	High eff.	1.6 gpf	5.1	8.16	
	Average eff.	3.5 gpf	5.1	17.90	
	Low eff.	5.5 gpf	5.1	28.10	1950s-1980
Shower	High eff.	2.5 gpm	5.3*	8.80	
	Average eff.	3.0 gpm	5.3*	10.60	
	Low eff.	4.3 gpm	5.3*	23.00	pre 1980
Faucets	High eff.	2.5 gpm	8.1*	13.50	
	Average eff.	3.0 gpm	8.1*	16.20	
	Low eff.	3.4 gpm	8.1*	27.00	pre 1980
Washers	High eff.	27 gpl	0.37	10.00	
	Average eff.	39 gpl	0.37	14.40	
	Low eff.	56 gpl	0.37	20.70	pre 1980
Dishwasher	High eff.	7 gpl	0.1	0.70	
	Average eff.	8.5 gpl	0.1	0.90	
	Low eff.	14 gpl	0.1	1.40	1980-1990

** In minutes per day*

Total water-use per capita per day	
High eff.	41.16
Average eff.	60.00
Low eff.	100.20

Table 3: Daily per fixture per capita water demand, used as input for SIMDEUM on Creaco et al. (2017) study

Fixture	Water use [GPCD]
Bathtub	4.1
Clothes washer	14.7
Dishwasher	2.0
Faucet	10.7
Shower	13.1
Toilets	18.0
Total	62.6

2.8. Plumbing codes

Regardless the type of fixtures, buildings must meet appropriate plumbing codes. As a household with plumbing design for high-use fixtures convert to modern fixtures that use less water (Vickers, 2001), water age issues may emerge as pipes are oversized to satisfy the larger demands. This section summarizes the most relevant points of the 2012 International Plumbing Code (ICC, 2012; chapter 6) that has been adopted by many communities including the City of Tucson (City of Tucson, 2018a). Chapter 6 of IPC code: Water supply and distribution is applied without amendments (City of Tucson, 2018b). The scope of this chapter, is that it *"... shall govern the materials, design and installation of water supply systems, both hot and cold, for the utilization in connection with human occupancy and habitation and shall govern the installation of individual water supply systems*" (ICC, 2012).

Premise plumbing systems must meet all points in the code. The following points are relevant extracts from the Chapter 6 of the 2012 International Plumbing Code:

603.1 Size of water service pipe: The water service pipe (e.g., from the distribution pipe to the entrance to the house) shall be not less than ¾ inch (19.1 mm) in diameter.

604.3 Water distribution system design criteria: The water distribution system shall be designed, and pipes shall be selected such that conditions of peak demand, the capacities at the fixture supply pipe outlets shall not be less than shown in Table 604.3 (Table 4).

604.5 Size of fixture supply: The minimum size of fixture supply pipe shall be as shown in Table 604.5 (Table 4). The fixture supply pipe shall terminate not more than 30 inches (752 mm) from the point of connection to the fixture.

Table 4: (summarized Tables 604.3 and 604.5) Water distribution system design capacity criteria

Table 604.3 WATER DISTRIBUTION SYSTEM DESIGN CRITERIA REQUIRED CAPACITY AT FIXTURE SUPPLY PIPE OUTLETS (*combined with*) **TABLE 604.5 MINIMUM SIZES OF FIXTURE WATER SUPPLY PIPES**

FIXTURE	FLOW RATE[a] (gpm)	FLOW PRESSURE (psi)	MINIMUM PIPE SIZE (in)
Bathtub, balanced pressure, thermostatic or combination balanced-pressure/thermo-static mixing valve	4.00	20	1/2
Bidet, thermostatic mixing valve	2.00	20	3/8
Combination fixture	4.00	8	1/2
Dishwasher, residential	2.75	8	1/2
Drinking fountain	0.75	8	3/8
Laundry tray	4.00	8	1/2
Lavatory	2.00	8	3/8
Shower	3.00	8	1/2
Shower, balanced-pressure, thermostatic or combination balanced-pressure/thermo-static mixing valve	3.00	20	1/2
Sillcock, house bibb	5.00	8	1/2
Sink, residential	2.50	8	1/2
Sink, service	3.00	8	3/4
Urinal, valve	12.00	25	3/4
Water closet, blow out, flushometer valve	25.00	45	1
Water closet, flushometer tank	1.60	20	3/8
Water closet, siphonic, flushometer valve	25.00	35	1
Water closet, tank, closed couple	3.00	20	1/2
Water closet, tank, one piece	6.00	20	1/2

607.2 Hot or tempered water supply to fixtures: The developed length of hot water piping, from the source of hot water to the fixtures that require hot water, shall not exceed 50 feet (15240 mm).

2.8.1. Peak demand estimation

To estimate the peak demand, the 2012 International Plumbing Code counts the load assigned to fixtures and converts them into flowrates using Table E103.3 (Appendix E of the code). More recently, Buchberger et al. (2017) examined various methods for estimating peak demands in buildings. They concluded that for small buildings (with less than 20 fixtures), the q_1+q_3 or the exhaustive enumeration methods are recommended as they account for discrete fixtures that exert a significant impact on system behavior.

The q_1+q_3 method ranks all fixtures along a branch line in descending order of their recommended fixture demand (Table 4). That is, the fixture with the largest demand is ranked 1 (q_1), the second largest 2 (q_2) and so on. Then, the q_1+q_3 method simply adds the demands for the rank 1 and the rank 3 fixtures to obtain an expedient and reasonably good estimate of the 99^{th} percentile demand, often identical to the value generated by a full exhaustive enumeration (Buchberger et al., 2017).

The code does not specify methods to calculate friction and minor losses. However, subsection 604.1 indicates that "*The design of water distribution system shall conform to* accepted engineering practice. *Methods utilized to determine pipe sizes shall be* approved".

CHAPTER 3 - METHODOLOGY

As discussed in the previous chapters, high water age can lead to water quality issues by altering its chemical, biological and physical properties. To that end, it is of interest to quantify water age in households and examine the effects of alternative plumbing layouts. To compute water age using a modeling approach, three main components are required; a numerical model to compute water age, a demand generator model for each fixture, and estimating and comparing residence times in several plumbing layouts. This chapter describes methods to complete these three tasks.

3.1. A numerical model to compute water age

As described in the literature review, a dynamic simulation approach is a better and more accurate tool than steady state when modeling water quality in distribution systems (Lansey and Boulos, 2005). EPANET 2 (Rossman, 2000) uses a dynamic Lagrangian technique, the Time-Driven Method, to track the location of discrete water parcels as they travel through the network. In this study, EPANET 2.1 is used to compute water age in a household premise plumbing system and is coupled with the MATLAB-Toolkit (Kyriakou and Eliades, 2018) to analyze model output. However, EPANET was determined to be incapable of modeling water quality in small pipes with low demands. To provide accurate results, modifications to the system representations were required as described in subsection 3.1.4.

3.1.1. Hydraulic relationships

Water age is driven by the movement of water. Thus, EPANET must first solve the conservation of mass and energy equations that describe network hydraulics. With known flow rates and velocities, EPANET identifies and tracks water quality fronts at discrete time steps as described in the cited literature on Chapter 2.

Conservation of mass at a node that connects two or more pipes under steady state conditions is written as:

$$\sum_{l \in J_{in,i}} Q_l - \sum_{l \in J_{out,i}} Q_l = q_i$$

where:

Q_l	Volumetric flow rate in pipe *l*
q_i	Volumetric flow withdrawal from node *i*
$J_{in,i}$	The set of pipes supplying flow into node *i*
$J_{out,i}$	Set of pipes carrying flow from node *i*

Conservation of energy for pipe *l* that connects nodes A and B is:

$$H_A - H_B = h_{L,l} + h_{m,l}$$

where:

H_A, H_B	Total head at nodes A and B, respectively
$h_{L,l}$	Major (friction) losses in pipe *l*
$h_{m,l}$	Minor (local) losses in pipe *l*

Minor losses are calculated by the product of the minor loss coefficient and the velocity head, as:

$$h_{m,l} = K \frac{V^2}{2g}$$

where:

K	Sum of the minor loss coefficients for appurtenances in pipe *l*
V	Flow velocity in the pipe *l*
g	Gravity acceleration constant

The minor loss coefficients for the different types of fittings are obtained from the EPANET manual (Rossman, 2000: p.32) (Table 5).

Table 5: Minor loss coefficients for selected fittings

K	Fitting
0.9	Elbow - short radius
0.4	Elbow - 45 degrees
0.6	T - run
1.8	T - branch

In the United States, friction losses are normally computed using the Hazen-Williams equation, but as the diameters of the pipes of interest in the present study are small (ranging from ½ to 1 inch), the Darcy-Weisbach equation is applied:

$$h_{L,l} = \frac{8 \cdot f_D \cdot L \cdot {Q_l}^2}{g\pi^2 D^5}$$

where:

f_D Darcy friction factor $f(\varepsilon/D, Re)$
L Pipe length
D Pipe diameter

The friction factor (f_D) depends on the flow regime that is distinguished by the Reynolds' number. Within EPANET, three different equations are used to compute f_D (Rossman, 2000):

- Laminar flow ($Re < 2000$): Hagen-Poiseuille formula;
- Fully turbulent flow ($Re > 4000$): Swamee and Jain approximation of the Moody Diagram;
- Transitional flow ($2000 < Re < 4000$): Cubic interpolation from the Moody diagram.

3.1.2. Model general aspects

The following assumptions/parameters were applied in the modeling process:

- The water age in the street pipe (source) is zero. Thus, the water age computed in the premises corresponds to the residence time within its plumbing system;

- The time variant demands are imposed using a unit base demand (1 L/s) in each outlet node combined with a demand pattern function following the simulated demand pattern. Thus, each value in the demand time series contains the demand for each minute, including the no-demand periods (i.e., a 0 would appear in the pattern);
- Each fixture is modeled as two nodes; one corresponding to the actual fixture, and the other one to the point of connection of the fixture to the premise distribution pipe. The nodes are separated by the stub, that is a ½ inch (12.7 mm) inner diameter pipe of length 1.64 ft (0.5 m). This allows to compute the age at the fixture itself, and in the pipe as the former depends heavily on the stagnation time;
- The friction losses (or major losses) are computed using the Darcy-Wesibach equation (subsection 3.1.1). The pipe material is plastic, brass, or copper with a common roughness of $5 * 10^{-6}$ ft (0.0015 mm) (Rossman, 2000: p.31);
- The local (minor) loss for each pipe fitting is computed with coefficients from Table 5;
- The street pipe pressure (i.e., source pressures) is 40 psi (28.12 meters of water);
- To model water age, an extended period analysis is completed by modeling a series of one-minute steady state simulations. The demand pattern for each fixture is obtained from the SIMDEUM simulation model described in the next section;
- Nodal elevations for first floor fixtures are 0 ft (0 m) or an equivalent elevation as the supply pipe while nodes on the second floor have elevation of 9.84 ft (3 m).

3.1.3. Modeling water heaters on EPANET

Water age is compared for traditional and instant water heaters. A traditional water heater is a hot water storage tank that is modeled as a large diameter pipe with a volume equal to the tank volume. For example, a 50-gallon (189 L) water heater was modeled by a pipe diameter of 6.1 inches (155 mm) and 32.81 ft (10 m) long. An instant or tankless heater is modeled as a negligible volume by a 1.64 ft (0.5 m) long pipe with an equivalent diameter as the connecting pipe.

3.1.4. Modifications to the model

Modeling water age in premise plumbing systems using EPANET was not possible due to numerical dispersion. To illustrate the issue, consider an 8-node and 8-pipe network (Figure 2):

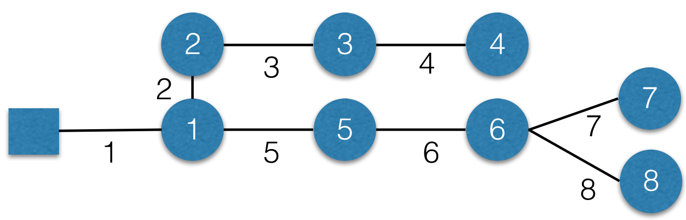

Figure 2: Network used to illustrate the issues in water age computation on EPANET

For reproducibility purposes, the network description is summarized in Table 6 and the time-steps (in minutes) with active demand in each node are shown in Table 7:

Table 6: Network description

Link information				Node Information		
Number	Length [m]	Diameter [mm]	Volume [L]	Number	Base demand [L/s]	Elevation [m]
1	10	12.7	1.27	1	0.1	1
2	6	12.7	0.76	2	0.13	1
3	8	12.7	1.01	3	0.05	1
4	0.5	12.7	0.06	4	0.13	1
5	10	12.7	1.27	5	0.05	1
6	10	12.7	1.27	6	0.05	1
7	5	12.7	0.63	7	0.23	1
8	5	12.7	0.63	8	0.17	1

Table 7: Demand pattern multipliers; during the specified minutes the multiplier is 1 and 0 elsewhere

Node	Minutes with demand						
1	1080:1084						
2	430	480					
3	425:426	1050:1051	1170:1171	1290:1291	1410:1411		
4	1380:1388						
5	425:426	425:426	1290:1291				
6	430	432	440	442	460	461	479
	472	1060	1070	1230	1232	1320	
7	1325						
8	1140:1144						

As seen in Table 7, the only demand for node 4 occurs between minutes 1380 and 1388 with a magnitude of 0.13 L/s. Consequently, a drop in water age, e.g. when fresh water arrives at that node, should only occur within that time frame. However, water age from EPANET linked through MATLAB with the EPANET Toolkit drops at approximately minute 950 (Figure 3).

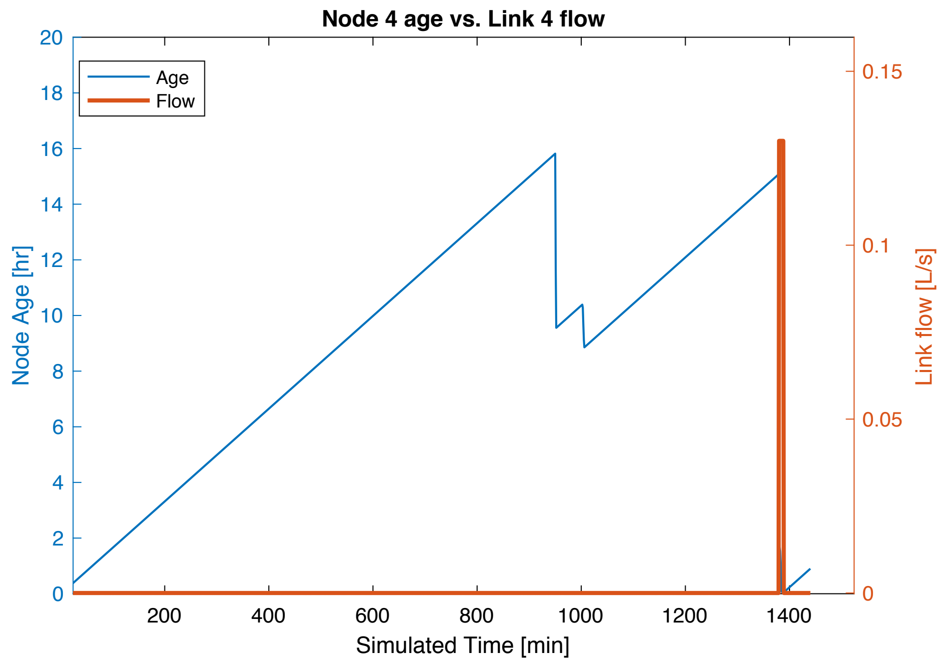

Figure 3: Time-series of water age in node 4, along with the upstream pipe flow illustrating the demand

A coding error within the toolkit was initially believed to be the cause of this incorrect result, but the problem was recreated directly in EPANET 2.0 (Figure 4). Therefore, the problem lies within the numerical algorithms within EPANET and has been identified by other modelers[1]. This erratic behavior is only observed in dead-ends, connected by a short pipe, during long periods with no demand at the terminal node.

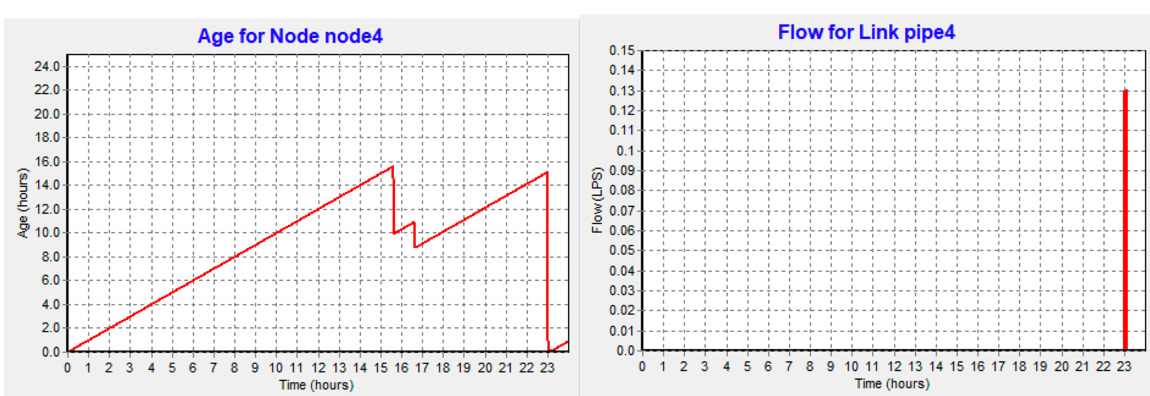

Figure 4: (left) Node 4 age time-series; (right) pipe flow time-series in the upstream pipe illustrating the demand

[1] https://communities.bentley.com/products/hydraulics___hydrology/f/haestad-hydraulics-and-hydrology-forum/85626/epanet-age-problem

The cause of the problem is likely the convergence of the gradient algorithm that simultaneously determines the total head and pipe flows. The algorithm solves conservation of mass at each node and conservation of energy for each link. A pipe flow rate of zero will cause a diagonal term in the gradient matrix to be zero and the matrix will be singular and not invertible. Thus, solutions converge to very low flow rates even for terminal pipes connected to a downstream node with no demand. In water distribution sized pipes, this causes virtually no head loss and the total heads at both ends of the pipe are essentially identical. In distribution size pipes, the computed flow rate is small compared to the pipe volume (e.g., in a 6-inch pipe) and water age impacts are minor.

However, in premise plumbing systems with small diameter and short pipes, the impact of the small flow rate is significant over a long time period and artificial fronts pass through the entire length of the pipe causing the results seen in this system. To overcome the water age-drop issue, several approaches were applied to resolve the problem without modifying the EPANET code with achieved varying levels of success.

Increasing the accuracy on EPANET

EPANET parameters were the first and most obvious means to correct this problem. The relevant parameters (hydraulics accuracy, maximum trials and quality tolerance) were modified from their default values to increase model accuracy. No combination of those factors produced improvements. Minor fluctuations between Newton's method iterations limits the ability of the method to converge at very high accuracies.

Closing pipes

Using the MATLAB-Toolkit, pipes were closed when no demands were present at the downstream nodes using three schemes. First, pipes connected to dead-end nodes were closed when no terminal nodal demand occurred at the node. Only the final pipe of the branch was closed since its downstream node was the only location with a water age miscalculation. In the example, pipe 4 was closed for all time steps except for minutes 1380 through 1388. Pipes 7 and 8 were closed during periods of no downstream demands. This approach resolves the water age issue for the terminal nodes but introduces more significant errors in computed water age for nodes upstream of the closed pipe (Figure 5).

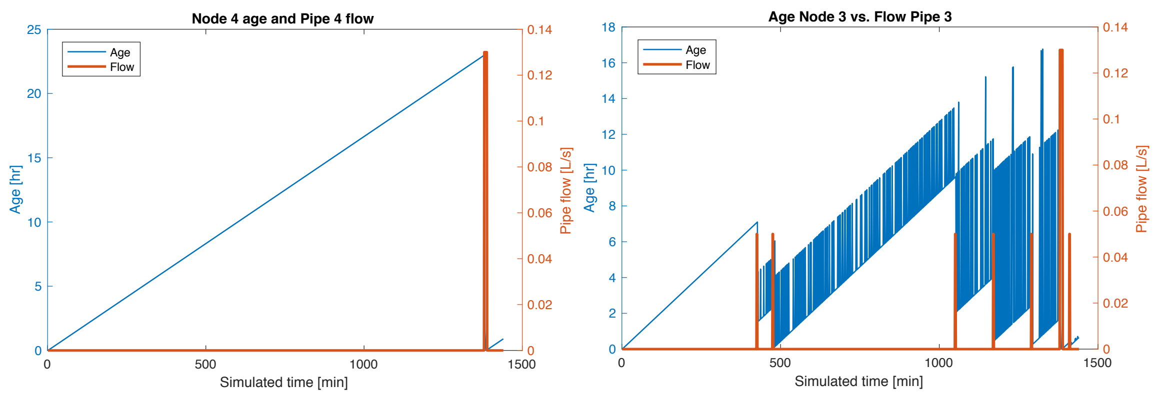

Figure 5: Resulting ages when closing pipes connecting to dead ends

In the second approach, all pipes in branches with no downstream demand were closed. This scheme solves the problem for the terminal node (node 4) but also introduces errors in upstream nodes (e.g., node 3). As seen in Figure 6, node 3's age drops suddenly then recovers when demands are applied.

The last approach consists of closing only the first pipe of a branch with no demand. This scheme does not solve the age-drop issue for the terminal node (node 4) and the water age time-series obtained is virtually identical to that for the first approach (Figure 3).

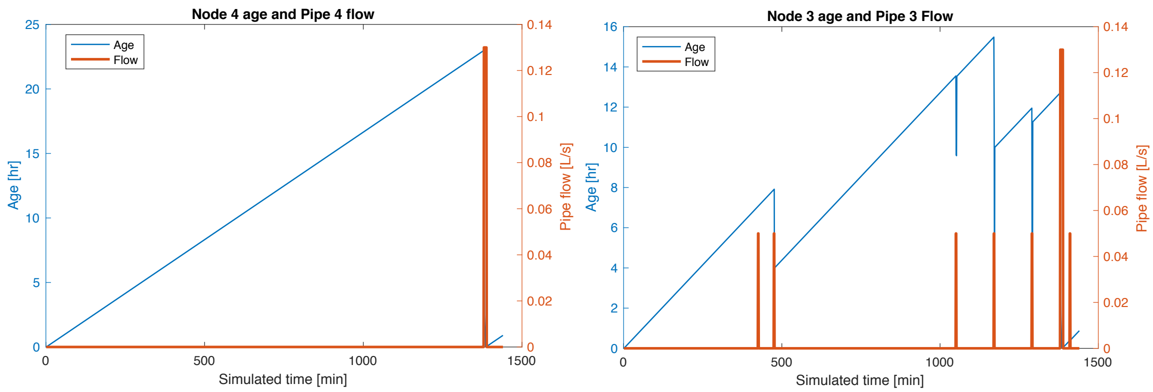

Figure 6: Age results when closing all pipes when downstream nodes have no demand

Introducing valves

To fully stop flow in the branched pipes, two types of valves are introduced under different configurations. A Flow Control Valve (FCV) was added. When the downstream nodes have no demand, its flow was setting to 0. Otherwise, its setting was equal to the demand or the sum of the overlapping downstream nodal demands. The results observed indicate the FCV has no impact on correcting the age-drop as its results are identical to the system without the valve (Figure 3).

In the noted on-line forum that reported the water age error in EPANET, another user suggested using Pressure Reducing Valves (PRV) at the start of each pipe branch with a setting of 0 psi, arguing that the PRV flow will converge to an absolute zero flow if there is no downstream demand[2]. This approach improved results for the terminal node (node 4) (Figure 7). Further, a preliminary inspection of results for node 3 also reveals consistent results as no artifacts as in Figures 5 and 6 are observed. However, a closer inspection of the node 3 water age reveals that the computed ages are in error. Age should drop between

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2 https://communities.bentley.com/products/hydraulics___hydrology/f/haestad-hydraulics-and-hydrology-forum/85626/epanet-age-problem

minutes 425 to 426 and 1170 to 1171 when demands are placed on node 3. The cumulative pipe volume upstream of node 3 is 0.8 gallons (3.04 liters) and the demand volume over those 2 minute block of 0.05 (L/s) demands is 6 L. That is, the volumetric demand is greater than the cumulative pipe volume upstream of the node and the entire pipe volume is replaced with fresh water during the single time step. This condition is not reflected with the PRV at the start of each branch approach.

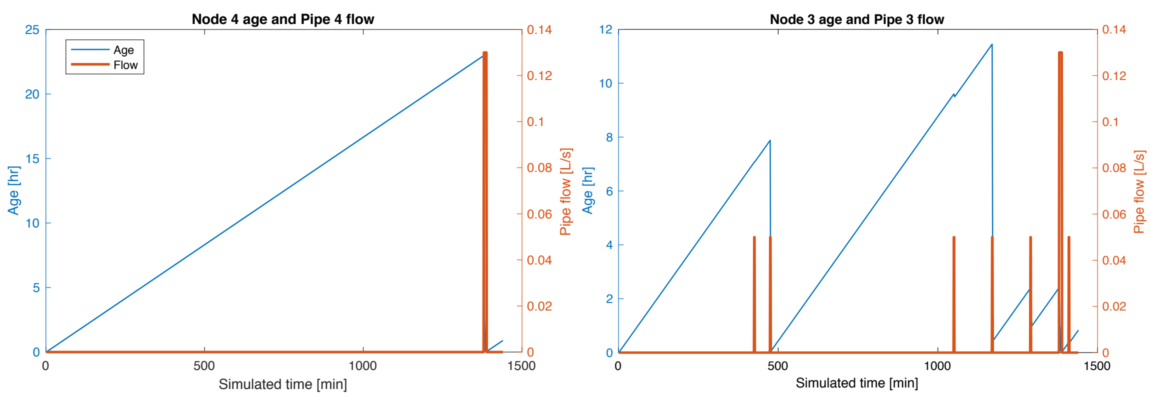

Figure 7: Age and flows obtained using PRVs at the start of each branch

Given the resulting ages using PRVs were the closest to the expected values, an alternative was to locate them at the pipe connected to terminal nodes (i.e., pipes 4, 7 and 8). The results for all nodes are as expected as illustrated in Figure 8 for nodes 4 and 3.

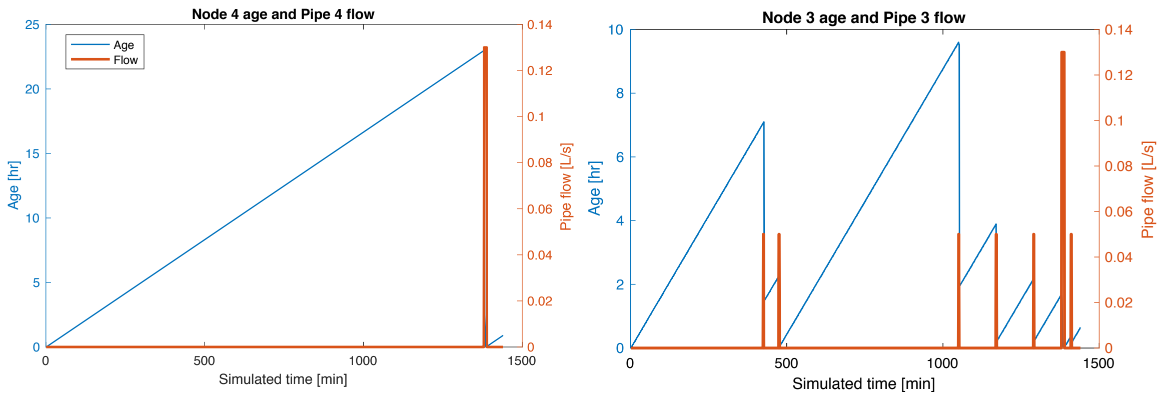

Figure 8: Age and flows obtained using PRVs at the dead-end pipes

Nonetheless and in spite of the preliminary good results for the PRVs approach at the dead ends, during long no demand periods for short pipes, water age misbehaves at upstream nodes. The results for a sequential network of 4 nodes with pipes of ½ in (12.7 mm) and 3.28 ft (1 m), and long periods of no demand (around 42 hours), are shown in Figure 9 for the first node and pipe. Water age does not drop, but it incorrectly plateaus. As a result, the PRV approach is also discarded.

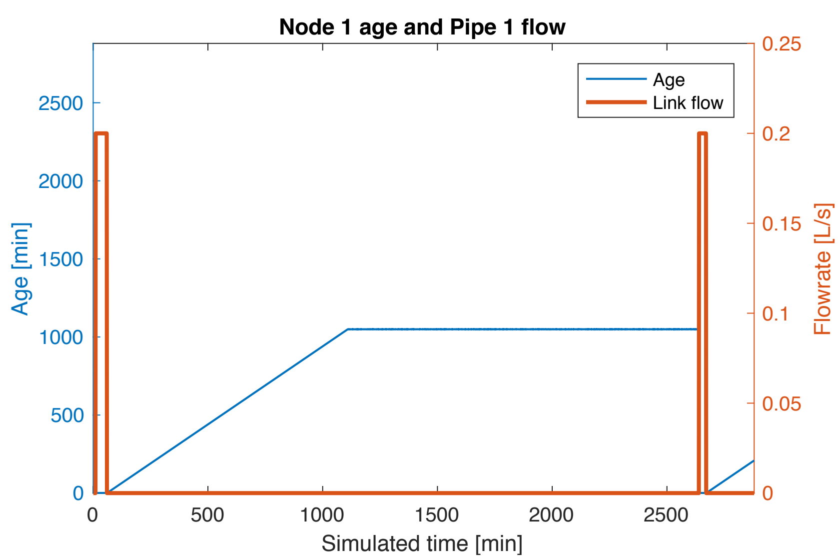

Figure 9: Age and flow for a sequential network comprised of 4 short pipes with long periods of no flow. Age plateaus in longs periods of no demand, incorrectly.

Modifying pipe volume

Water age issues occur in short small diameter pipes during under long periods of no demand including pipes that are not dead-ends. Our hypothesis is that these modeling errors are introduced by the low flow rates caused by inexact hydraulic solutions. The most efficient solution is likely to modify the EPANET source code to zero flows in branches that do not have downstream demands or turn off advective transport in those pipes during water quality modeling. Here, our goal is to perform hydraulic and water age analysis without altering the EPANET code.

The solution approach recognizes that these errors do not occur in water distribution size pipes because of their larger pipe volumes and long detention time with low flow rates. Therefore, the successful approach was to increase the pipe volumes during the water age analysis. However, changing the pipe volumes alters the system hydraulics thus a two-step process for modeling hydraulic and water age was required.

In branched networks, like most premises, pipe flow rates are demand driven and equal to the sum of the demands at downstream nodes, but withdrawals are not affected by the pressure at the node. The first step of the hydraulics/water age computation is to simulate the premise plumbing hydraulics as described in the following sections. This provides the flow and pressure distribution in the network.

To evaluate water age, pipe lengths and demands were multiplied by the same factor to maintain the volume/flow relationship. The demands determined in the hydraulic analysis above were then scaled by the same factor and applied to the enlarged network. Water age for the flow remains consistent with the expected case. Since the pipes are larger, the minor flows with zero demand become travel less distance in each time-step, and have little, if any, effect on the water age profiles (Figure 10) for the case where pipe lengths and demands were scaled by a factor of 2.

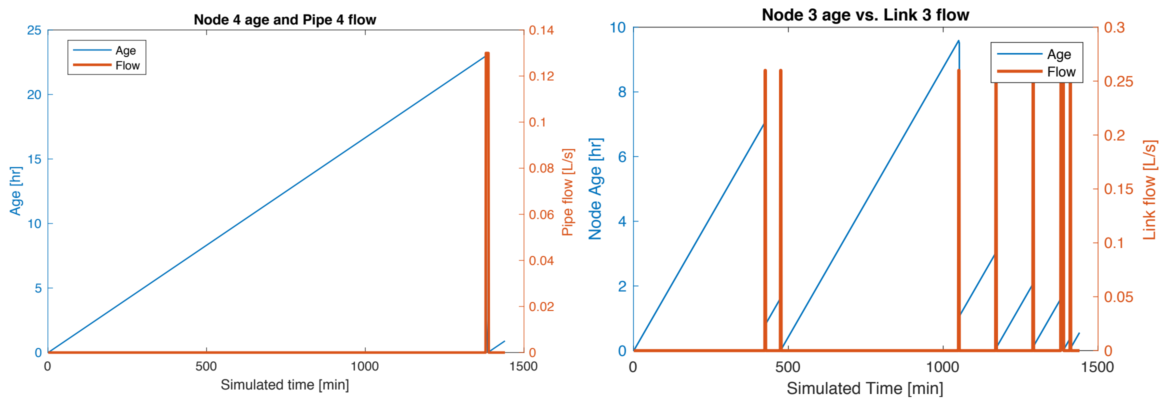

Figure 10: Age results for nodes 4 and 3 when increasing pipe lengths

However, it was found that for long periods of no demand and/or smaller volume pipes, larger factors are required to ensure consistent results. If the factor is too big, the hydraulic analysis does not converge as the longer pipe length and high velocities from the increased demands results in excessive head losses. Note that increasing the reservoir head does not solve this issue.

To overcome this problem, pipe diameters were scaled by the square root of the multiplier applied to nodal demands. This retained the volumetric ratio between demand and pipes and provided expected results, regardless of the multiplier, network, and duration of zero demands when a factor of 10 was used. These results are reproducible in EPANET as well as through the Toolkit (Figure 11).

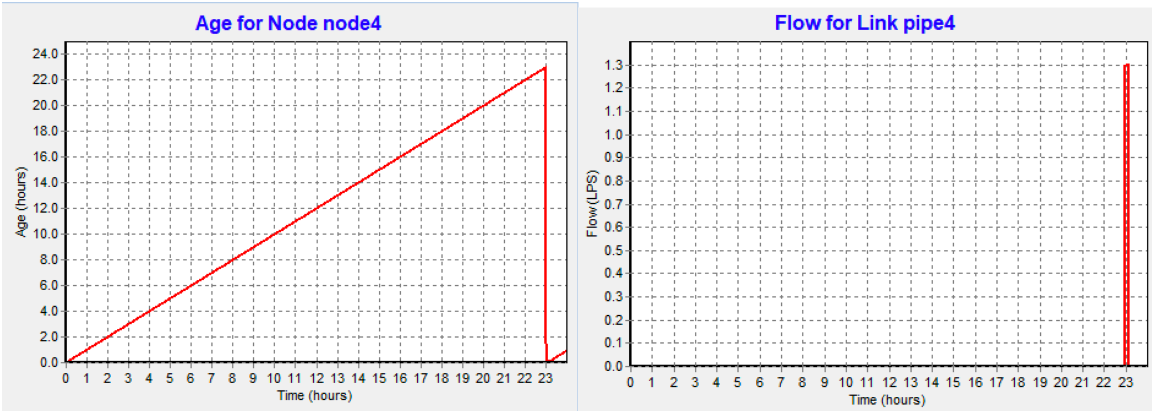

Figure 11: Age and pipe flow from EPANET, using the diameter factor approach

In summary, to overcome the issue of small diameter short pipes without modifying EPANET, a series of alternative schemes were tested to alter the premise plumbing system representation. Errors arose in all schemes except for scaling the diameters. Consequently, this approach is used in this thesis. Although it proved satisfactory in evaluating water age, it has the disadvantage that the pressures for the simulated demands must be computed twice: prior to and after modifying the diameters.

3.2. Stochastic demand generation model

To compute more realistic ages at each fixture, the usage patterns for the outlets are required at a small time-step. As was presented in the literature review, SIMDEUM (Blokker et al., 2010) is a stochastic end-use model for simulating demands at the fixture level. The model and adaptation for this study are presented in subsections 3.2.1 and 3.2.2, respectively.

3.2.1. SIMDEUM model and parameters

SIMDEUM is driven by the rectangular pulse model from Buchberger and Wells (1996). However, the probability density functions describing the time of use, intensity and duration are specified per end-use, rather than per fixture. Some fixtures have multiple uses, such as the kitchen tap that may be used for water consumption or for washing the dishes, and each use will have its own durations resulting in different model parameters. In addition, the parameters describing the probability density functions are retrieved from statistical data from water-use surveys and partly from technical information on water-using appliances instead of flow measurements (Blokker et al., 2010).

Within SIMDEUM, the household water demand pattern, Q, [L/s] is estimated by:

$$Q = \sum_{k=1}^{M} \sum_{j=1}^{N} \sum_{i=1}^{F_{jk}} B\left(I_{ijk}, D_{ijk}, \tau_{ijk}\right) \ \left[\frac{L}{s}\right]$$

$$B\left(I_{ijk}, D_{ijk}, \tau_{ijk}\right) = \begin{cases} I_{ijk} & \tau_{ijk} < T < \tau_{ijk} + D_{ijk} \\ 0 & elsewere \end{cases}$$

Where,

k	All end-uses from 1 to M
j	All users from 1 to N
I	All busy times per end-use from 1 to F_{jk}
F_{jk}	The frequency of use for user j and end-use k
D	Pulse duration [s]
I	Pulse intensity, equals to the flow [L/s]
τ_{ijk}	End-use start time (time of use)

End-uses (k)

Blokker et al. (2010) originally considered eight fixtures with fifteen end-use types. As noted, this model was developed in the Netherlands, but later Creaco et al. (2017) parametrized SIMDEUM using information from several sources that were relevant to the

Milford, Ohio field campaign. The list of fixtures and end-uses for the local study are shown in Table 8. When using this simulation model as a predictive tool, it is important to estimate the percentage of houses that possess a specific appliance (i.e., the penetration rate). Here, we assume known house plans and the fixtures.

Users (j)

The number and type of water users are the key model parameters for two reasons. First, the frequency of use is given per person. Second, the time of water use (τ_{ijk}) is strongly related to the users' diurnal patterns (presence at home and sleep-wake rhythms). Consequently, the ages and occupations of users must be defined: children (elementary school), teens (secondary school or college), adults with jobs in home, adults with jobs away from home and retired senior citizens (Blokker et al., 2010) (Table 9).

Frequency of use (F)

Within SIMDEUM, the number of uses (pulses) occurring through a day are modeled through their frequencies that are defined by the number of uses per person per day, except for the kitchen tap that is given in per household per day, as it is less related to individual users (Blokker et al., 2010) (Table 8). For most uses, the frequency is represented by a Poisson process with a single statistical parameter (average number of uses per day). A kitchen tap's use is represented by a negative binomial distribution.

Pulse intensity (I)

Given the occurrence of a particular use, the flow, in liters per second, for each end-use must be defined. Use rates by fixture were derived from water-use survey and appliances manuals (Table 8). For bathroom and kitchen taps, a uniform distribution was assumed for the intensity as the faucets are not always operated at the same flow (Blokker et al., 2010).

Pulse duration (D)

The demand duration of each end-use was originally determined by Blokker et al. (2010) using information of water surveys or from appliance manuals for dishwasher and washing machines. The water closet tank fill time is almost constant.

End-uses that involve human intervention are described with a log-normal distribution. The mean durations are listed in Table 8 by fixture. Their variances were assumed to be 130% of the mean value for taps and 50% for the showers. Alternatively, a χ^2 distribution can be used for the duration of the shower.

Table 8: SIMDEUM input parameters as used in Creaco et al. (2017)

Fixture	End-use type	Use %	Frequency [day^{-1}]		Duration [s]		Intensity [L/s]	
			μ	pdf	μ	pdf	μ	pdf
Bath (120 L)		100	0.128	Poisson	600	N/A	0.2	N/A
Bathroom tap	Washing and shaving	33	4.1	Poisson	40	Lognormal	0.16	Uniform
	Brushing teeth	67			15			
Dishwasher		100	0.25	Poisson	*Specific* (4x45 s, 0.17 L/s, 30 L)			
Kitchen tap	Consumption	37.5	12.7	Negative	16	Lognormal	0.167	Uniform
	Dishes	25		binomial	48		0.25	
	Washing hands	25		(3, 0.192)	15		0.167	
	Other	12.5			37		0.167	
Shower		100	0.7	Poisson	510	χ^2	0.139	N/A
Washing machine		100	0.37	Poisson	*Specific* (4x198 s, 0.19 L/s, 152 L)			
Water closer		100	5.05	Poisson	108	N/A	0.125	N/A

Start time of water use (τ)

Blokker et al. (2010) assumed that the start time of water use is strongly related to residents' diurnal patterns, i.e., low likelihood when people sleep and zero when they are away from home. The end-use model uses normal probability distributions to draw random numbers for the start time of each use based on residents' diurnal patterns as follows:

- During the sleeping hours, the total volume of water use is estimated to be 1.5% of the total daily demand.
- Peak hours are the half hour after getting up or returning home and the half hour before leaving home or going to bed. The fraction of the total demand occurring in these periods is 65%.
- The rest of the water use then corresponds to 33.5% of the daily water use.

Table 9: diurnal pattern statistics for the different people based on their activities

People's habit	Statistical parameter	Child	Teen	Adult w/out-of-home job	Adult w/o out-of-home job	Senior	Total
Time of getting up	μ	7:00	7:00	7:00	8:00	8:00	7:00
	σ	1:00	1:00	1:00	1:00	1:00	1:00
Time of leaving house	μ	8:15	8:15	8:00	13:00	13:00	8:00
	σ	1:45	1:45	1:45	3:00	3:00	1:45
Duration of being away	μ	7.25	7.25	8.00	6.00	6.00	7.75
	σ	2.80	2.80	3.40	3.00	3.00	3.30
Duration of sleep	μ	9.00	9.00	8.00	8.00	8.00	8.00
	σ	2.00	2.00	2.00	2.00	2.00	2.00

3.2.2. Adaptation of SIMDEUM for the present study

The demand simulator was adapted for the present study (named SIMUDEUM-UA) in three ways as described in the following paragraphs. As seen in Table 8, the duration, frequency and intensity are generated randomly from different probability density functions. The duration of the tap uses (for bathroom and kitchen taps) is described using a lognormal distribution, but the mean values are provided instead of the mean of the logarithms. These values are not the same so a normal distribution was used in the simulation model. Finally, Creaco et al. (2017) used a complex pattern for washing machines and dishwashers with 4 withdrawals during a wash cycle. Since they are closely spaced, a single total demand was used here to represent the total demand volume. The parameter set for the current model are summarized in Table 10:

Table 10: SIMDEUM input parameters used in the present study

Fixture	End-use type	Use %	Frequency [day^{-1}]		Duration [s]		Intensity [L/s]	
			µ	pdf	µ	pdf	µ	pdf
Bath (120 L)		100	0.128	Poisson	600	N/A	0.2	N/A
Bathroom tap	Washing and shaving	33	4.1	Poisson	40	Normal	0.16	Uniform
	Brushing teeth	67			15			
Dishwasher		100	0.25	Poisson	180	N/A	0.17	N/A
Kitchen tap	Consumption	37.5	12.7	Negative	16	Normal	0.167	Uniform
	Dishes	25		binomial	48		0.25	
	Washing hands	25		(3, 0.192)	15		0.167	
	Other	12.5			37		0.167	
Shower		100	0.7	Poisson	510	Normal	0.139	N/A
Washing machine		100	0.37	Poisson	792	N/A	0.19	N/A
Water closer		100	5.05	Poisson	108	N/A	0.125	N/A

The model here relates the total use by fixture type for each resident in a household. In homes with multiple fixtures of the same type (i.e., 3 water closets), the demand by individual fixture is required.. Without specific information on the distribution of use, the likelihood of selecting each fixture is assumed to be the same.

Lastly, demands were split between cold and hot water. While water closets only require cold water, the dishwashers use only hot water. Other fixtures use a mixture of hot and cold water to meet their target temperature. The source water temperatures are 55°F (12.8°C) and 140°F (60°C) for cold and hot water, respectively. The target temperature along with the resulting proportions are shown in Table 11 for each fixture.

Table 11: Target temperature, cold and hot water use percentages for each fixture

Fixture	Target temperature		Cold	Hot
	°F	°C	[%]	[%]
WC	55	12.8	100	0
Dishwasher	140	60.0	0	100
Shower	105	40.6	41.2	58.8
Bath	105	40.6	41.2	58.8
Bathroom tap	97.5	36.4	50	50
Kitchen tap	97.5	36.4	50	50
Washing machine	97.5	36.4	50	50

3.3. Household models

The third component needed to calculate the effects of different plumbing layouts on residential water age is plumbing system configurations. To form the hydraulic model, pipe lengths and fittings for the cold and hot water systems must be known. Given a building plan with known fixture locations, a Computer Aided Design (CAD) model can draw alternative plumbing systems at scale and lengths determined. The next two subsections present CAD models for two houses analyzed in this study. Their actual plumbing layouts are shown and described in Appendix A. Only branched systems were tested.

3.3.1. House 1

House 1 is a 1300 ft^2 (120 m^2) two story home, with 3 bedrooms and 2.5 bathrooms. CAD plans displaying the nodes (fixtures) are shown in Figures 12 and 13 for the cold system and the hot system, respectively. Fixture types and their use percentages are summarized in Table 12. Demands were simulated for four residents; 2 teens and 2 adults; one with and one without a job outside of the home.

Table 12: house 1 node description and usage percentages when multiple fixtures of a kind exist

	Cold system			Hot system		
	Number	**Description**	**Usage %**	**Number**	**Description**	**Usage %**
	1	Water heater		13	Water heater	
	2	Kitchen sink		14	Kitchen sink	
	3	Washing machine		15	Dish washer	
1st floor master bedroom	4	Bath tube/shower 1	50	16	Washing machine	
	5	WC1	50	17	Bath tube/shower	50
	6	Bathroom tap 1	50	18	Bathroom tap 1	50
Aux restroom	7	WC2	20	19	Bathroom tap 2	20
	8	Bathroom tap 2	20	20	Shower	50
2nd floor bathroom	9	Shower 2	50	21	Bathroom tap 3	30
	10	WC3	30			
	11	Bathroom tap 3	30			

Peak demand estimation in House 1's branches

To use the q_1+q_3 method described in the literature review (Buchberger et al., 2017), the fixtures along a branch are first ranked. In this study, ranking is done on a room by room basis using the cold-water demands specified in the International Plumbing Code (IPC) (Table 4). The exception is the dishwasher machine that is placed on the hot water system. The cold-water pipes are sized first. The corresponding hot water system pipes are assumed to the same diameter that results in a conservative design for the hot water system. Table 13 lists house 1's peak demand estimates for all layouts.

Table 13: Peak demand estimation for house 1

			Demand		Demand for analysis		
Room	**Node**	**Description**	**[GPM]**	**[L/s]**	**Rank**	**[GPM]**	**[L/s]**
1	15	Dishwasher	2.75	0.17	1	2.75	0.17
1	2	Kitchen sink	2.5	0.16	2	0	0.00
1	3	Washing machine	2.5	0.16	3	2.5	0.16
2	4	Bath tube/shower 1	3	0.19	1	3	0.19
2	5	WC1	3	0.19	2	0	0.00
2	6	Bathroom tap 1	2.5	0.16	3	2.5	0.16
3	7	WC2	3	0.19	1	3	0.19
3	8	Bathroom tap 2	2.5	0.16	2	0	0.00
4	9	Shower 2	3	0.19	1	3	0.19
4	10	WC3	3	0.19	2	0	0.00
4	11	Bathroom tap 3	2.5	0.16	3	2.5	0.16
		$\sum$	30.25	1.91		19.25	1.21
						Reduction [%]	**36.36**

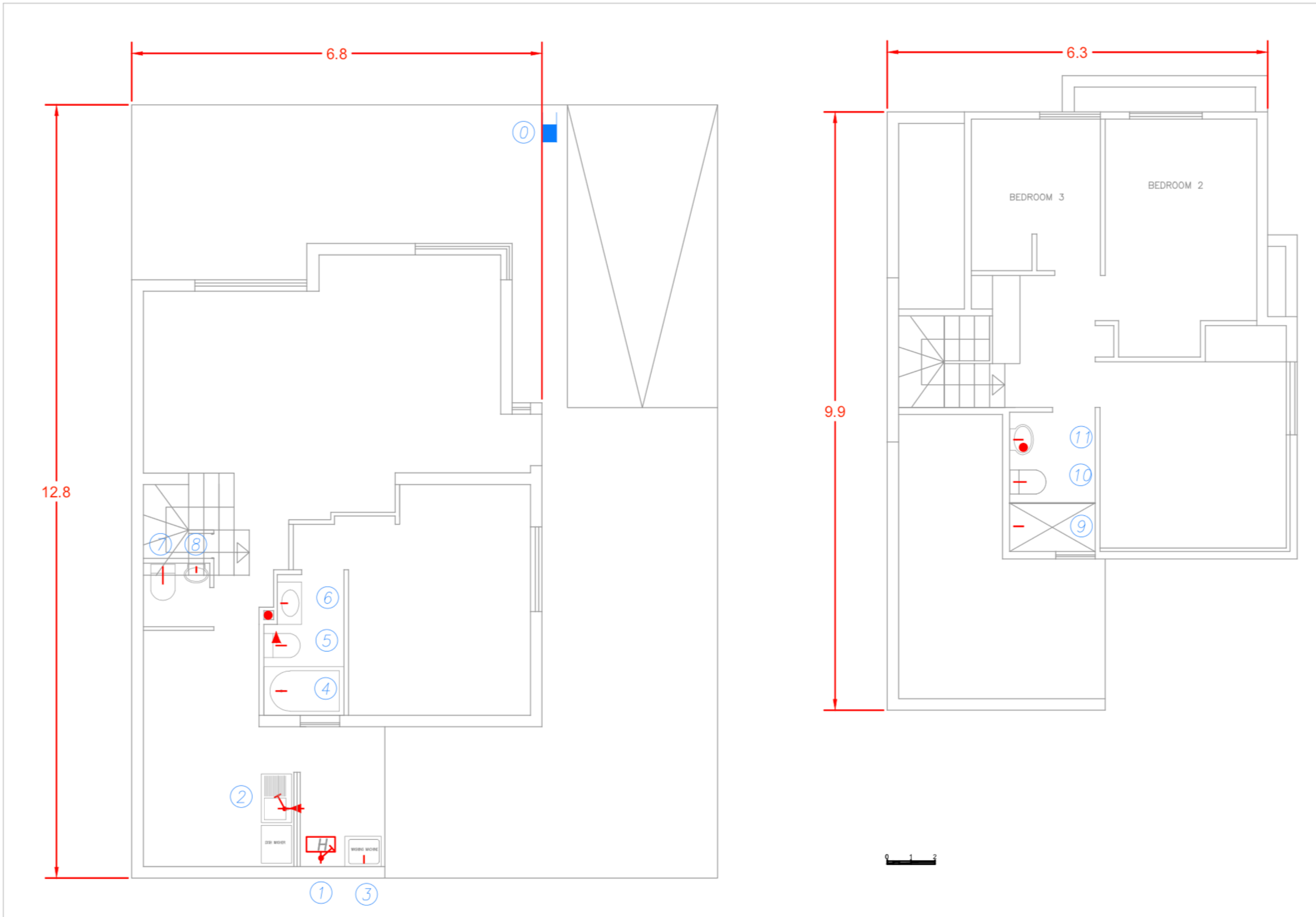

Figure 12: house 1 plan, including the nodes for each fixture in the cold system. Measurement in meters

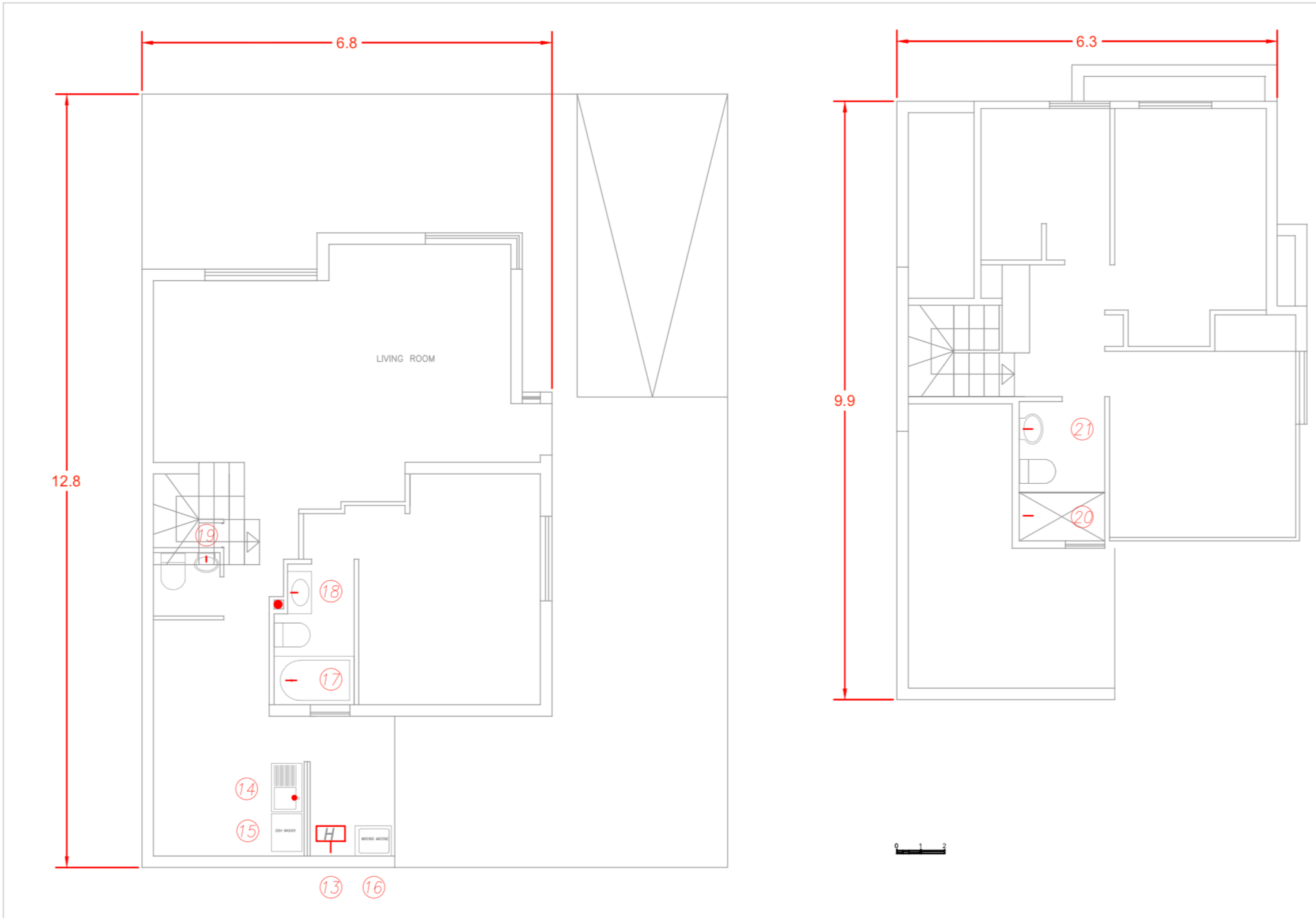

Figure 13: house 1 plan, including the nodes for each fixture in the hot system. Measurement in meters

3.3.2. House 2

House 2 is a 4050 ft^2 (376 m^2) single story house, with 4 bedrooms and 3.5 bathrooms. The layout was taken from Pepper Viner's website[3]. Five people are assumed to live in this house; 2 adults with a job outside of the home, 2 teens and 1 senior citizen. The fixture types and their usage rates are summarized in Table 14. The usage percentages for the house's fixtures are computed as one over the number of fixtures of that type given no better information is available. The CAD plan is shown in Figure 14 with cold and hot fixture locations.

Table 14: house 2 node description and usage percentages when multiple fixtures of a kind exist

Cold system			**Hot system**		
Number	**Description**	**Usage [%]**	**Number**	**Description**	**Usage [%]**
1	Water heater		21	Water heater	
2	Bathroom tap 1	16.7	22	Bathroom tap 1	16.7
3	WC 1	25.0	24	Shower 1	33.3
4	Shower 1	33.3	25	Dishwasher	
5	*Unpopulated*		26	Kitchen sink	
6	Kitchen sink		27	Washing machine	
7	Washing machine		28	Shower 2	33.3
8	Shower 2	33.3	30	Bathroom tap 2	16.7
9	WC 2	25.0	31	Bathroom tap 3	16.7
10	Bathroom tap 2	16.7	32	Bathroom tap 4	16.7
11	Bathroom tap 3	16.7	35	Bathroom tap 5	16.7
12	Bathroom tap 4	16.7	36	Bathtub	
13	WC 3	25.0	37	Bathroom tap 6	16.7
14	WC 4	25.0	38	Shower 3	33.3
15	Bathroom tap 5	16.7			
16	Bathtub				
17	Bathroom tap 6	16.7			
18	Shower 3	33.3			

[3] https://www.pepperviner.com/house-plans-custom-homes/custom-home-floor-plans/#prettyPhoto[gallery_slider_6]/0

Peak demand estimation in House 2's branches

Table 15 lists the estimated peak demands for sizing House 2 pipes.

Table 15: Peak demand estimation for house 2

			Demand		Demand for analysis		
Room	**Node**	**Description**	**[GPM]**	**[L/s]**	**Rank**	**[GPM]**	**[L/s]**
1	25	Dish washer	2.75	0.17	1	2.75	0.17
1	6	Kitchen sink	2.5	0.16	2	0	0.00
2	3	WC 1	3	0.19	1	3	0.19
2	4	Shower	3	0.19	2	0	0.00
2	2	Bathroom tap 1	2.5	0.16	3	2.5	0.16
3	7	Washing machine	2.5	0.16	1	2.5	0.16
4	9	WC 2	3	0.19	1	3	0.19
4	8	Shower	3	0.19	2	0	0.00
4	11	Bathroom tap 2	2.5	0.16	3	2.5	0.16
4	10	Bathroom tap 3	2.5	0.16	4	0	0.00
1	13	WC 3	3	0.19	1	3	0.19
2	12	Bathroom tap 4	2.5	0.16	2	0	0.00
1	16	Bathtube	4	0.25	1	4	0.25
2	14	WC 4	3	0.19	2	0	0.00
3	18	Shower	3	0.19	3	3	0.19
4	15	Bathroom tap 5	2.5	0.16	4	0	0.00
5	17	Bathroom tap 6	2.5	0.16	5	0	0.00
		$\sum$	47.75	3.01		26.25	1.66
					Reduction [%]		**45.0**

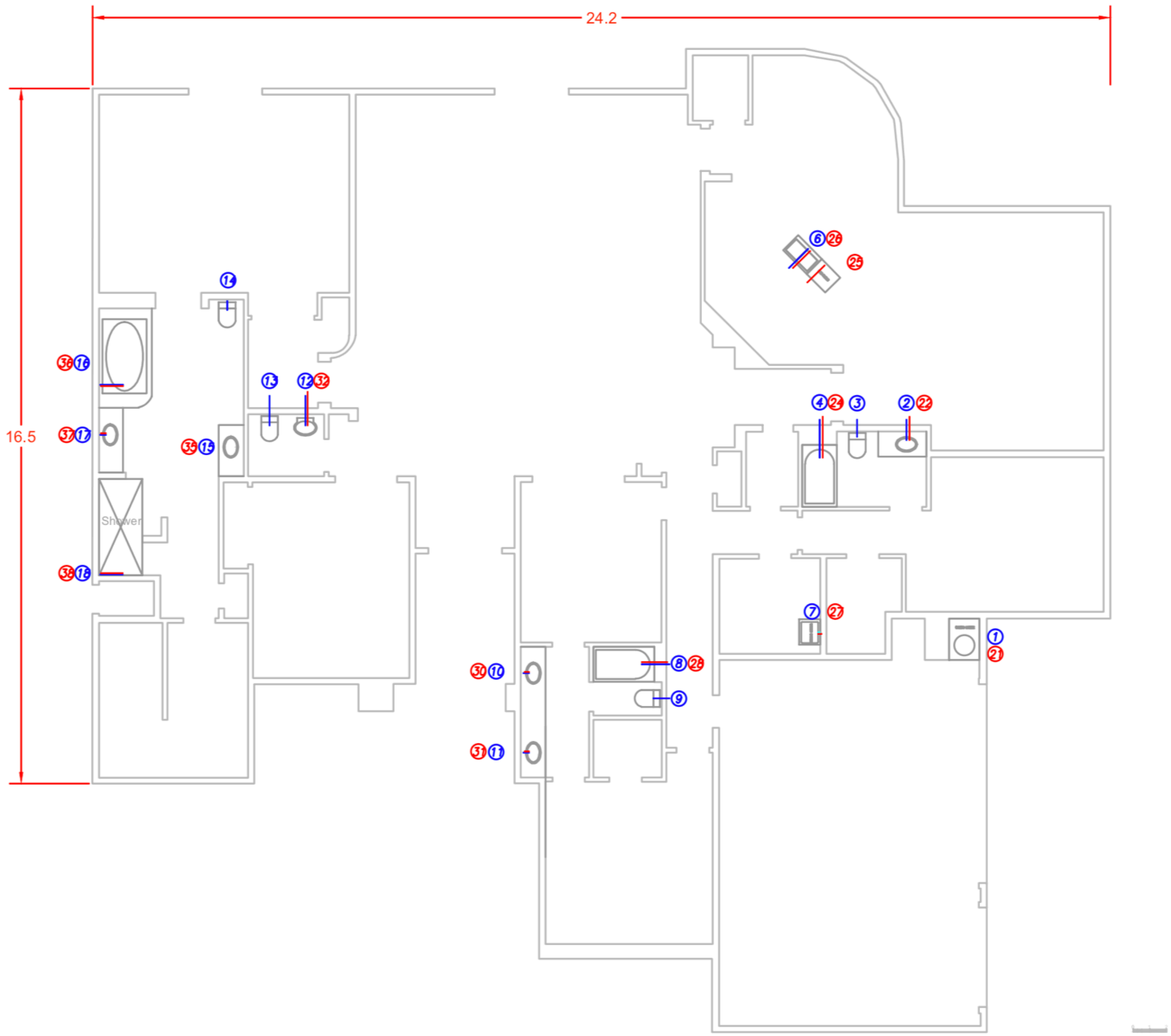

Figure 14: house 2 CAD plan, the blue circles are the nodes with cold water fixtures, while the red ones for hot water fixtures

3.4. Metrics to describe water age

Applying the methodology described in the previous sections, the water age is obtained at each node at each minute for 30 and 90 days (two different independent simulations, each with its own seed for generating random calls). Fixtures that withdrawal hot and cold water are modeled using 4 nodes (one for each cold and hot system at the outlet, plus two more at the point of connection to the residential distribution pipe), as described on subsection 3.1.2). Thus, a substantial set of data is generated, and an understandable reduced set of metrics are computed to characterize water quality and compare the effects of layout design.

- **Absolute maximum age (Abs. max.)**: Corresponds to the absolute maximum age observed at any node during the simulation period.
- **Mean maximum age (Mean max.)**: The maximum age is computed per node for the whole simulation period and the mean maximum age over all nodes is determined.
- **Grand mean age (Mean)**: The mean age is computed per node for the whole simulation period. Then, the grand mean age corresponds to the direct average of all demand nodes mean age.

Metrics are computed for pipe outlet (i.e. point of water use) and in the distribution pipe (upstream the stub connecting to the point of use) for the cold-water network and the hot-water system.

A secondary goal is to understand whether the pipe sizing code requirements are overly conservative or liberal. To that end, the minimum pressures at any time step are computed at each demand node in the network for the entire simulation period, and the results are compared with the pressures obtained using the q_1+q_3 peak discharge method for the code's (ICC, 2012) fixture demands (Table 4).

3.5. Mathematical model and general procedure

To evaluate system hydraulics and compute water residence times, EPANET 2.1 was coupled with the MATLAB-Toolkit. The base pipe networks were collected from plumbing layouts using the scale CAD models of the two houses (Figures 12 and 13 for house 1, and 14 for house 2). Pipe lengths are measured, and the number and type of fittings are counted. This information is input in the EPANET models described above. The fittings counted in the CAD model are used to calculate the minor loss coefficients for each pipe, while the friction losses were computed using Darcy-Weisbach equation.

To overcome numerical issues and erroneous water ages calculated by EPANET when modeling short, small diameter pipes that are impacted by periods of no demand, base demands and pipe diameters were scaled by a factor of 10 and the by the square root of 10, respectively (subsection 3.1.4.). Demands are generated using SIMDEUM-UA with a one-minute time step for each fixture type for each household. The entire simulation was of 30 and 90 days, both using different seeds (hence, 30 is not a subset of 90 days).

CHAPTER 4 - RESULTS

Using the tools described in Chapter 3, alternative configurations and operations are examined for houses 1 and 2 hydraulic and water age conditions in premise plumbing systems. The chapter's first section compares the design pressure head estimates from the IPC demands with those computed using the simulated demands. Second, the impact of layout variations on water age is assessed with a traditional tank heater within all configurations. Next, the effect of water heater type on hot water residence time is examined by simulating the same tested layouts using tank and instant water heaters. Finally, the effects of auto-flushers on systems with instant heaters is examined for Legionella control through high temperature flushing, as recommended by the WHO (2007) (section 2.3.4.)

In all applications, water age is computed at the outlet of the fixture/node (i.e. the actual withdrawal point) and at the connecting point of the distribution pipe, as described on section 3.4. The water age is computed relative to flow entering the service pipe.

4.1. Pressure results from the plumbing code and from the simulations

To document that the q_1+q_3 method is appropriate for sizing premise plumbing pipes, the pressure heads obtained for the different fixtures using the estimated peak demands from the q_1+q_3 method (Table 13 for house 1, Table 15 for house 2) are compared with the minimum pressures obtained from the 90-day simulated demands (Tables 16 and 17).

Table 16: Pressures required and obtained for each node in meters of water, using the Uniform Plumbing Code and simulated demands for house 1

		Layout 1		Layout 2		Layout 3	
Node	**Required**	**Code**	**Simulation**	**Code**	**Simulation**	**Code**	**Simulation**
Water heater	0	21.63	19.21	21.63	19.21	23.75	25.70
Kitchen sink	5.63	23.16	22.06	23.16	22.06	23.62	26.40
Washing machine	5.63	21.49	20.10	21.49	20.10	24.04	26.71
Bath tube/shower 1	5.63	23.84	26.86	23.84	26.86	22.58	26.59
WC1	14.07	24.05	26.84	23.98	26.84	22.72	26.57
Bathroom tap 1	5.63	23.71	26.71	23.81	26.73	22.54	26.46
WC2	14.07	21.15	26.69	20.99	26.61	20.62	26.48
Bathroom tap 2	5.63	21.48	26.76	21.52	26.77	21.34	26.50
Shower 2	5.63	16.12	23.31	16.40	23.33	14.22	22.98
WC3	14.07	16.69	23.20	16.73	23.11	14.54	22.77
Bathroom tap 3	5.63	16.69	23.41	16.73	23.42	14.55	23.07
Dishwasher	5.63	21.00	18.30	21.00	18.30	23.12	24.79

Table 17: (cont.) Pressures required and obtained for each node in meters of water, using the code and simulated demands, for house 1

		Layout 4		Layout 5	
Node	**Required**	**Code**	**Simulation**	**Code**	**Simulation**
Water heater	0	25.62	25.52	25.27	25.63
Kitchen sink	5.63	25.92	25.95	25.61	26.49
Washing machine	5.63	25.47	26.40	25.12	26.52
Bath tube/shower 1	5.63	24.55	27.13	20.65	25.37
WC1	14.07	25.13	27.16	20.80	24.87
Bathroom tap 1	5.63	25.14	27.19	20.38	24.71
WC2	14.07	25.64	27.53	22.67	26.14
Bathroom tap 2	5.63	25.97	27.53	22.99	26.24
Shower 2	5.63	19.25	23.82	19.02	23.73
WC3	14.07	19.82	23.76	19.59	23.67
Bathroom tap 3	5.63	19.82	24.01	19.59	23.91
Dishwasher	5.63	24.91	24.67	24.56	24.54

Pressure heads computed using the IPC demands are almost always greater than the pressures from the simulated conditions in EPANET, with the water heater and the dishwasher being frequently the exception as the code demands were applied to the cold water system and the dishwasher only has hot water demand in the simulated demands. The maximum difference is 8.76 m (12.5 psi) for the second-floor shower and the mean difference is 2.8 m (4.1 psi). These results indicate the code is being conservative, even with the q_1+q_3 method for peak demands.

For house 2 (Table 18), the higher pressures from the simulated demands are consistently higher than the IPC demand conditions, reinforcing the conclusion that the code demands are conservative, as the maximum difference is 11.60 m (16.49 psi) and the mean difference is 8.6 m (12.2 psi).

Table 18: Pressures required and obtained for each node in meters of water, using the code and simulated demands for house 2

		Layout 1		Layout 2		Layout 3	
Description	**Required**	**Code**	**Simulated**	**Code**	**Simulated**	**Code**	**Simulated**
Water heater	0	21.12	26.88	21.12	26.88	16.63	25.46
Bathroom tap 1	5.63	15.40	26.15	17.20	26.56	15.29	25.43
WC 1	14.07	14.96	25.87	16.92	26.30	15.17	25.25
Shower 1	5.63	15.28	25.52	18.97	26.59	15.78	25.41
Kitchen sink	5.63	15.28	25.48	19.49	26.78	16.33	25.52
Washing machine	5.63	19.70	26.82	19.70	26.82	16.61	25.60
Shower 2	5.63	18.81	25.74	18.93	26.42	17.36	25.42
WC 2	14.07	18.22	25.83	18.36	26.57	17.16	25.74
Bathroom tap 2	5.63	18.44	26.36	17.66	26.61	18.94	26.10
Bathroom tap 3	5.63	17.83	26.06	17.61	26.59	18.25	25.88
Bathroom tap 4	5.63	17.85	26.65	15.01	26.27	20.04	26.82
WC 3	14.07	17.41	26.65	14.67	26.27	19.71	26.82
WC 4	14.07	17.69	26.64	15.50	26.32	20.53	26.87
Bathroom tap 5	5.63	17.69	26.40	15.37	26.01	20.40	26.56
Bathtub	14.07	16.49	26.40	15.15	26.29	20.19	26.84
Bathroom tap 6	5.63	17.15	26.63	15.96	26.48	20.99	26.97
Shower 3	5.63	15.95	26.61	16.32	26.56	21.09	26.98
Dish washer	5.63	18.43	25.15	19.98	26.10	15.47	24.58

Since the simulated demands are generated stochastically, a different seed will generate a different set of pressure and a longer simulation will likely result in lower simulated pressures. Further, the method to estimate peak demands involves grouping the demand per branch/room, and a different layout will result in different peak demands.

4.2. Impact of layout configuration on water age

4.2.1. House 1

Water age at each fixture in House 1 is computed for the five layouts shown in Appendix A. Tables 19 and 20 summarize the comparison metrics described on Chapter 3. Extended metrics are listed in the electronic supplemental material.

To interpret these results, the House 1 layouts are described and compared. Layout 1 is a typical design that meets the pressure requirements and minimizes pipe cost by connecting segments in the most direct path. Layout 2 follows the same configuration as Layout 1 except that the water closets are connected at the end of branches. When WC's are flushed the water in the branch is replaced with fresh water with the goal of reducing water age in the entire branch (Hypothesis 2 on Section 1.1), given a 1.6 gallon (6 liters) flush is capable of draining 69.1 ft (21.1 m) of ¾ inch pipe.

To reduce water age in the hot water system, Layout 3 is a one-branch system with the heater placed at one of the most upstream nodes. Finally, Layouts 4 and 5 are highly branched and flushing the lines during normal use is not effective given the configuration of fixtures on the branches. These layouts are considered poor designs from a water age perspective and demonstrate the range for the possible results for this sized home.

Random demand patterns are developed for 30 and 90 day durations. Since the daily pattern varies over time, statistics on water age change with the time series duration. For any statistical sample, results should converge if the series is sufficiently long. Here, we limit the series to 90 days.

Table 19: Results summary for house 1 layouts, simulation 30 days, ages computed at the outlet nodes

Simulation time [day]		30				
Location		At the outlet				
				Layout		
		1	**2**	**3**	**4**	**5**
Cold	**Abs. max [hr]**	58.2	58.2	58.3	58.1	58.1
	Mean max [hr]	36.0	35.8	35.8	35.9	37.6
	Mean [hr]	9.0	8.7	9.0	8.8	9.2
Hot	**Abs. max [hr]**	68.7	68.7	68.7	68.7	68.7
	Mean max [hr]	55.4	55.4	56.2	55.8	56.6
	Mean [hr]	21.2	21.2	21.0	21.4	22.2

Table 20: Results summary for house 1 layouts, simulation 90 days, ages computed at the outlet nodes

Simulation time [day]		90				
Location		At the outlet				
				Layout		
		1	**2**	**3**	**4**	**5**
Cold	**Abs. max [hr]**	86.9	86.9	87.1	86.9	86.9
	Mean max [hr]	46.8	45.9	42.1	50.5	51.6
	Mean [hr]	10.6	10.1	10.2	10.0	10.2
Hot	**Abs. max [hr]**	96.7	96.7	96.8	126.3	115.3
	Mean max [hr]	65.3	65.3	65.2	78.4	78.3
	Mean [hr]	24.2	24.2	24.0	25.3	26.1

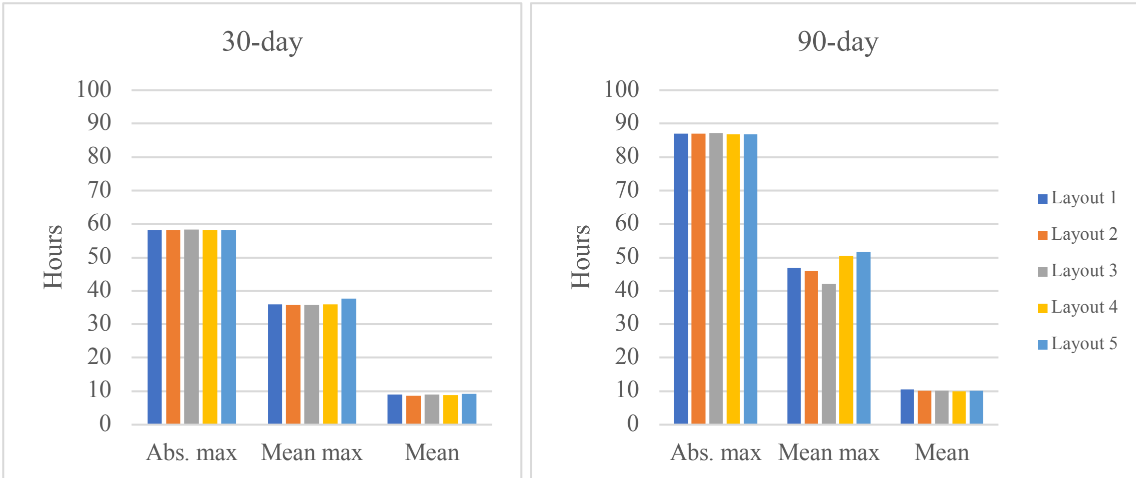

Figure 15: Results summary for house 1, cold-system, at the outlet.

As seen in Tables 19 and 20, and Figure 15, the absolute maximum age (i.e. at any time and any node) is fairly constant regardless of the layout configuration. A change occurs between 30 and 90 days (Figure 15) due to the higher likelihood of an extreme low demand day in the longer sequence. The conclusions also hold true for the mean maximum age (average of the maximum ages in each node) and the mean age (grand mean of all the mean ages in each node).

The mean residence times for the cold-water system is around 9 hours for a 30-day simulation and a slightly greater than 10 hours for a 90-day simulation. On the other hand, the hot water mean residence time is around 21 hours for the shorter simulation and over 24 hours for the longer sequence. This result demonstrates that traditional water heaters have a significant residence time due to their capacity (50 gallons in this home).

Water ages do not vary significantly except for layouts 4 and 5. These layouts were expected to have long residence times given their configurations, as described earlier. In closer examination, the volume of water with extreme ages are very small. This water is associated with the volume of water in the pipe stubs connecting the fixture with the residential distribution pipes. To confirm this assessment, water age statistics were computed for the junction of the distribution with the stub pipe for each fixture to eliminate the long idle times in the stubs from water age calculations. The junction age data are listed in Tables 21 and 22 and shown Figures 16 and 17.

Table 21: Results summary for house 1 layouts, simulation 30 days, ages computed at the distribution pipe

Simulation time [day]		30				
Location		At the distribution pipe				
				Layout		
		1	**2**	**3**	**4**	**5**
Cold	**Abs. max [hr]**	58.2	19.9	21.0	58.1	58.1
	Mean max [hr]	22.7	13.0	13.6	31.1	23.8
	Mean [hr]	5.8	3.2	3.8	7.5	6.2
Hot	**Abs. max [hr]**	67.3	67.3	67.3	67.4	67.4
	Mean max [hr]	44.6	44.6	43.0	51.0	46.0
	Mean [hr]	16.6	16.6	16.0	18.5	17.7

Table 22: Results summary for house 1 layouts, simulation 90 days, ages computed at the distribution pipe

Simulation time [day]		90				
Location		At the distribution pipe				
				Layout		
		1	**2**	**3**	**4**	**5**
Cold	**Abs. max [hr]**	86.9	21.0	24.3	86.9	86.9
	Mean max [hr]	31.3	15.3	16.1	44.7	34.1
	Mean [hr]	7.0	3.5	4.3	8.4	7.1
Hot	**Abs. max [hr]**	96.3	96.3	96.8	98.9	98.9
	Mean max [hr]	55.7	55.7	51.7	67.6	61.4
	Mean [hr]	19.8	19.8	19.2	21.3	20.3

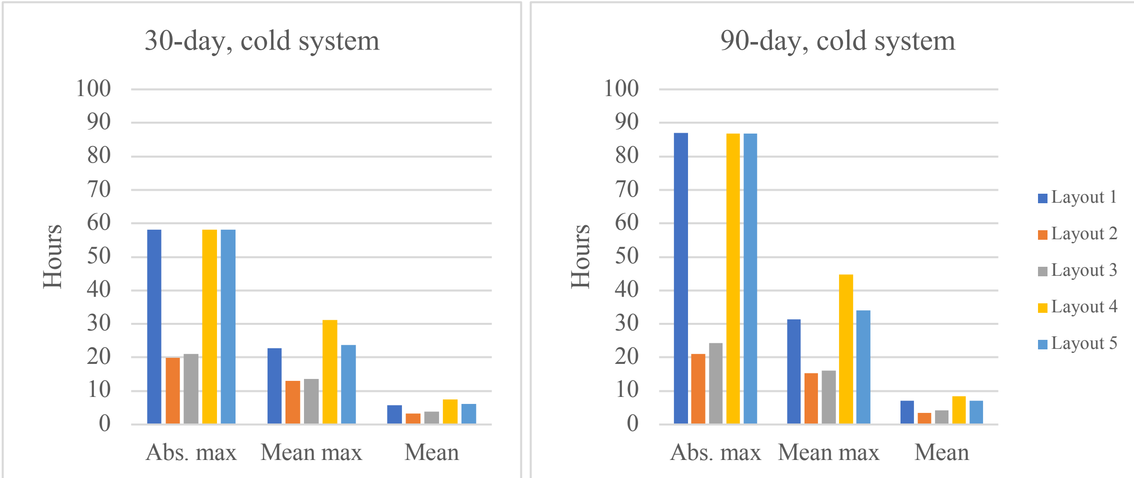

Figure 16: Results for house 1, cold-system, at the distribution pipe.

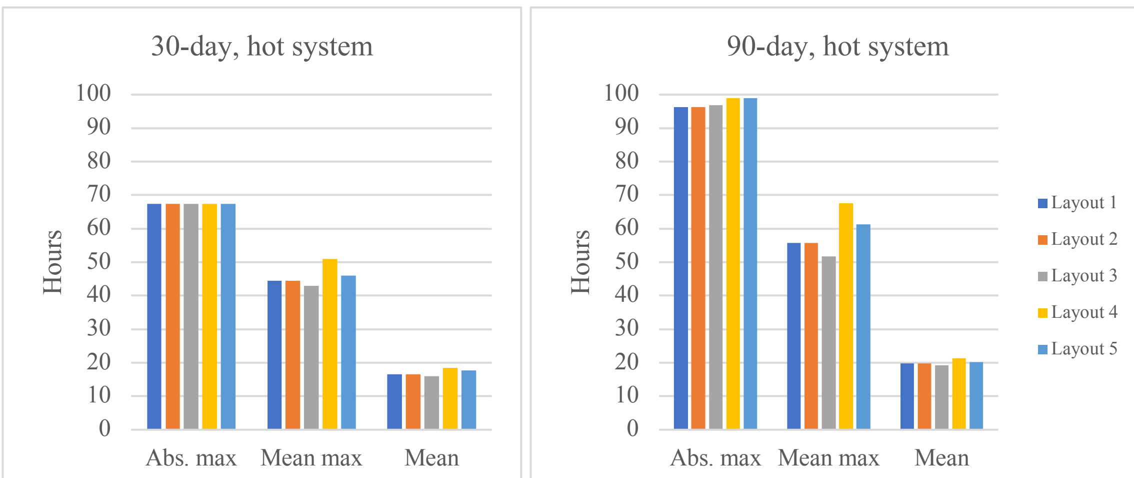

Figure 17: Results for house 1, hot-system, at the distribution pipe.

In cold water network, the layout is seen to have a significant impact on water age in the premise plumbing pipes. In particular, layout 2 that is almost identical to layout 1 except that the water closets are located at the end of pipe branches has an absolute maximum water age (ABWA) that is a quarter of layout 1's ABWA value. Similarly, layout 2's mean water age is about half of that in layout 1. Layout 3, the single branch system, is also a substantial improvement over layout 1, but not as effective as layout 2. The single branch has a significant volume that is not fully renewed with single toilet flush, so some old water remains in the system for longer periods of time.

The expected poorest design, Layout 4 has the poorest results with a mean and mean maximum water ages that are 30% and 37% greater than the expected traditional design (layout 1). The difference between the best (layout 2) and the worst (layout 4) when looking at the 90-day simulation, is 75.8%, 65.8%, and 58.6% for the absolute maximum, the mean maximum, and mean water ages, respectively.

Comparing the results in Tables 19 and 20 with 21 and 22, it is confirmed the stubs have a significant impact on water age and layout modifications are not effective in decreasing maximum water age at the point of use when considering those pipes. The water age in a pipe stub is governed by the fixture's idle times. However, the volume of the stubs is quite small, around 0.017 gallons or less than a quarter cup (0.063 liters). This implies the first flush of water coming out of the fixture may be quite old, but the water age will quickly have a significantly lower age.

On the other hand, and as seen in Figure 17, the premise plumbing layout's impact on hot-water residence times is much smaller than for the cold-water system as the strategy to reduce ages is primarily placement of the water closets at the terminus of branches. Given this is not generally considered as an option for hot water systems as typically the toilets are not connected to the hot water system, their results do not significantly change across the five designs. This situation is further discussed in section 4.4.

4.2.2. House 2

Three layouts were examined for House 2. Layout 1 is a traditional design, with small branches distributing water to each bathroom and kitchen. The main premise distribution pipe diameter decreases in the downstream direction as less water is conveyed to fewer fixtures. Layout 2 is similar to 1 but the design improvements identified for House

1 were included; water closets were connected at the end of the branches where possible and two branches were replaced by a continuous pipe. For layout 3, the main change compared to Layout 1 is to move the water heater downstream in the premise distribution pipe to examine the location impact on hot water age.

All water age statistics for House 2 range from 0 to 200 hours. Tables B-8 and B-9 in Appendix B and Figures 18 and 19 herein summarize the results obtained at the fixtures for simulation periods of 30 and 90 days, respectively.

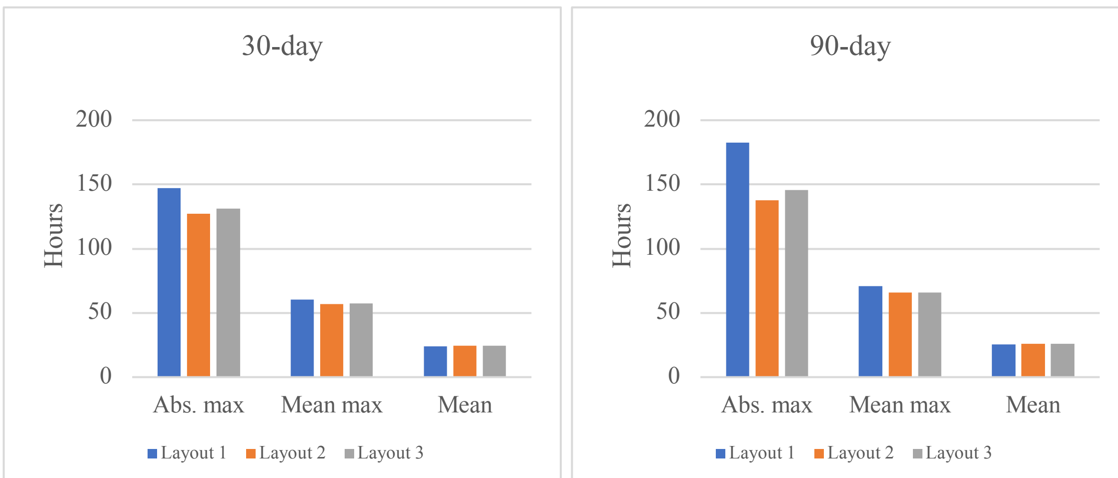

Figure 18: Results summary for house 2, cold-system, at the outlet

The mean residence time is about 24 and 60 hours for the cold and hot water, respectively, during the 30-day simulation for all designs. During the 90-day simulation, the cold and hot mean ages increased slightly to 25.5 and 63 hours, respectively. Compared with house 1, which is about one third of the size, the mean residence time is about a factor of three larger. This is due to the size of home and pipes but also impacted by the number of fixtures relative to the number of residents and the time between fixture use.

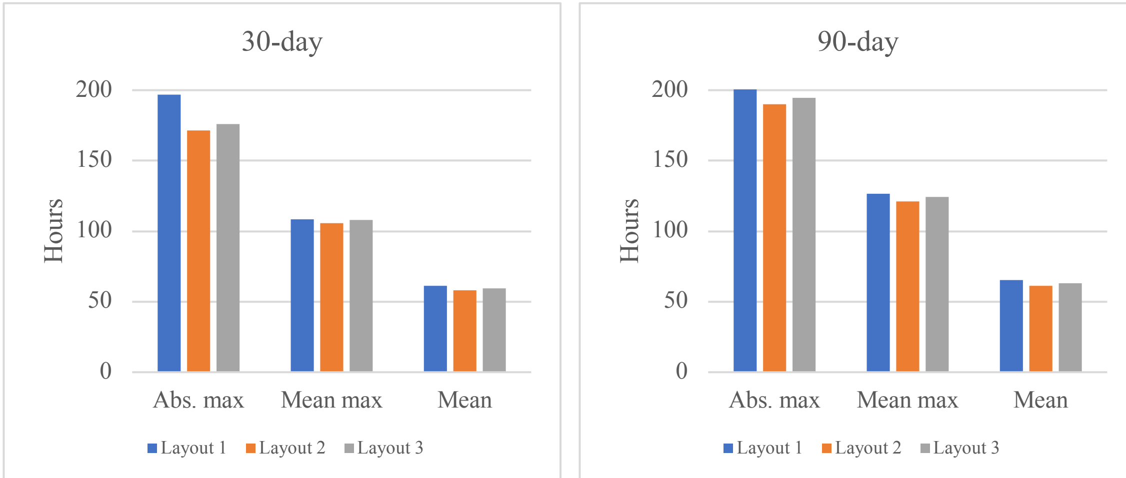

Figure 19: Results summary for house 2, hot-system, at the outlet

The variation between layouts is quite small for the average age and the mean maximum age. However, the absolute maximum age varies by more than 10% for the best (layout 2) and the worst layouts (layout 1). The cold water maximum ages were 13.7% and 24.4% lower for layout 2 for the 30 and 90-day, respectively. The hot water absolute maximum was 12.7% and 10.3% lower for the 30 and 90 day simulation, respectively, for the more efficient layout.

Like House 1, the traditional heater has significantly higher residence times for all of the water age metrics, particularly for the average maximums that increases by about 80%.

The results for water age in the distribution pipe (i.e., upstream of the stubs) are shown on Tables B-10 and B-11 on Appendix B, and in Figures 20 and 21:

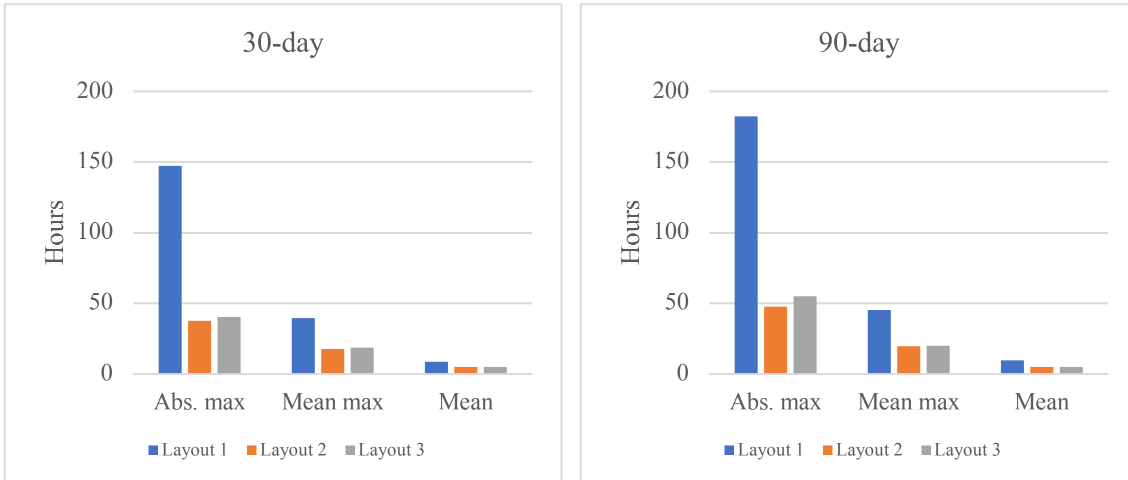

Figure 20: Results summary for house 2, cold-system, at the distribution pipe

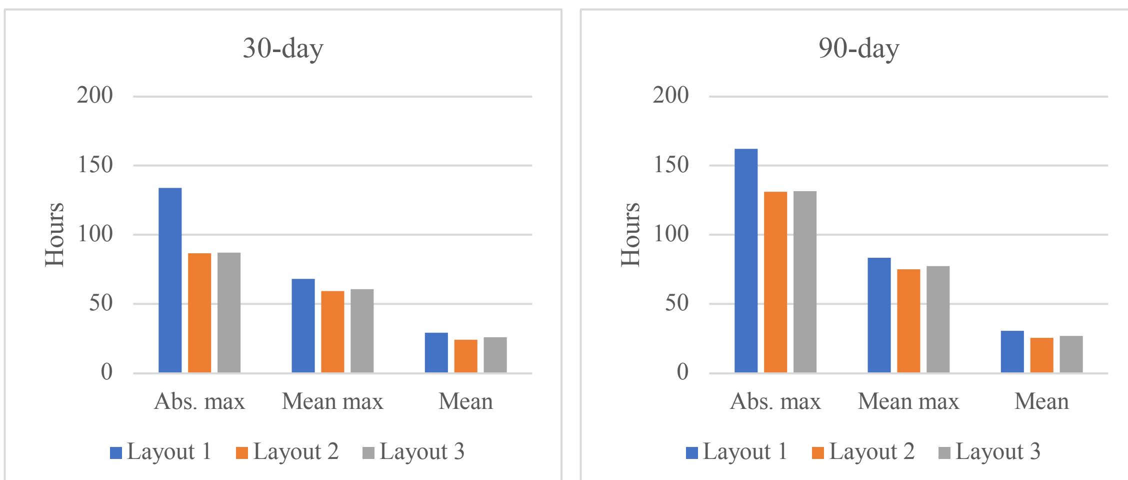

Figure 21: Results summary for house 2, hot-system, at the distribution pipe

The modifications to Layout 1 is substantial, particularly for the cold water. Comparing the worst (layout 1) and best layouts (layout 2), the absolute maximum age is 74.0% lower, the average maximum is reduced by 57.5%, while the mean age is reduced by 45.1% for the cold system. The hot water, on the other hand, had more moderate reductions (19.1% for the absolute maximum, 10.0% for the average maximum, and 16.9% for the mean age). Comparing layouts 2 and 3, which are similar excepts Layout 3 has the heater towards the downstream side of the premise pipe, the metrics do not change radically but having the heater upstream continues to have the lowest overall water age.

Comparing Figures 18 and 20, and 19 and 21, the effects of the stubs are clear. The absolute maximum cold-water age for layout 2 is around 65.6% to 70.5% lower upstream of the stubs. The hot water, on the other hand, the reduction is more moderate for the same metric, at 49.5% for layout 2.

4.3. Effect of water heater type on the age of hot water

A difficulty in hot water heater tanks is that it greatly increases water age. As discussed in section 2.2, when water is heated, chlorine disinfectant decays faster resulting in low disinfectant concentrations in the hot water plumbing system that may allow for microbial regrowth. In this section, results are presented for the alternative layouts for the two houses with the tank hot water heater is replaced by a tankless system. Analyses are driven by the same 30 and 90-day demand sequences as applied as in the previous case.

4.3.1. House 1

Tables B-12 and B-13 on Appendix B list the resulting metrics for the hot water system for the traditional and tankless water heaters at the fixture level. Changes in water age are quantified as a percent difference where negative values mean the instant heater reduces the age as shown in Figure 22. The instant heater significantly reduces water age compared with the traditional heater, although the absolute maximum age is not as reduced as the other two metrics. The effect is small for the absolute maximum on most layouts (reduction of ~3%). For the mean of the maximum ages, the effects range from ~5% to ~20, depending on the layout. Nonetheless, the average age was significantly reduced by the instant heater in almost all cases (~40%) for the same layout, as expected.

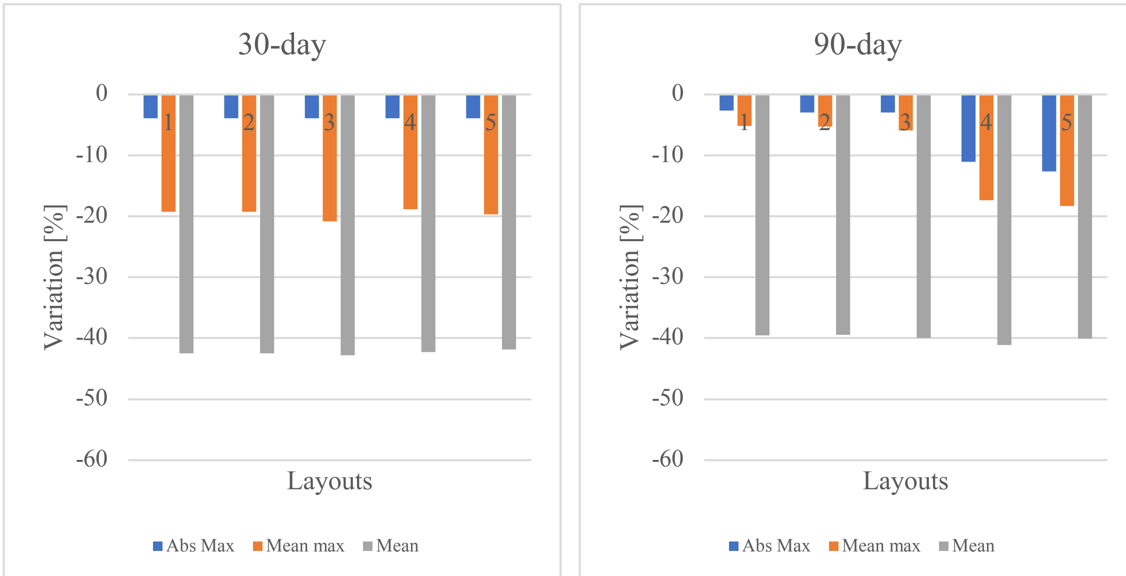

Figure 22: house 1 hot water residence time variation, traditional versus instant heater, at the node

Figure 23 illustrate the results for premise distribution pipe age, while Tables B-11 and B-12 on Appendix B summarizes them. The absolute maximum was reduced by about 10% with the on-demand water heater, but the average maximums were reduced around 22% and 36% depending on the simulation period. The greatest age reduction is observed for the mean age, which is around 50% for most layouts.

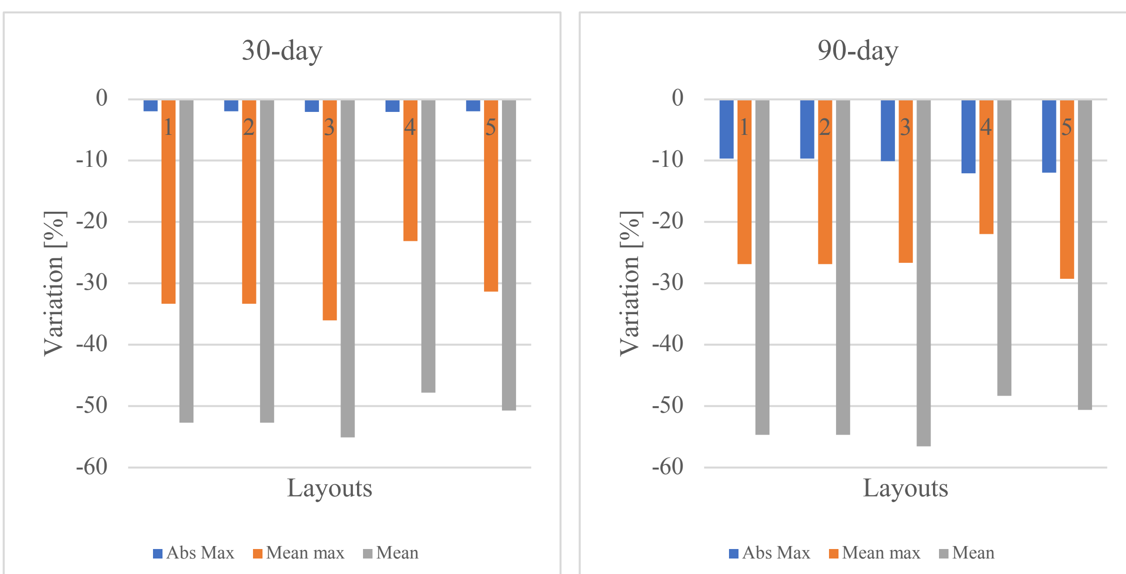

Figure 23: house 1 hot water residence time variation, traditional versus instant heater, at premise's distribution pipe

4.3.2. House 2

Figure 24 compares the results at the outlets for the two types of heaters for the three House 2 layouts for 30 and 90-day simulations. Numerical metric values are summarized in Appendix's B Tables B-13 and B-14. Similar results are observed compared to house 1; the absolute maximum age is reduced (~4% to ~14%) as well as the average of the maximums (~13% to ~17%). The average water age is again the metric that has the greatest reduction (~20%) compared to around 40% for house 1.

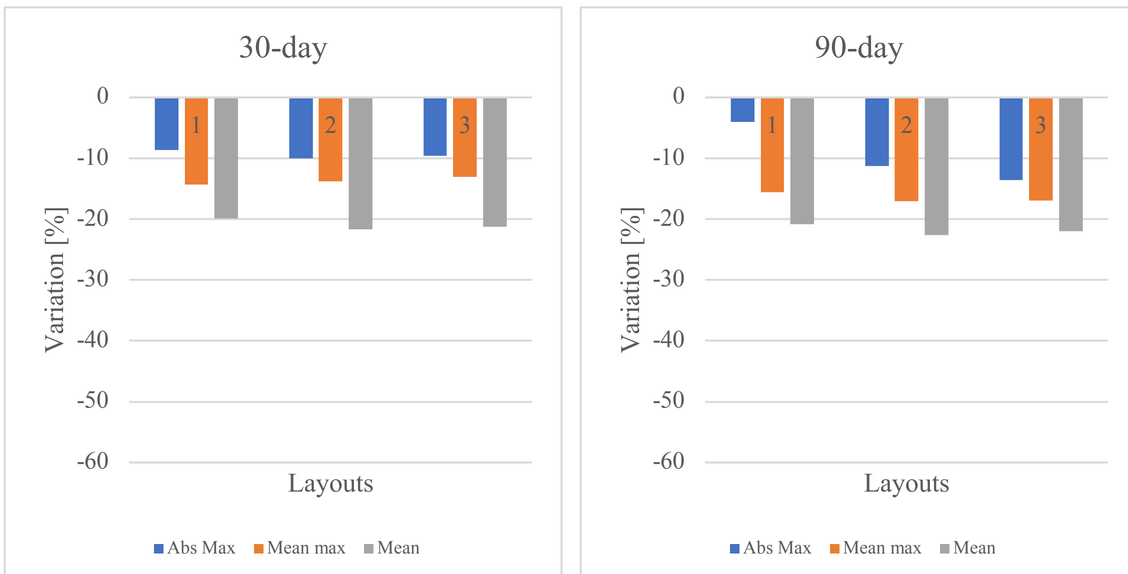

Figure 24: house 2 hot water residence time variation, traditional versus instant heater, at the node

Statistics for residential distribution pipe water age are listed in Tables B-15 and B-16 (Appendix B) for different water heaters and illustrated on Figure 25. The effect of the water heater type at the distribution pipe have similar but more pronounced trends than for outlet/fixture level results, similar of what occurred in house 1.

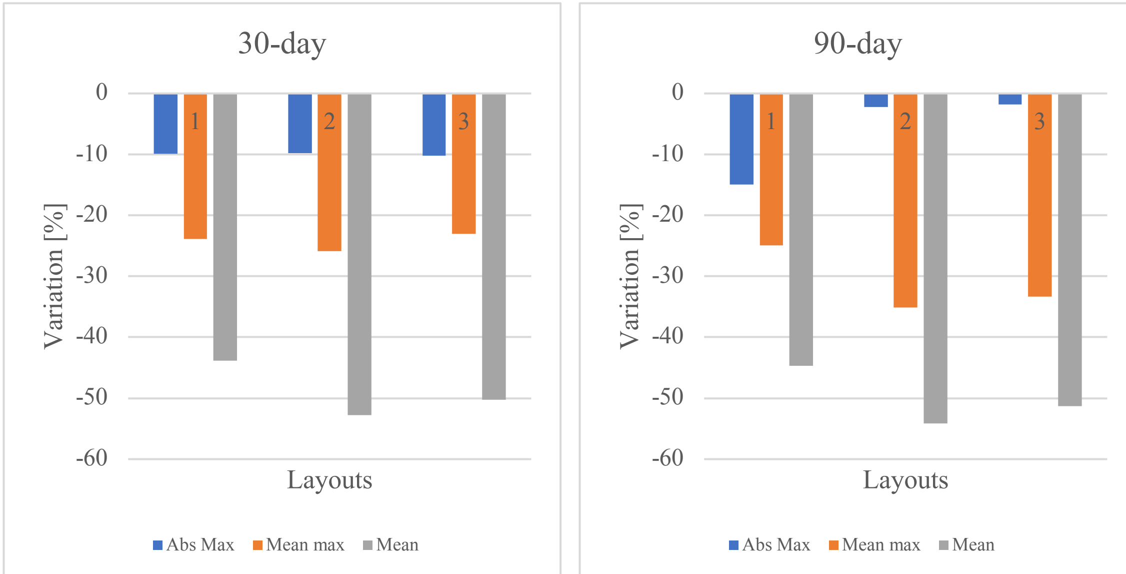

Figure 25: house 2 hot water residence time variation, traditional versus instant heater, at premise's distribution pipe

4.4. Auto-flushers

The benefit of altering the premise plumbing system layout is observed in the previous section by the consequent reductions in cold-water residence times and, potentially, water quality gains. The primary change was to connect water closets at the end of the branches. It is hypothesized that a further improvement can be achieved with auto-flushers installed in cold and hot delivery systems. This hydraulic measure is consistent with the USEPA (2016) recommendation of flushing the system at regular intervals. This design was not simulated here but the longest residence time would be the time between flushes on a given branch. It is further hypothesized that combining flushing with introduction of high temperature water will reduce/eliminate Legionella infections. The next sections expands on this concept.

Alternative system for "disinfecting" for Legionella

Auto-flushers would automatically flush toilets at prescribed intervals or after a defined period of non-use on the branch or household if other metering is in place. Technology for the former system is readily available at low cost.

To sterilize much of the hot piping system, the WHO (2007) recommends maintaining water heaters at temperatures above 60 °C (140º F) and installing temperature regulators at fixtures. This approach is costly in terms of energy. An alternative is short term increases in temperature to superheat the system and auto-flushers to evacuate the system after a sufficient retention time. Tankless water heaters could be programmed to accomplish this task. The pipe system however, must be designed with super heating flush in mind, to avoid scaling, wasting water and energy, and to be efficiently disinfect the pipes. To avoid burning residents flushing could be programmed to occur at times that the probability of using water is low (4:00 am) and auto stop valves installed if a demand occurs during the flushing process. Also, temperature mixing valves at the points of use are a second option but it has been noted that regrowth can occur downstream of these valves.

For flushing to be efficient, auto-flushers must be installed on the last node of every branch. Hence, to maximize benefits, premise plumbing system should be designed to minimize the number of branches to avoid wasting water and the length of connecting stubs for the disinfection process to be efficient. The best option is to install auto-flushers on water closet tanks to minimize the risk of scalding while reducing Legionella proliferation in the toilet tanks. This design requires connecting the hot water system to the toilet; a configuration that normally would not be constructed.

Numerical Study of Hot Water Flushing

To examine the benefits of the above approach, a system with an instant water heater was considered due to its efficiency. An auto-flusher was located at several locations in Houses 1 and 2. The flushing rules were as following:

- Period: 24 hours
- Clock time to flush: 4 am (to prevent scalding)
- Flush volume: 2 US gallons (7.57 L)
- Flush duration: 2 minutes

As expected, the benefits of improved water quality (lower age) depended heavily on its location. Due to the pipe configuration, the water age is reduced significantly only in the branch that contains the flusher and other branches see a small benefit for changes in the main supply pipe. For the configurations tested, the improvement in age was smaller than replacing the tank heater for House 1.

For House 2, a new layout was posed (layout 4 on Appendix A) to accommodate two hot water flushers. The pipe network was laid out such it only contained two branches, and a flusher was installed at the end of each branch. As expected, the maximum age at distribution pipe matches the flushing cycle length (24 hours). The effect at the fixture is minimal and similar to the impact of layout (Section 4.2). Water in the fixture stubs ages directly with the fixture use and largely uncontrollable without specific measures at each fixture. However, approaches like those suggested to change flow patterns and auto-flushers significantly reduce the pipe length in which regrowth could likely occur potential.

CHAPTER 5 - CONCLUSIONS

Water quality degrades with the time that water spends in pipes, as, over time, the residual disinfectant decays and by-products are created, also leaving the water more susceptible to pathogen regrowth. Legionella is arguable the deadliest of those pathogens in the United States, and efforts are underway to reduce the likelihood of infecting potable water consumers. One of such efforts is identifying and eliminating conditions within residential plumbing systems that can lead to increased residence times. The main objective of this study is to contribute to those efforts by quantitatively assessing water age in alternative residential plumbing layouts, based on the hypothesis that the layout's impact on water age is significant. Further, it is believed that good design practices, like connecting high volumetric demands at the end of each branch and switching from traditional water heaters to tankless ones, lead to a reduction of the time water spends in the residential pipe system.

To test those hypothesis, several premise plumbing layouts were designed to meet the specifications defined in the plumbing code and the residence times were computed using a mathematical model that represents water movement in the residence under dynamic conditions. Water use patterns for each fixture were simulated using a stochastic demand generation model on a minute-by-minute basis for simulation periods of 30 and 90 days. The effects on water age of traditional and instant heaters and auto-flushers were quantitatively assessed. The resulting water ages from the alternative plumbing layouts and from the different heater types determined good design practices that identify and eliminate conditions that can lead to an increased residence time.

Six primary conclusions were drawn from the results. First, water age depends primarily in the usage pattern of the fixtures. If fixtures are not used, water will age in the small pipe that connects the outlet to the premise distribution pipe (stubs) described as fixture supply pipes in the code. Only specialized plumbing systems that have circulating water combined with minimum stub's lengths that enable the mixing of fresh water with water sitting on the short fixture supply pipe by hydrodynamic effects and diffusion will be able to truly mitigate the water aging in stubs. Those special systems are designed for sensitive facilities such as laboratories and hospitals, were the premise distribution pipes are very close to the point of use. For residential plumbing systems however, those systems may be unfeasible due to higher costs associated with more distribution pipe required to get closer to the outlets and minimize the stub lengths. They also create longer distribution systems that have higher energy losses, and consequently, may require larger pipe diameters to meet the code specifications. It was shown here that increasing the pipes sizes detrimentally impacts water age.

The second conclusion is derived from the first one is that the water aging on the stubs is significant. Depending on the layout, the absolute maximum age in the stubs can be almost three times older as the water in the point of connection to the distribution pipe, while the average residence time is approximately 2.4 times greater on the outlet than on the distribution pipe. However, the volume of the stubs is small (typically 0.06 liters or 0.017 US gallons) as the code limits their lengths to 0.75 m (30 in). This implies that the volume of old water it is small, and the stubs are flushed under most demands. Nonetheless, biofilm formation may occur within the stubs. Water aging in stubs leads to the validation of hypothesis 3, proving true that the fixture supply pipes act as dead-ends.

Third, it was found that the layout can have a significant impact on absolute maximum age even when the age is computed at the outlet. For House 2, layout 2 reduced the absolute maximum age by 24.4% from layout 1. However, the rest of the metrics for this house did not show significant improvement. For House 1, no metric was reduced when age is computed downstream the stub; implying that the water age at the fixture is controlled by its usage patterns. Fixtures infrequently used in large homes are particularly prone to stagnant water. A small use may flush the stub but replenish it with also somewhat old water if the distribution system upstream it is not optimally designed for freshwater as a criterion.

If the ages are computed in the distribution pipe upstream the stub, the layout has a significant impact on water age, leading to the fourth conclusion. It was found that the absolute maximum age could be decreased up to 76% (house 1, between layouts 1 and 2, with similar results from house 2 layouts 1 and 2). The mean of the maximum ages at each node saw a decrease of up to 66% (house 1, between layouts 4 and 2, with similar results for house 2 (layouts 1 and 2)). Similarly, the mean residence time was reduced up to 58% (house 1, between layouts 4 and 2). This result also validates hypothesis 1: the effect of the plumbing on water age is significant, as the reductions are greater than 30% for all the metrics tested.

Another strategy to achieve water age reductions was to connect water closets to the ends of the branches. This approach was designed into layouts 2 in both houses in their layout 2. Metrics for these designs were lowest age metrics among all configurations which validates hypothesis 2. It is concluded then, that connecting the water closets at the end of the branches it is a good design practice that lowers the overall cold-water age throughout the residence.

Since toilets only use cold water, connecting the water closets at the end of the branches does not improve hot-water age. To lower hot-water residence times, an option is to replace traditional tank heaters with tankless-instant heater systems. Numerical results demonstrate that tankless systems reduce water age across all layouts for all the metrics at the outlet and the point of connection of the fixture to the distribution system. The average hot water age had the largest improvements with reductions of 40% and 20% at the fixture of Houses 1 and 2, respectively, and reductions of approximately 50% for both houses when the ages are computed at the distribution pipes. These finding validates hypothesis 4 as it is shown that tankless heaters reduce hot-water ages throughout the residence.

To further decrease water age, auto-flushers were installed for fixtures throughout the home. USEPA (2016) recommends flushing the system at regular intervals. Further, the WHO (2007) recommends flushing with water at a temperature of at least 60 °C (140 °F) to help sterilize the hot system between the heater and the flush point. The alternative of maintaining tank water heaters at the same high temperature is more energy intensive. In numerical experiments, auto-flushers were installed in the hot water systems with a fixed volume withdrawal on a 24 hour cycle. As expected, their implementation reduced overall residence time. To achieve large water age reductions, auto-flusher location at the end of branches with high water age is critical. These locations depend on the inhabitants behavior. But, designer and architects can inform these decisions. In practice, these uncertainties can be overcome using smart devices that measure the idle time at fixtures at the branch terminals. When a time threshold is reached, the system can be flushed guaranteeing a safe upper bound for the age without wasting excessive water.

Lastly, it was found that pressures computed using the q_1+q_3 method to estimate the peak demands are a conservative estimate compared with simulated demand conditions. Further studies are required on a range of residential layouts with longer time series of stochastically generated demands to draw firm conclusions. Longer simulations than considered here may result in overlapping demands and lower pressures. Nonetheless, oversized pipes are detrimental for water age and should be avoided. They also require large volumes to flush the system.

APPENDIX A - LAYOUTS: CAD MODELS AND DESCRIPTIONS

A.1. house 1 – Layout 1

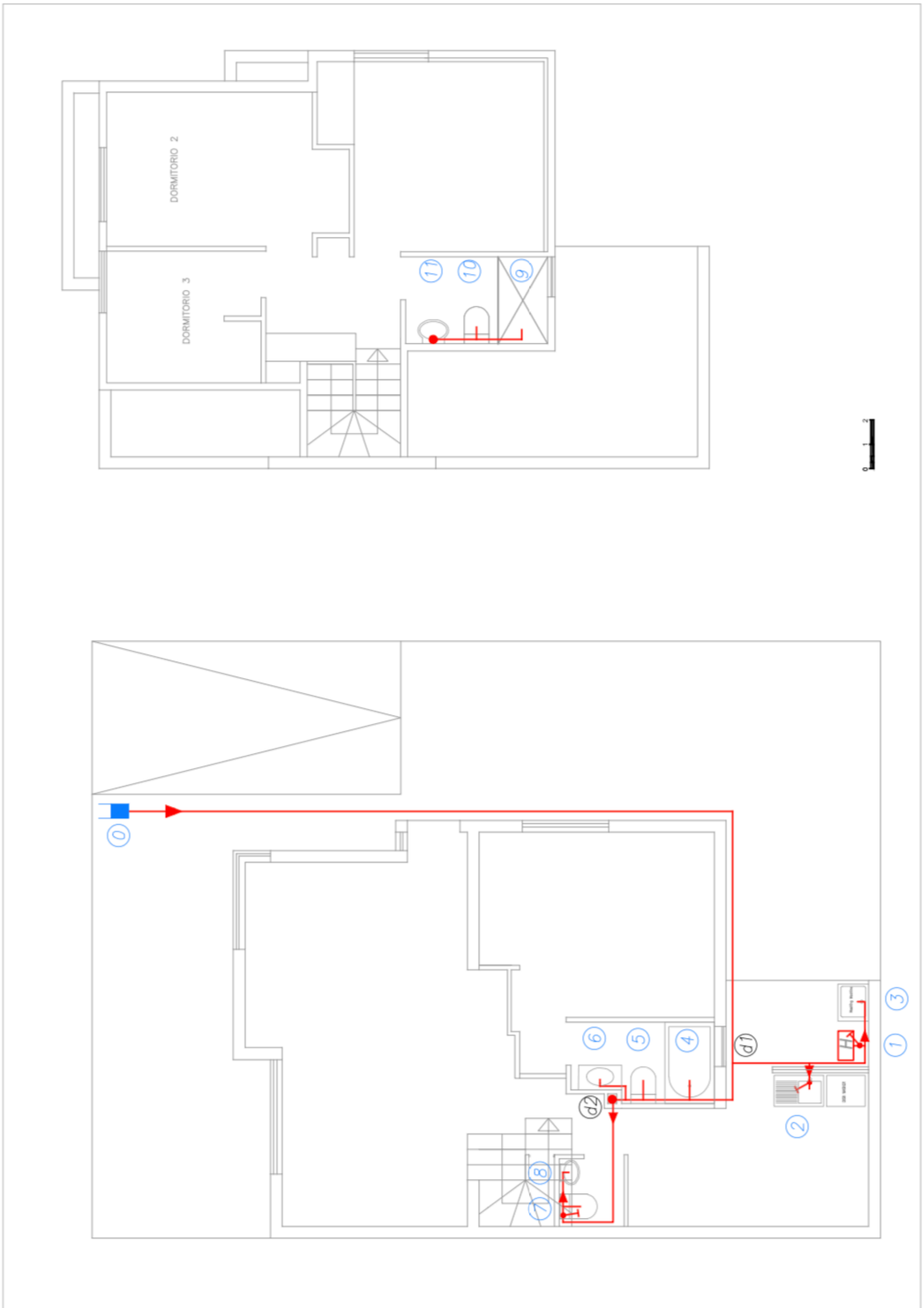

Figure A-1: house 1, layout 1 for the cold system

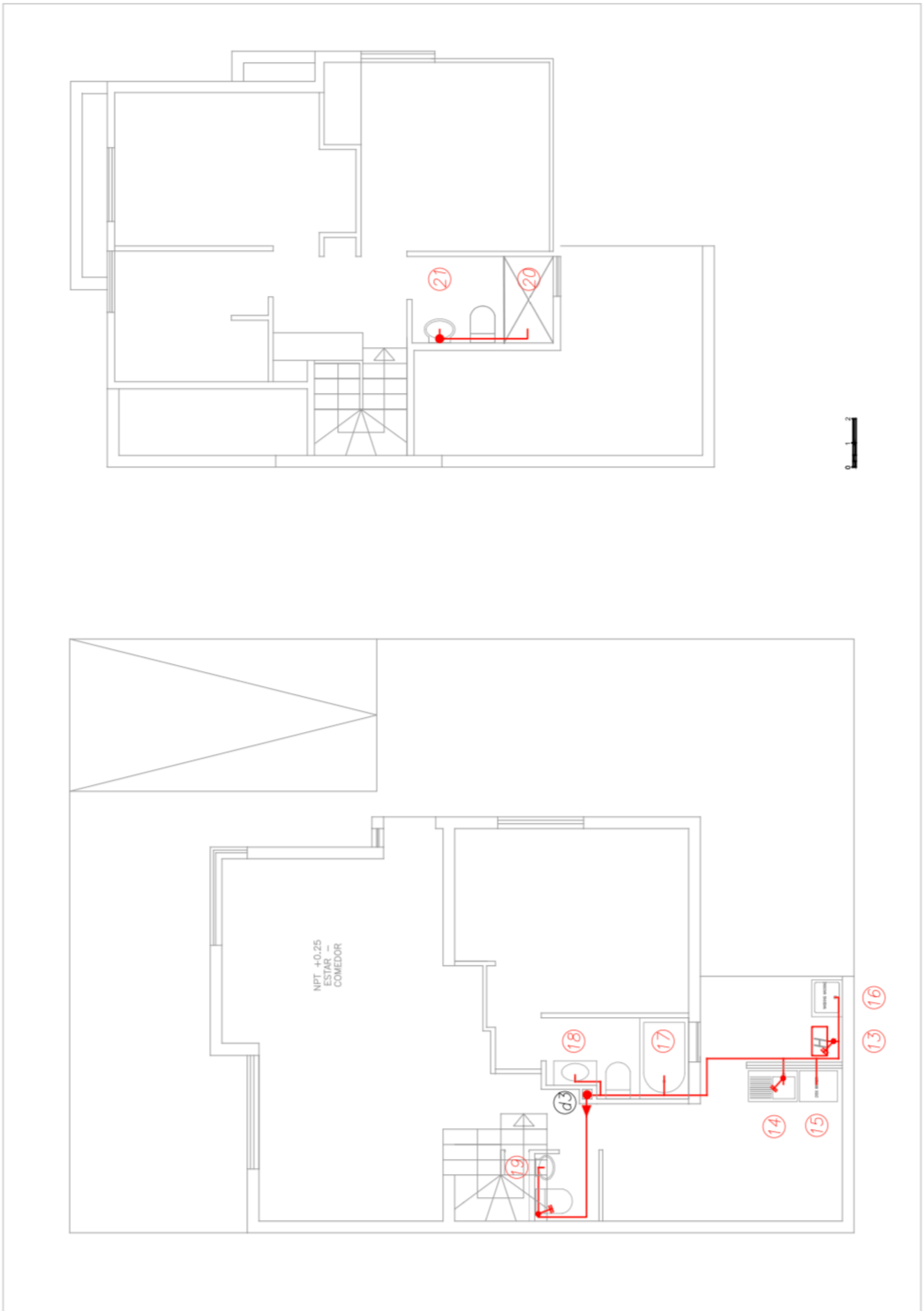

Figure A-2: house 1, layout 1 for the hot system

Table A-1: house 1 - Layout 1: Pipe description

Piping description - Cold					
Number	**Node from**	**Node to**	**Diameter [mm]**	**Length [m]**	**K total**
1	res	d1	25.4	13.85	0.9
2	d1	2	12.7	1.25	1.8
3	2	1	12.7	1.18	1.5
4	1	3	12.7	0.71	0.6
5	d1	4	25.4	1.29	1.5
6	4	5	25.4	0.75	0.6
7	5	6	25.4	0.5	0.6
8	6	d2	12.7	0.5	0.6
9	d2	7	12.7	3.05	3.6
10	7	8	12.7	0.55	0.6
11	d2	11	12.7	3	1.5
12	11	10	12.7	0.7	0.6
13	10	9	12.7	0.73	0.6

Piping description - Hot					
Number	**Node from**	**Node to**	**Diameter [mm]**	**Length [m]**	**K total**
15	13	16	12.7	0.71	1.8
16	13	15	12.7	0.64	1.5
17	15	14	12.7	0.54	0.6
18	14	17	12.7	2.54	2.4
19	17	18	12.7	1.04	0.6
20	18	d3	12.7	0.22	0.6
21	d3	19	12.7	3.59	3.6
22	d3	21	12.7	3	1.5
23	21	20	12.7	1.43	0.6

Table A-2: house 1 - Layout 1 nodal description, code requirements, and design results

Cold node system		**Demand**		**Pressure**			
				Requirement		**Results**	
Number	**Description**	**[GPM]**	**[L/s]**	**[psi]**	**[m]**	**[m]**	**OK?**
1	Water heater	0	0	0	0	21.63	OK
2	Kitchen sink	2.5	0.16	8	5.63	23.16	OK
3	Washing machine	2.5	0.16	8	5.63	21.49	OK
4	Bath tube/shower 1	3	0.19	8	5.63	23.84	OK
5	WC1	3	0.19	20	14.07	24.05	OK
6	Bathroom tap 1	2.5	0.16	8	5.63	23.71	OK
7	WC2	3	0.19	20	14.07	21.15	OK
8	Bathroom tap 2	2.5	0.16	8	5.63	21.48	OK
9	Shower 2	3	0.19	8	5.63	16.12	OK
10	WC3	3	0.19	20	14.07	16.69	OK
11	Bathroom tap 3	2.5	0.16	8	5.63	16.69	OK

Hot node system							
Number	**Description**						
13	Water heater					21.63	OK
14	Kitchen sink					21.27	OK
15	Dish washer	2.75	0.18	8	5.63	21.00	OK
16	Washing machine					21.53	OK
17	Bath tube/shower					21.27	OK
18	Bathroom tap 1					21.27	OK
19	Bathroom tap 2					21.27	OK
20	Shower					18.27	OK
21	Bathroom tap 3					18.27	OK

A.2. house 1 – Layout 2

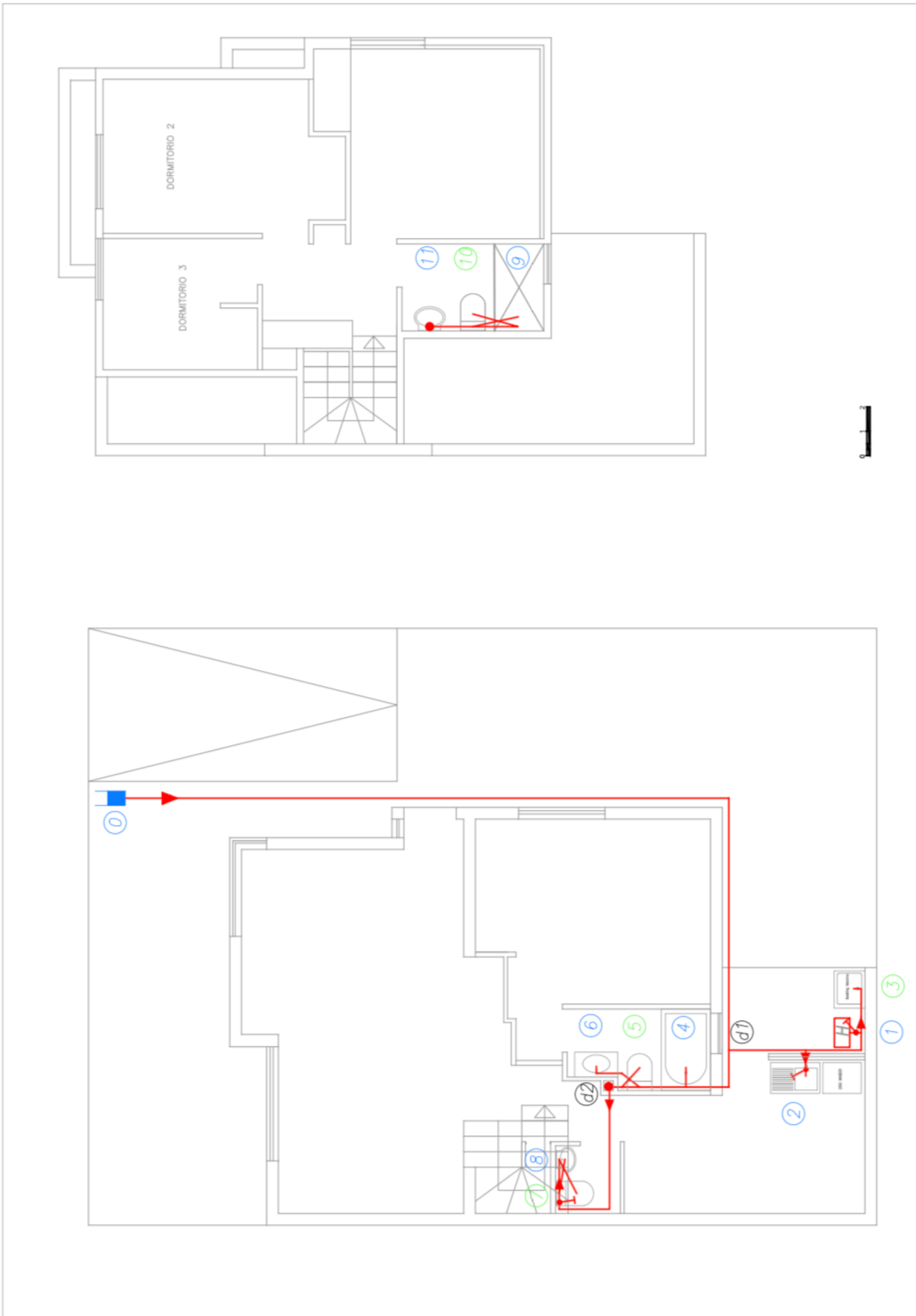

Figure A-3: house 1, layout 2 for the cold system

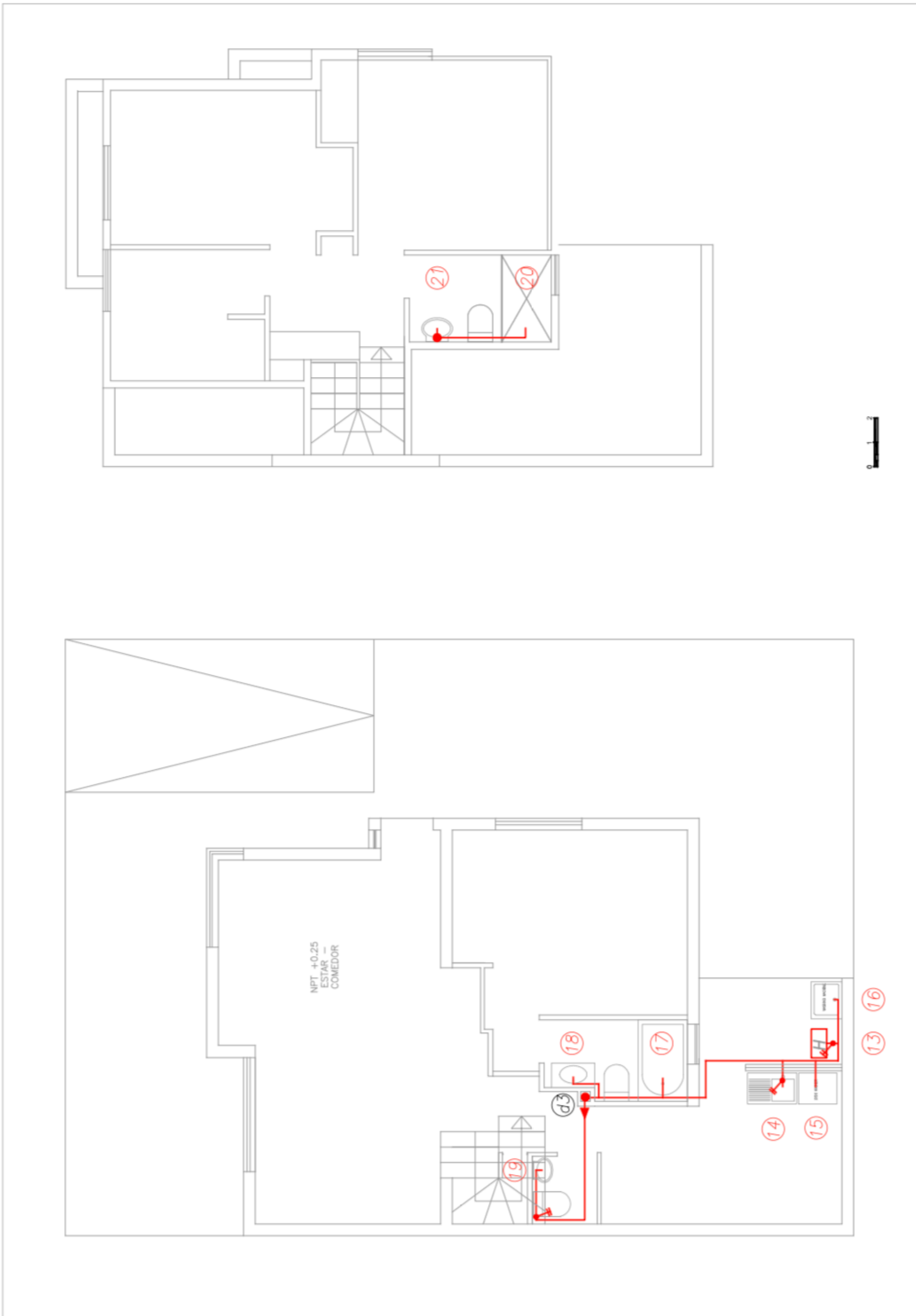

Figure A-4: house 1, layout 2 for the hot system

Table A-3: house 1 - Layout 2: Pipe description

Piping description - Cold					
Number	**Node from**	**Node to**	**Diameter [mm]**	**Length [m]**	**K total**
1	res	d1	25.4	13.85	0.9
2	d1	2	12.7	1.25	1.8
3	2	1	12.7	1.18	1.5
4	1	3	12.7	0.71	0.6
5	d1	4	25.4	1.29	1.5
6	4	6	25.4	0.75	0.6
7	6	5	25.4	0.5	0.6
8	5	d2	12.7	0.5	0.6
9	d2	8	12.7	3.05	3.6
10	8	7	12.7	0.55	0.6
11	d2	11	12.7	3	1.5
12	11	9	12.7	0.7	0.6
13	9	10	12.7	0.73	0.6

Piping description - Hot					
Number	**Node from**	**Node to**	**Diameter [mm]**	**Length [m]**	**K total**
15	13	16	12.7	0.71	1.8
16	13	15	12.7	0.64	1.5
17	15	14	12.7	0.54	0.6
18	14	17	12.7	2.54	2.4
19	17	18	12.7	1.04	0.6
20	18	d3	12.7	0.22	0.6
21	d3	19	12.7	3.59	3.6
22	d3	21	12.7	3	1.5
23	21	20	12.7	1.43	0.6

Table A-4: house 1 - Layout 2 nodal description, code requirements, and design results

Cold node system		**Demand**		**Pressure**			
				Requirement		**Results**	
Number	**Description**	**[GPM]**	**[L/s]**	**[psi]**	**[m]**	**[m]**	**OK?**
1	Water heater	0	0	0	0	21.63	OK
2	Kitchen sink	2.5	0.16	8	5.63	23.16	OK
3	Washing machine	2.5	0.16	8	5.63	21.49	OK
4	Bath tube/shower 1	3	0.19	8	5.63	23.84	OK
5	WC1	3	0.19	20	14.07	24.05	OK
6	Bathroom tap 1	2.5	0.16	8	5.63	23.71	OK
7	WC2	3	0.19	20	14.07	21.15	OK
8	Bathroom tap 2	2.5	0.16	8	5.63	21.48	OK
9	Shower 2	3	0.19	8	5.63	16.12	OK
10	WC3	3	0.19	20	14.07	16.69	OK
11	Bathroom tap 3	2.5	0.16	8	5.63	16.69	OK
Hot node system							
Number	**Description**						
13	Water heater					21.63	OK
14	Kitchen sink					21.27	OK
15	Dish washer	2.75	0.18	8	5.63	21.00	OK
16	Washing machine					21.53	OK
17	Bath tube/shower					21.27	OK
18	Bathroom tap 1					21.27	OK
19	Bathroom tap 2					21.27	OK
20	Shower					18.27	OK
21	Bathroom tap 3					18.27	OK

A.3. house 1 – Layout 3

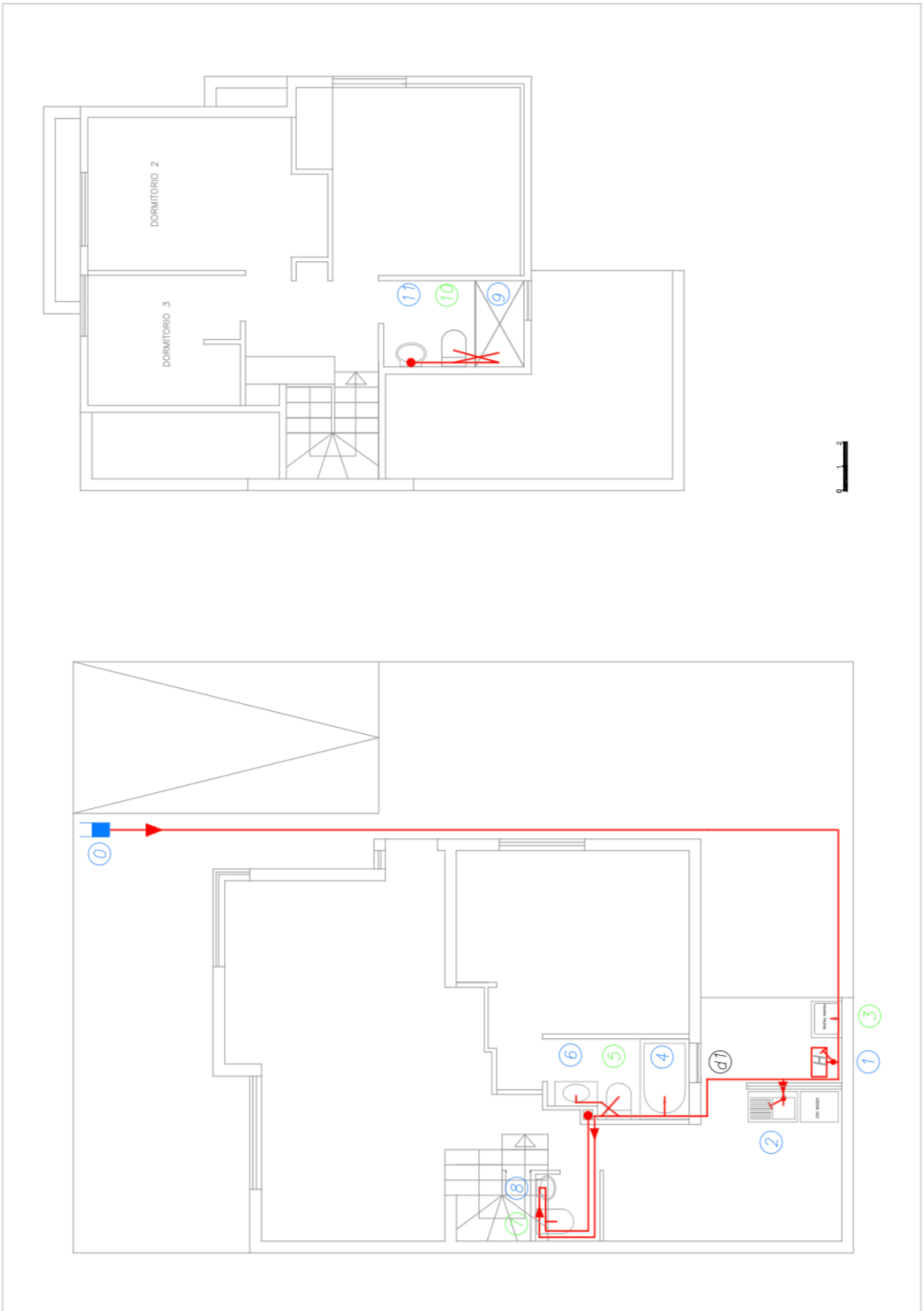

Figure A-5: house 1, layout 3 for the cold system

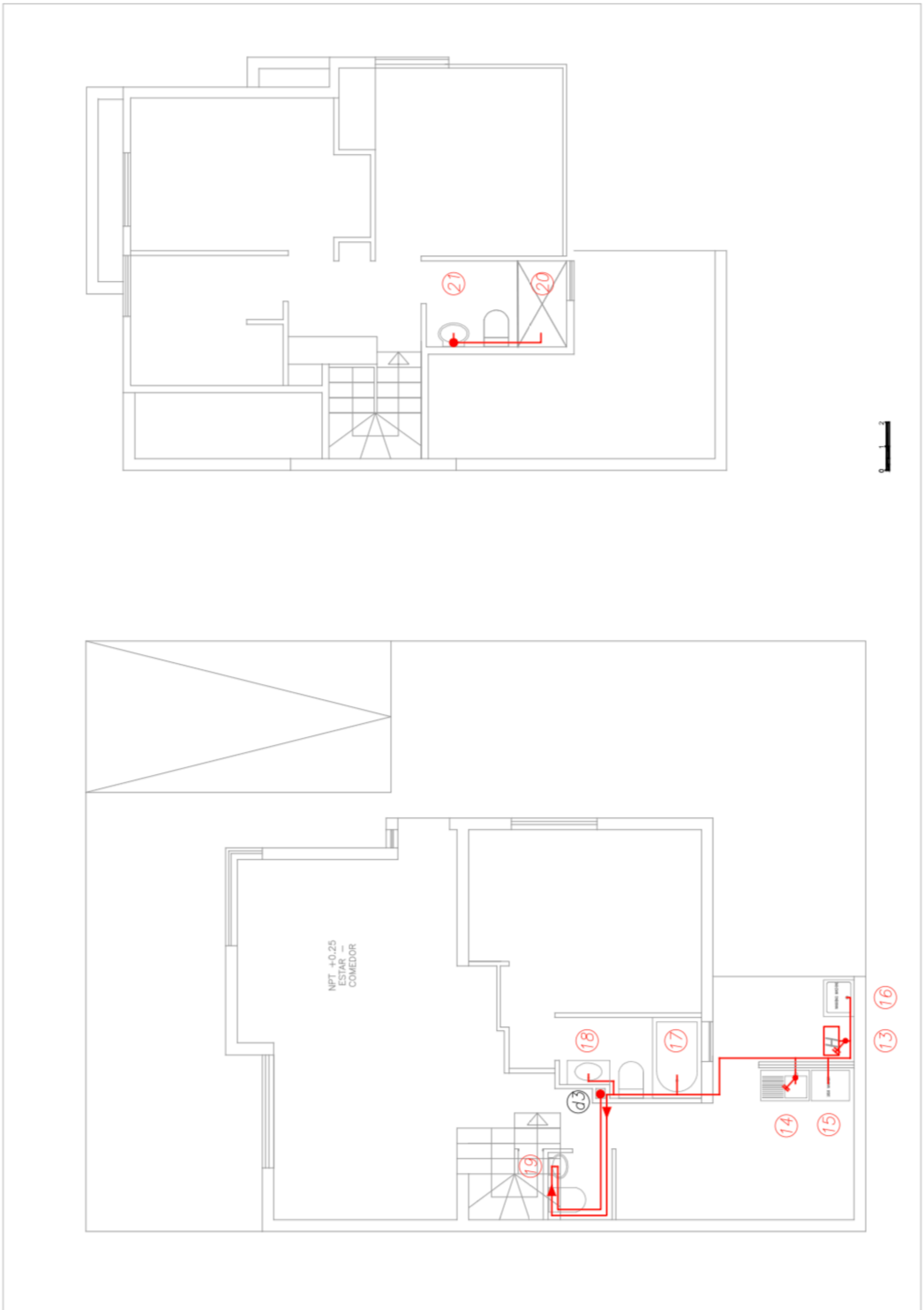

Figure A-6: house 1, layout 3 for the hot system

Table A-5: house 1 - Layout 3: Pipe description

Piping description - Cold					
Number	Node from	Node to	Diameter [mm]	Length [m]	K total
1	res	3	25.4	15.14	0.9
2	d1	2	25.4	1.25	0.6
3	2	1	25.4	1.18	1.5
4	1	3	25.4	0.71	0.6
5	d1	4	25.4	1.29	1.8
6	4	6	25.4	0.75	0.6
7	6	5	25.4	0.5	0.6
8	5	d91	19.05	0.5	0.6
9	d91	8	19.05	3.72	2.7
10	8	7	19.05	0.7	1.5
9p	7	d95	19.05	2.74	2.4
11	d95	11	12.7	3	1.5
12	11	10	12.7	0.7	0.6
13	10	9	12.7	0.73	0.6

Piping description - Hot					
Number	Node from	Node to	Diameter [mm]	Length [m]	K total
15	13	16	12.7	0.71	1.8
16	13	15	12.7	0.64	1.5
17	15	14	12.7	0.54	0.6
18	14	17	12.7	2.54	2.4
19	17	18	12.7	1.04	0.6
20	18	d93	12.7	0.22	0.6
21	d93	19	12.7	3.59	2.7
21p	19	d96	12.7	3.59	4.2
22	d93	21	12.7	3	0.9
23	21	20	12.7	1.43	0.6

Table A-6: house 1 - Layout 3 nodal description, code requirements, and design results

Cold node system		**Demand**		**Pressure**			
				Requirement		**Results**	
Number	**Description**	**[GPM]**	**[L/s]**	**[psi]**	**[m]**	**[m]**	**OK?**
1	Water heater	0	0	0	0	23.75	OK
2	Kitchen sink	2.5	0.16	8	5.63	23.62	OK
3	Washing machine	2.5	0.16	8	5.63	24.04	OK
4	Bath tube/shower 1	3	0.19	8	5.63	22.58	OK
5	WC1	3	0.19	20	14.07	22.72	OK
6	Bathroom tap 1	2.5	0.16	8	5.63	22.54	OK
7	WC2	3	0.19	20	14.07	20.77	OK
8	Bathroom tap 2	2.5	0.16	8	5.63	21.49	OK
9	Shower 2	3	0.19	8	5.63	14.38	OK
10	WC3	3	0.19	20	14.07	14.70	OK
11	Bathroom tap 3	2.5	0.16	8	5.63	14.70	OK
Hot node system							
Number	**Description**						
13	Water heater					23.75	OK
14	Kitchen sink					23.39	OK
15	Dish washer	2.75	0.18	8	5.63	23.12	OK
16	Washing machine					23.65	OK
17	Bath tube/shower					23.39	OK
18	Bathroom tap 1					23.39	OK
19	Bathroom tap 2					23.39	OK
20	Shower					20.39	OK
21	Bathroom tap 3					20.39	OK

A.4. house 1 – Layout 4

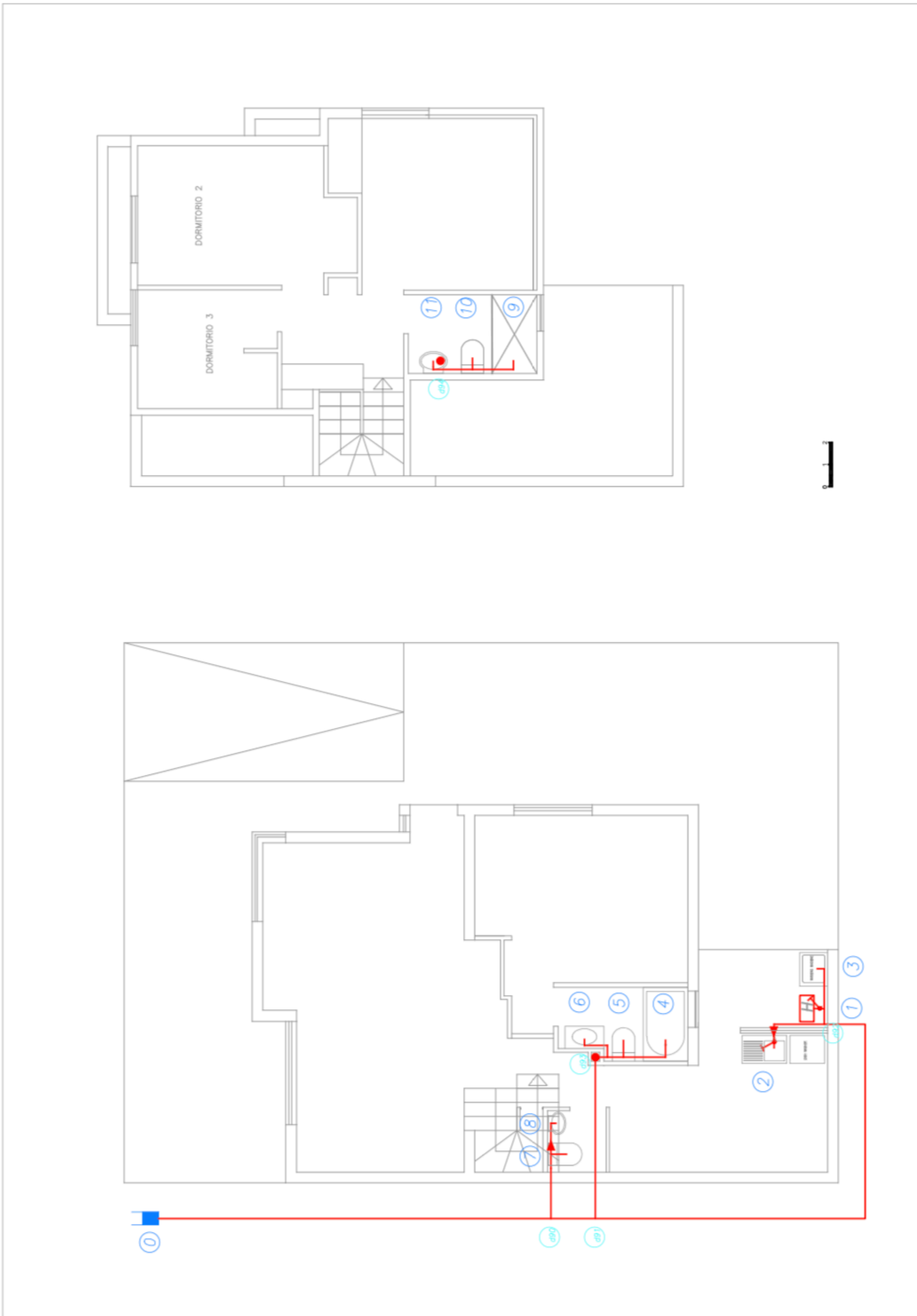

Figure A-7: house 1, layout 4 for the cold system

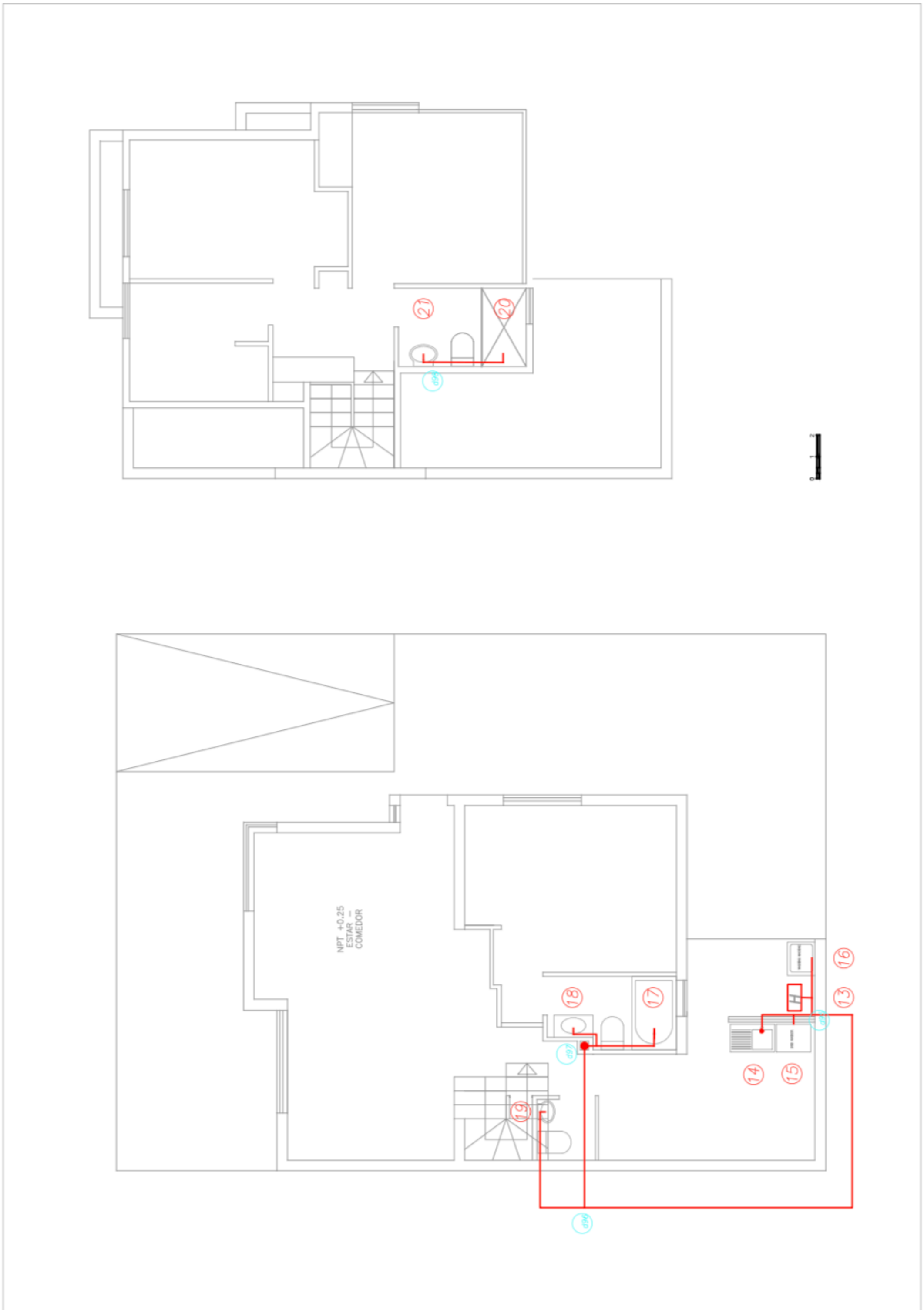

Figure A-8: house 1, layout 4 for the hot system

Table A-7: house 1 - Layout 4: Pipe description

Piping description - Cold					
Number	**Node from**	**Node to**	**Diameter [mm]**	**Length [m]**	**K total**
1	res	d90	25.4	7.02	0
2	d90	7	12.7	1.15	1.8
3	7	8	12.7	0.55	0.6
4	d90	d91	25.4	0.8	0.6
5	d91	d92	25.4	9.03	2.4
6	d92	1	25.4	0.19	1.8
7	1	3	12.7	0.71	0.6
8	d92	2	12.7	0.9	0.6
9	d91	d93	25.4	2.89	1.8
10	d93	6	12.7	0.21	1.8
11	6	5	12.7	0.29	0.6
12	5	4	12.7	0.75	0.6
13	d93	d94	12.7	3	1.8
14	d94	11	12.7	0.13	1.8
15	d94	10	12.7	0.57	0.6
16	10	9	12.7	0.73	0.6

Piping description - Hot					
Number	**Node from**	**Node to**	**Diameter [mm]**	**Length [m]**	**K total**
17	13	16	12.7	0.71	1.8
18	13	d95	12.7	0.31	0.6
19	d95	15	12.7	0.33	1.8
20	15	16	12.7	0.57	0.6
21	d95	d96	12.7	9.03	3.6
22	d96	19	12.7	2.52	1.5
23	d96	d97	12.7	2.91	1.8
24	d97	18	12.7	0.21	1.8
25	18	17	12.7	1.04	0.6
26	d97	d98	12.7	3	1.8
27	d98	21	12.7	0.18	1.8
28	d98	20	12.7	1.25	1.8

Table A-8: house 1 - Layout 4 nodal description, code requirements, and design results

Cold node system		**Demand**		**Pressure**			
				Requirement		**Results**	
Number	**Description**	**[GPM]**	**[L/s]**	**[psi]**	**[m]**	**[m]**	**OK?**
1	Water heater	0	0	0	0	25.62	OK
2	Kitchen sink	2.5	0.16	8	5.63	25.92	OK
3	Washing machine	2.5	0.16	8	5.63	25.47	OK
4	Bath tube/shower 1	3	0.19	8	5.63	24.55	OK
5	WC1	3	0.19	20	14.07	25.13	OK
6	Bathroom tap 1	2.5	0.16	8	5.63	25.14	OK
7	WC2	3	0.19	20	14.07	25.64	OK
8	Bathroom tap 2	2.5	0.16	8	5.63	25.97	OK
9	Shower 2	3	0.19	8	5.63	19.25	OK
10	WC3	3	0.19	20	14.07	19.82	OK
11	Bathroom tap 3	2.5	0.16	8	5.63	19.82	OK
Hot node system							
Number	**Description**						
13	Water heater					25.62	OK
14	Kitchen sink					25.17	OK
15	Dish washer	2.75	0.18	8	5.63	24.91	OK
16	Washing machine					25.52	OK
17	Bath tube/shower					25.40	OK
18	Bathroom tap 1					25.40	OK
19	Bathroom tap 2					25.40	OK
20	Shower					22.40	OK
21	Bathroom tap 3					22.40	OK

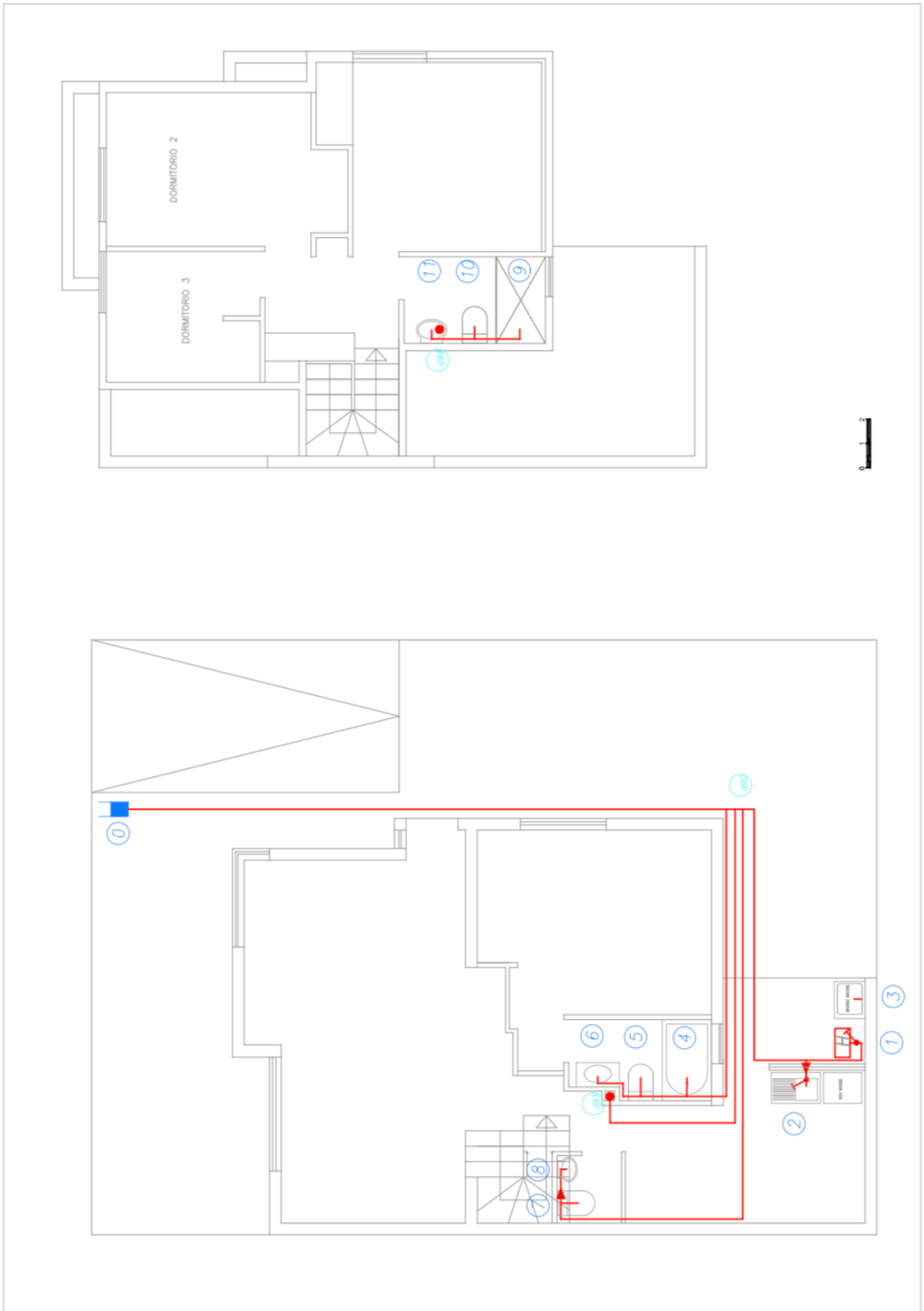

Figure A-9: house 1, layout 5 for the cold system

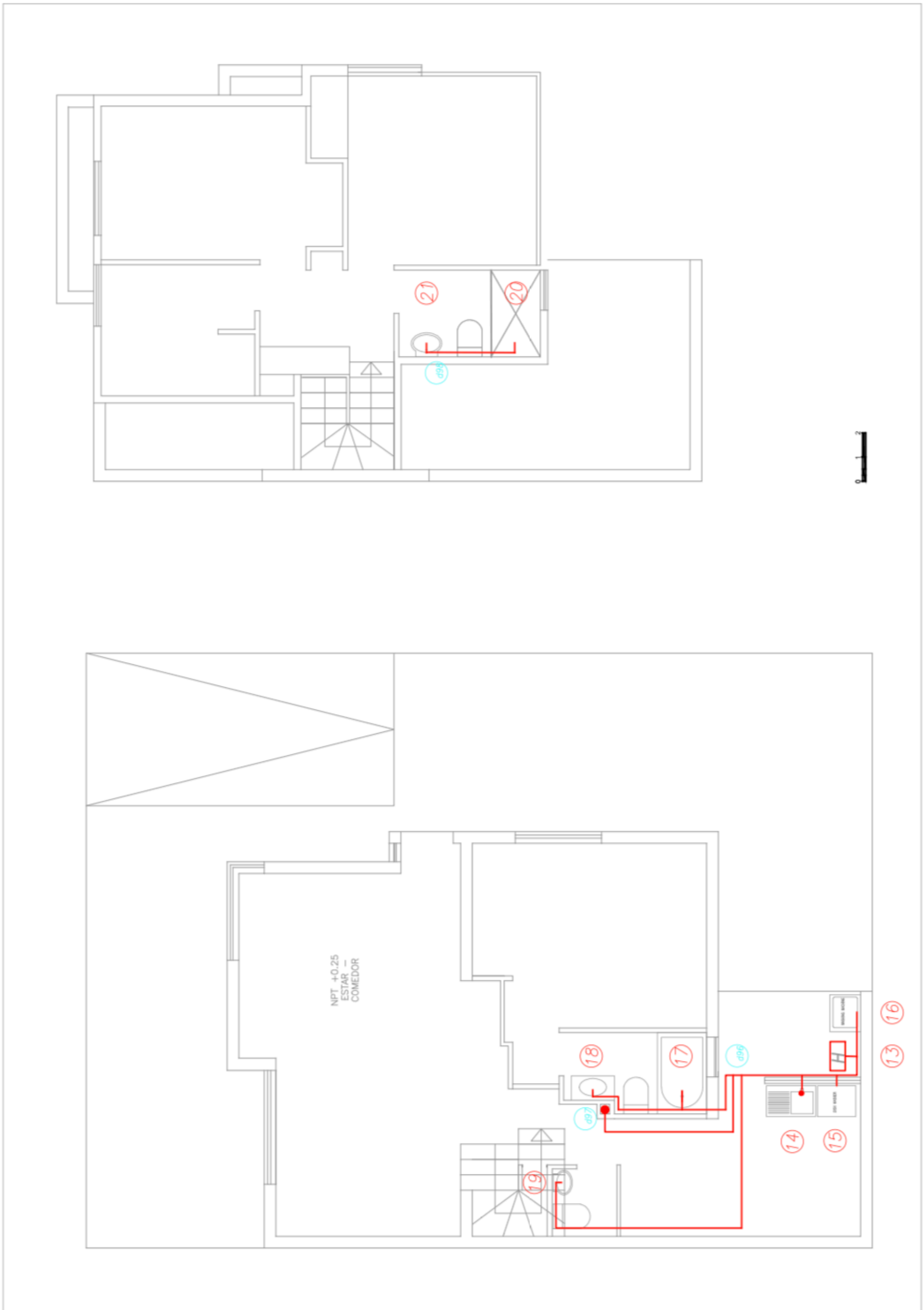

Figure A-10: house 1, layout 5 for the hot system

Table A-9: house 1 - Layout 5: Pipe description

Piping description - Cold					
Number	Node from	Node to	Diameter [mm]	Length [m]	K total
1	source	d90	25.4	9.9	0
2	d90	4	12.7	5.31	2.7
3	4	5	12.7	0.75	0.6
4	5	6	12.7	0.75	0.6
5	d90	d93	25.4	7.14	2.7
6	d93	d94	12.7	3	0.9
7	d94	11	12.7	0.25	1.8
8	11	10	12.7	0.7	0.6
9	10	9	12.7	0.73	0.6
10	d90	7	12.7	9.88	3.6
11	7	8	12.7	0.7	1.5
12	d90	2	25.4	4.93	2.4
13	2	1	25.4	1.18	1.5
14	1	3	12.7	0.71	0.6

Piping description - Hot					
Number	Node from	Node to	Diameter [mm]	Length [m]	K total
15	13	16	12.7	0.71	1.8
16	13	15	12.7	0.64	2.7
17	15	14	12.7	0.57	0.6
18	14	d96	12.7	1.24	0.6
19	d96	17	12.7	1.27	2.4
20	17	18	12.7	1.46	0.6
21	d96	d97	12.7	3	3.6
22	d97	d98	12.7	3	0.9
23	d98	21	12.7	0.25	0.6
24	21	20	12.7	1.43	1.5
25	d96	19	12.7	6.25	3.6

Table A-10: house 1 - Layout 5 nodal description, code requirements, and design results

Cold node system		**Demand**		**Pressure**			
				Requirement		**Results**	
Number	**Description**	**[GPM]**	**[L/s]**	**[psi]**	**[m]**	**[m]**	**OK?**
1	Water heater	0	0	0	0	25.27	OK
2	Kitchen sink	2.5	0.16	8	5.63	25.61	OK
3	Washing machine	2.5	0.16	8	5.63	25.12	OK
4	Bath tube/shower 1	3	0.19	8	5.63	20.65	OK
5	WC1	3	0.19	20	14.07	20.80	OK
6	Bathroom tap 1	2.5	0.16	8	5.63	20.38	OK
7	WC2	3	0.19	20	14.07	22.67	OK
8	Bathroom tap 2	2.5	0.16	8	5.63	22.99	OK
9	Shower 2	3	0.19	8	5.63	19.02	OK
10	WC3	3	0.19	20	14.07	19.59	OK
11	Bathroom tap 3	2.5	0.16	8	5.63	19.59	OK
Hot node system							
Number	**Description**						
13	Water heater					25.27	OK
14	Kitchen sink					24.82	OK
15	Dish washer	2.75	0.18	8	5.63	24.56	OK
16	Washing machine					25.17	OK
17	Bath tube/shower					24.82	OK
18	Bathroom tap 1					24.82	OK
19	Bathroom tap 2					24.82	OK
20	Shower					21.82	OK
21	Bathroom tap 3					21.82	OK

A.5. house 2 – Layout 1

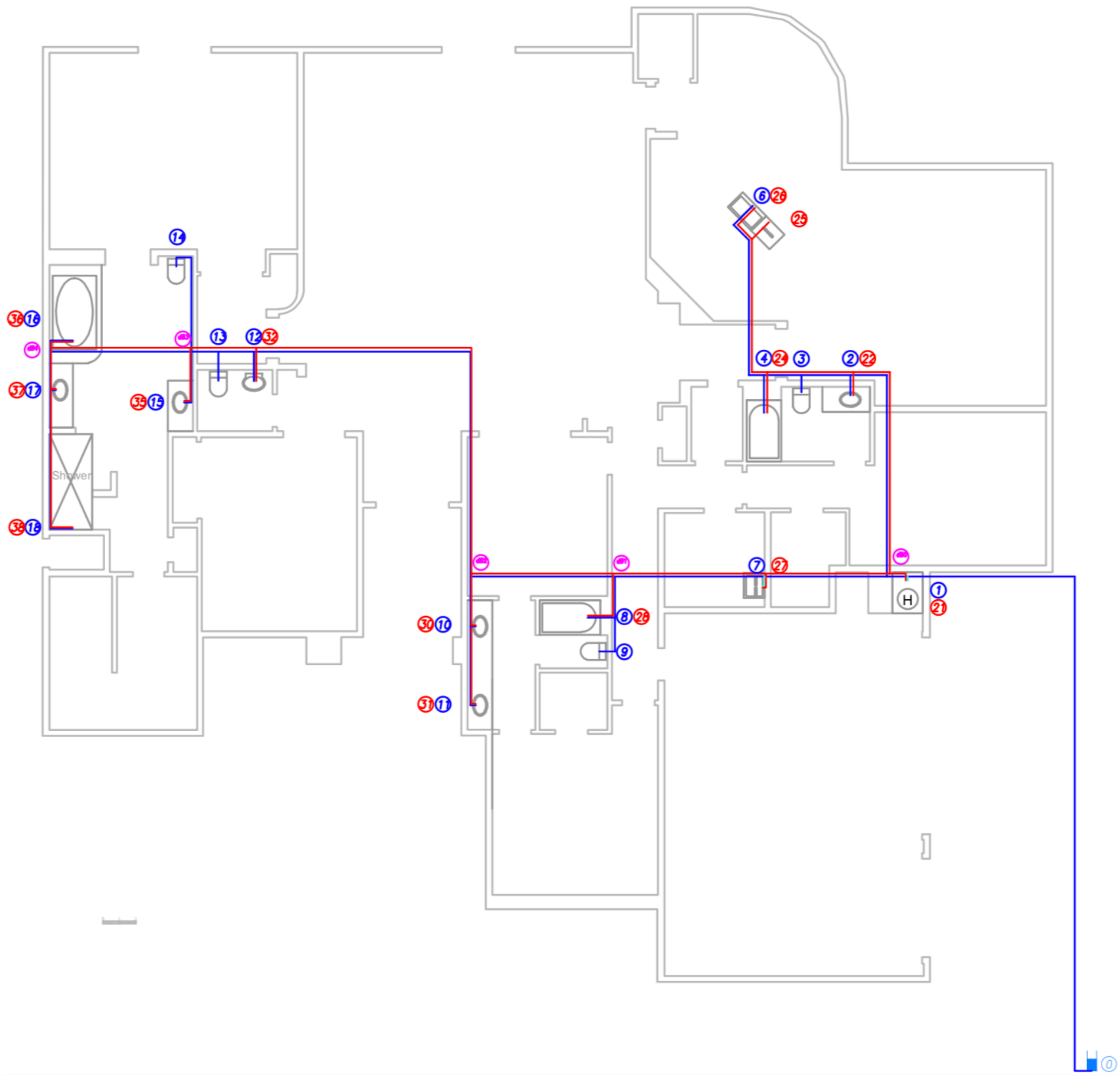

Figure A-11: house 2, layout 1 for both hot (red) and cold (blue) systems

Table A-11: house 2 - Layout 1: Pipe description

Piping description - Cold					
Number	**Node from**	**Node to**	**Diameter [mm]**	**Length [m]**	**K total**
1	res	1	25.4	15.85	0.9
2	1	d80	25.4	0.5	0.6
3	d80	2	12.7	5.7	2.7
4	2	3	12.7	1.17	0.6
5	3	4	12.7	0.9	0.6
6	4	5	12.7	3.59	1.5
7	5	6	12.7	0.52	0
8	d80	7	25.4	2.94	0.6
9	7	d81	25.4	3.57	0.6
10	d81	8	12.7	0.99	1.8
11	8	9	12.7	0.81	0.6
12	d81	d82	25.4	3.47	0.6
13	d82	10	12.7	1.2	1.8
14	10	11	12.7	1.89	0.6
15	d82	12	25.4	10.57	2.4
16	12	13	25.4	0.85	0.6
17	13	d83	25.4	0.65	0.6
18	d83	14	25.4	2.62	1.8
19	d83	15	12.7	1.31	1.8
20	d83	d84	12.7	3.37	0.6
21	d84	16	12.7	0.27	1.8
22	d84	17	12.7	0.92	1.5
23	17	18	12.7	3.32	0.6

Piping description - Hot					
Number	**Node from**	**Node to**	**Diameter [mm]**	**Length [m]**	**K total**
30	21	d90	25.4	0.39	0
31	d90	22	12.7	5.7	2.7
32	22	24	12.7	2.06	0.6
33	24	25	12.7	3.56	1.5
34	25	26	12.7	0.48	0.6
35	d90	27	25.4	2.97	0.6
36	27	d91	25.4	3.66	0.6
37	d91	28	12.7	1	1.8
38	d91	d92	25.4	3.37	0.6
39	d92	30	12.7	1.24	1.8
40	30	31	12.7	1.89	0.6
41	d92	32	19.05	10.58	1.5
42	32	d93	19.05	1.57	0.6
43	d93	35	12.7	1.27	1.8
44	d93	d94	19.05	3.34	0.6
45	d94	36	12.7	0.14	1.8
46	d94	37	12.7	0.93	1.5
47	37	38	12.7	3.32	0.6

Table A-12: house 2 - Layout 1 nodal description, code requirements, and design results

Cold node system		**Demand**		**Pressure**			
				Requirement		**Results**	
Number	**Description**	**[GPM]**	**[L/s]**	**[psi]**	**[m]**	**[m]**	**OK?**
1	Water heater	0	0	0	0	21.12	OK
2	Bathroom tap 1	2.5	0.16	8	5.63	15.40	OK
3	WC 1	3	0.19	20	14.07	14.96	OK
4	Shower 1	3	0.19	8	5.63	15.28	OK
6	Kitchen sink	2.5	0.16	8	5.63	15.28	OK
7	Washing machine	2.5	0.16	8	5.63	19.70	OK
8	Shower 2	3	0.19	8	5.63	18.81	OK
9	WC 2	3	0.19	20	14.07	18.22	OK
10	Bathroom tap 2	2.5	0.16	8	5.63	18.44	OK
11	Bathroom tap 3	2.5	0.16	8	5.63	17.83	OK
12	Bathroom tap 4	2.5	0.16	8	5.63	17.85	OK
13	WC 3	3	0.19	20	14.07	17.41	OK
14	WC 4	3	0.19	20	14.07	17.69	OK
15	Bathroom tap 5	2.5	0.16	8	5.63	17.69	OK
16	Bathtub	4	0.25	20	14.07	16.49	OK
17	Bathroom tap 6	2.5	0.16	8	5.63	17.15	OK
18	Shower 3	3	0.19	8	5.63	15.95	OK

Hot node system							
Number	**Description**						
21	Water heater					21.12	OK
22	Bathroom tap 1					19.73	OK
24	Shower 1					19.27	OK
25	Dish washer	2.75	0.17	8	5.63	18.17	OK
26	Kitchen sink					18.43	OK
27	Washing machine					21.10	OK
28	Shower 2					21.10	OK
30	Bathroom tap 2					21.10	OK
31	Bathroom tap 3					21.10	OK
32	Bathroom tap 4					21.10	OK
35	Bathroom tap 5					21.10	OK
36	Bathtub					21.10	OK
37	Bathroom tap 6					21.10	OK
38	Shower 3					21.10	OK

A.6. house 2 – Layout 2

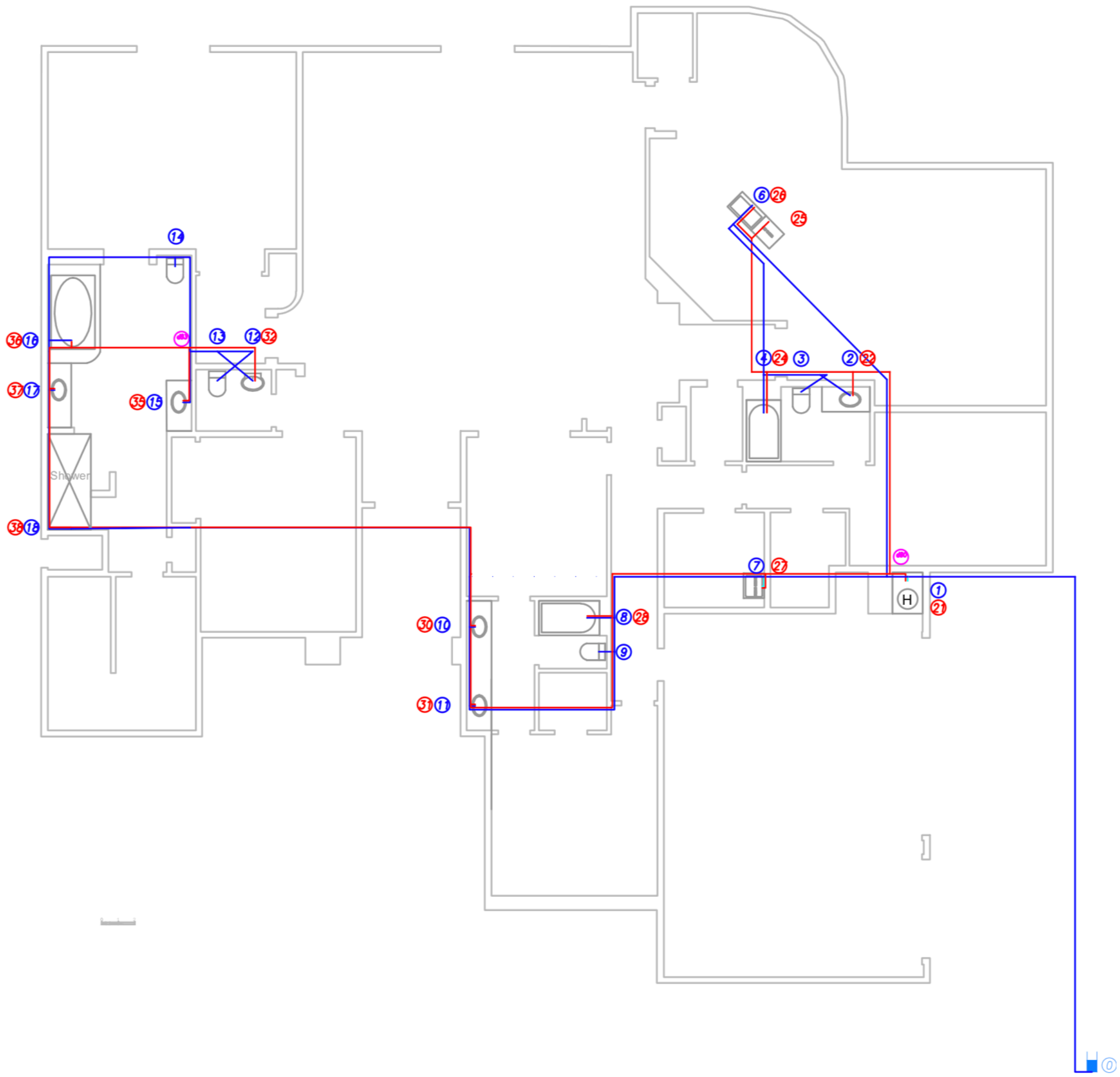

Figure A-12: house 2, layout 2 for both hot (red) and cold (blue) systems

Table A-13: house 2 - Layout 2: Pipe description

Piping description - Cold					
Number	Node from	Node to	Diameter [mm]	Length [m]	K total
1	res	1	25.4	15.85	0.9
2	1	d80	25.4	0.5	0.6
3	d80	6	19.05	9.94	2.2
4	6	4	19.05	3.99	1.5
5	4	2	12.7	1.35	1.5
6	2	3	12.7	0.5	0.6
7	d80	7	25.4	2.94	0.6
8	7	8	25.4	4.56	1.5
9	8	9	25.4	0.81	0.6
10	9	11	25.4	4.95	2.4
11	11	10	25.4	1.89	0.6
12	10	18	25.4	12.43	1.5
13	18	17	19.05	3.32	1.5
14	17	16	19.05	1.19	0.6
15	16	14	19.05	5	1.5
16	14	d83	19.05	2.62	1.5
17	d83	15	12.7	1.21	0.6
18	d83	12	12.7	0.65	1.8
19	12	13	12.7	0.5	0.6

Piping description - Hot					
Number	Node from	Node to	Diameter [mm]	Length [m]	K total
30	21	d80	25.4	0.38	0
31	d80	22	19.05	5.71	2.7
32	22	24	19.05	2.06	0.6
33	24	25	12.7	3.56	1.5
34	25	26	12.7	0.48	1
35	d80	27	25.4	2.97	0.6
36	27	28	25.4	3.66	1.5
37	28	31	25.4	5.59	2.4
38	31	30	25.4	1.96	0.6
39	30	38	19.05	12.42	1.5
40	38	37	19.05	3.32	1.5
41	37	36	19.05	1.5	1.5
42	36	d103	12.7	2.81	0.6
43	d103	35	12.7	1.27	1.8
44	d103	32	12.7	1.57	0.6

Table A-14: house 2 - Layout 2 nodal description, code requirements, and design results

Cold node system		**Demand**		**Pressure**			
				Requirement		**Results**	
Number	**Description**	**[GPM]**	**[L/s]**	**[psi]**	**[m]**	**[m]**	**OK?**
1	Water heater	0	0	0	0	21.12	OK
2	Bathroom tap 1	2.5	0.16	8	5.63	17.20	OK
3	WC 1	3	0.19	20	14.07	16.92	OK
4	Shower 1	3	0.19	8	5.63	18.97	OK
6	Kitchen sink	2.5	0.16	8	5.63	19.49	OK
7	Washing machine	2.5	0.16	8	5.63	19.70	OK
8	Shower 2	3	0.19	8	5.63	18.93	OK
9	WC 2	3	0.19	20	14.07	18.36	OK
10	Bathroom tap 2	2.5	0.16	8	5.63	17.66	OK
11	Bathroom tap 3	2.5	0.16	8	5.63	17.61	OK
12	Bathroom tap 4	2.5	0.16	8	5.63	15.01	OK
13	WC 3	3	0.19	20	14.07	14.67	OK
14	WC 4	3	0.19	20	14.07	15.50	OK
15	Bathroom tap 5	2.5	0.16	8	5.63	15.37	OK
16	Bathtub	4	0.25	20	14.07	15.15	OK
17	Bathroom tap 6	2.5	0.16	8	5.63	15.96	OK
18	Shower 3	3	0.19	8	5.63	16.32	OK

Hot node system							
Number	**Description**						
21	Water heater					21.12	OK
22	Bathroom tap 1					20.89	OK
24	Shower 1					20.82	OK
25	Dish washer	2.75	0.17	8	5.63	19.72	OK
26	Kitchen sink					19.98	OK
27	Washing machine					21.10	OK
28	Shower 2					21.10	OK
30	Bathroom tap 2					21.10	OK
31	Bathroom tap 3					21.10	OK
32	Bathroom tap 4					21.10	OK
35	Bathroom tap 5					21.10	OK
36	Bathtub					21.10	OK
37	Bathroom tap 6					21.10	OK
38	Shower 3					21.10	OK

A.7. house 2 – Layout 3

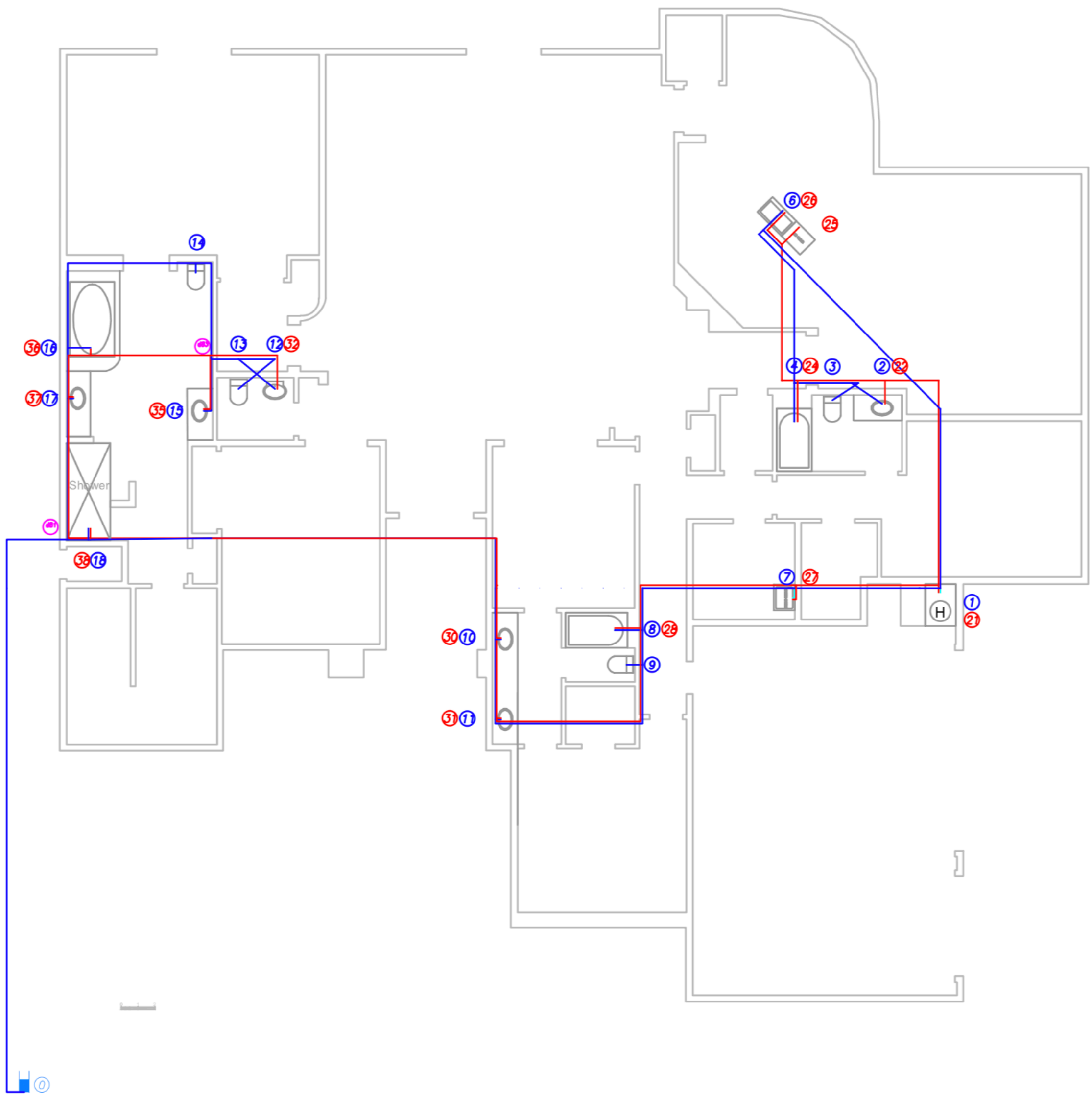

Figure A-13: house 2, layout 3 for both hot (red) and cold (blue) systems

Table A-15: house 2 - Layout 3: Pipe description

Piping description - Cold					
Number	**Node from**	**Node to**	**Diameter [mm]**	**Length [m]**	**K total**
1	res	d81	25.4	14.43	0.9
2	1	6	25.4	10.13	1.9
3	d81	18	25.4	0.53	0.6
4	6	4	19.05	3.99	1.9
5	4	2	19.05	1.35	1.5
6	2	3	19.05	0.5	0.6
7	1	7	25.4	3.42	0.6
8	7	8	25.4	4.56	1.5
9	8	9	25.4	0.81	0.6
10	9	11	25.4	4.95	2.4
11	11	10	25.4	1.89	0.6
12	10	18	25.4	12.43	1.5
13	d81	17	19.05	3.32	1.8
14	17	16	19.05	1.19	0.6
15	16	14	19.05	5	1.5
16	14	d83	19.05	2.62	1.5
17	d83	15	12.7	1.21	0.6
18	d83	12	12.7	0.65	1.8
19	12	13	12.7	0.5	0.6

Piping description - Hot					
Number	**Node from**	**Node to**	**Diameter [mm]**	**Length [m]**	**K total**
20	21	22	19.05	6.09	2.7
21	22	24	19.05	2.06	0.6
22	24	25	12.7	3.56	1.5
23	25	26	12.7	0.48	1
24	21	27	25.4	3.35	0.6
25	27	28	25.4	3.66	1.5
26	28	31	25.4	5.59	2.4
27	31	30	25.4	1.96	0.6
28	30	38	19.05	12.42	1.5
29	38	37	19.05	3.32	1.5
30	37	36	19.05	1.5	1.5
31	36	d103	12.7	2.81	0.6
32	d103	35	12.7	1.27	1.8
33	d103	32	12.7	1.57	0.6

Table A-16: house 2 - Layout 3 nodal description, code requirements, and design results

Cold node system		**Demand**		**Pressure**			
				Requirement		**Results**	
Number	**Description**	**[GPM]**	**[L/s]**	**[psi]**	**[m]**	**[m]**	**OK?**
1	Water heater	0	0	0	0	16.63	OK
2	Bathroom tap 1	2.5	0.16	8	5.63	15.29	OK
3	WC 1	3	0.19	20	14.07	15.17	OK
4	Shower 1	3	0.19	8	5.63	15.78	OK
6	Kitchen sink	2.5	0.16	8	5.63	16.33	OK
7	Washing machine	2.5	0.16	8	5.63	16.61	OK
8	Shower 2	3	0.19	8	5.63	17.36	OK
9	WC 2	3	0.19	20	14.07	17.16	OK
10	Bathroom tap 2	2.5	0.16	8	5.63	18.94	OK
11	Bathroom tap 3	2.5	0.16	8	5.63	18.25	OK
12	Bathroom tap 4	2.5	0.16	8	5.63	20.04	OK
13	WC 3	3	0.19	20	14.07	19.71	OK
14	WC 4	3	0.19	20	14.07	20.53	OK
15	Bathroom tap 5	2.5	0.16	8	5.63	20.40	OK
16	Bathtub	4	0.25	20	14.07	20.19	OK
17	Bathroom tap 6	2.5	0.16	8	5.63	20.99	OK
18	Shower 3	3	0.19	8	5.63	21.09	OK
Hot node system							
Number	**Description**						
21	Water heater					16.63	OK
22	Bathroom tap 1					16.39	OK
24	Shower 1					16.32	OK
25	Dish washer	2.75	0.17	8	5.63	15.21	OK
26	Kitchen sink					15.48	OK
27	Washing machine					16.61	OK
28	Shower 2					16.61	OK
30	Bathroom tap 2					16.61	OK
31	Bathroom tap 3					16.61	OK
32	Bathroom tap 4					16.61	OK
35	Bathroom tap 5					16.61	OK
36	Bathtub					16.61	OK
37	Bathroom tap 6					16.61	OK
38	Shower 3					16.61	OK

A.8. house 2 – Layout 4

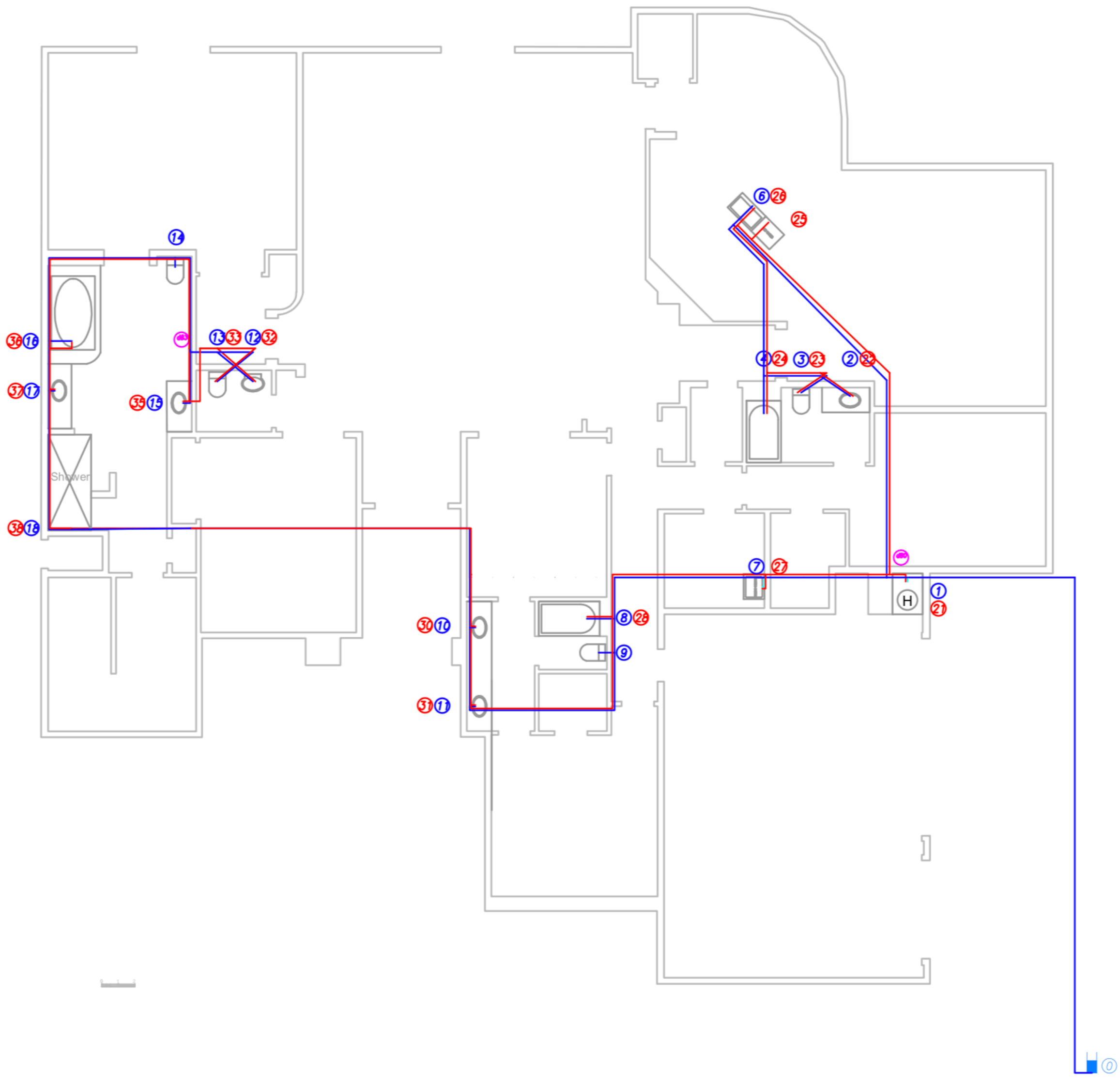

Figure A-14: house 2, layout 4 for both hot (red) and cold (blue) systems

Table A-17: house 2 - Layout 4: Pipe description

Piping description - Cold					
Number	Node from	Node to	Diameter [mm]	Length [m]	K total
1	res	1	25.4	15.85	0.9
2	1	d80	25.4	0.5	0.6
3	d80	6	19.05	9.94	2.2
4	6	4	19.05	3.99	1.5
5	4	2	12.7	1.35	1.5
6	2	3	12.7	0.5	0.6
7	d80	7	25.4	2.94	0.6
8	7	8	25.4	4.56	1.5
9	8	9	25.4	0.81	0.6
10	9	11	25.4	4.95	2.4
11	11	10	25.4	1.89	0.6
12	10	18	25.4	12.43	1.5
13	18	17	19.05	3.32	1.5
14	17	16	19.05	1.19	0.6
15	16	14	19.05	5	1.5
16	14	d83	19.05	2.62	1.5
17	d83	15	12.7	1.21	0.6
18	d83	12	12.7	0.65	1.8
19	12	13	12.7	0.5	0.6

Piping description - Hot					
Number	Node from	Node to	Diameter [mm]	Length [m]	K total
30	21	d80	25.4	0.38	0
31	d80	25	19.05	9.38	2.2
32	25	26	12.7	0.48	0.6
33	26	24	12.7	3.78	1
34	24	22	12.7	1.27	1.5
35	d80	27	25.4	2.97	0.6
36	27	28	25.4	3.66	1.5
37	28	31	25.4	5.59	2.4
38	31	30	25.4	1.96	0.6
39	30	38	19.05	12.42	1.5
40	38	37	19.05	3.32	1.5
41	37	36	19.05	1.5	1.5
42	36	35	12.7	8.89	2.4
43	35	32	12.7	3.04	3.3
44	22	23	12.7	0.5	0.6
45	32	33	12.7	0.5	0.6

Table A-18: house 2 - Layout 4 nodal description, code requirements, and design results

Cold node system		**Demand**		**Pressure**			
				Requirement		**Results**	
Number	**Description**	**[GPM]**	**[L/s]**	**[psi]**	**[m]**	**[m]**	**OK?**
1	Water heater	0	0	0	0	21.12	OK
2	Bathroom tap 1	2.5	0.16	8	5.63	17.20	OK
3	WC 1	3	0.19	20	14.07	16.92	OK
4	Shower 1	3	0.19	8	5.63	18.97	OK
6	Kitchen sink	2.5	0.16	8	5.63	19.49	OK
7	Washing machine	2.5	0.16	8	5.63	19.70	OK
8	Shower 2	3	0.19	8	5.63	18.93	OK
9	WC 2	3	0.19	20	14.07	18.36	OK
10	Bathroom tap 2	2.5	0.16	8	5.63	17.66	OK
11	Bathroom tap 3	2.5	0.16	8	5.63	17.61	OK
12	Bathroom tap 4	2.5	0.16	8	5.63	15.01	OK
13	WC 3	3	0.19	20	14.07	14.67	OK
14	WC 4	3	0.19	20	14.07	15.50	OK
15	Bathroom tap 5	2.5	0.16	8	5.63	15.37	OK
16	Bathtub	4	0.25	20	14.07	15.15	OK
17	Bathroom tap 6	2.5	0.16	8	5.63	15.96	OK
18	Shower 3	3	0.19	8	5.63	16.32	OK

Hot node system							
Number	**Description**						
21	Water heater					21.12	OK
22	Bathroom tap 1					20.79	OK
24	Shower 1					20.79	OK
25	Dish washer	2.75	0.17	8	5.63	20.53	OK
26	Kitchen sink					20.79	OK
27	Washing machine					21.10	OK
28	Shower 2					21.10	OK
30	Bathroom tap 2					21.10	OK
31	Bathroom tap 3					21.10	OK
32	Bathroom tap 4					21.10	OK
35	Bathroom tap 5					21.10	OK
36	Bathtub					21.10	OK
37	Bathroom tap 6					21.10	OK
38	Shower 3					21.10	OK

APPENDIX B - EXTENDED RESULTS

B.1. Pressure: Code versus simulated demands

B.1.1. house 1

Table B-1: Pressures required and obtained for each node in meters of water, using the Uniform Plumbing Code and simulated demands for house 1

		Layout 1		Layout 2		Layout 3	
Node	**Required**	**Code**	**Simulation**	**Code**	**Simulation**	**Code**	**Simulation**
Water heater	0	21.63	19.21	21.63	19.21	23.75	25.70
Kitchen sink	5.63	23.16	22.06	23.16	22.06	23.62	26.40
Washing machine	5.63	21.49	20.10	21.49	20.10	24.04	26.71
Bath tube/shower 1	5.63	23.84	26.86	23.84	26.86	22.58	26.59
WC1	14.07	24.05	26.84	23.98	26.84	22.72	26.57
Bathroom tap 1	5.63	23.71	26.71	23.81	26.73	22.54	26.46
WC2	14.07	21.15	26.69	20.99	26.61	20.62	26.48
Bathroom tap 2	5.63	21.48	26.76	21.52	26.77	21.34	26.50
Shower 2	5.63	16.12	23.31	16.40	23.33	14.22	22.98
WC3	14.07	16.69	23.20	16.73	23.11	14.54	22.77
Bathroom tap 3	5.63	16.69	23.41	16.73	23.42	14.55	23.07
Dishwasher	5.63	21.00	18.30	21.00	18.30	23.12	24.79

Table B-2: (cont.) Pressures required and obtained for each node in meters of water, using the code and simulated demands, for house 1

		Layout 4		Layout 5	
Node	**Required**	**Code**	**Simulation**	**Code**	**Simulation**
Water heater	0	25.62	25.52	25.27	25.63
Kitchen sink	5.63	25.92	25.95	25.61	26.49
Washing machine	5.63	25.47	26.40	25.12	26.52
Bath tube/shower 1	5.63	24.55	27.13	20.65	25.37
WC1	14.07	25.13	27.16	20.80	24.87
Bathroom tap 1	5.63	25.14	27.19	20.38	24.71
WC2	14.07	25.64	27.53	22.67	26.14
Bathroom tap 2	5.63	25.97	27.53	22.99	26.24
Shower 2	5.63	19.25	23.82	19.02	23.73
WC3	14.07	19.82	23.76	19.59	23.67
Bathroom tap 3	5.63	19.82	24.01	19.59	23.91
Dishwasher	5.63	24.91	24.67	24.56	24.54

B.1.2. house 2

Table B-3: Pressures required and obtained for each node in meters of water, using the code and simulated demands for house 2

		Layout 1		Layout 2		Layout 3	
Description	**Required**	**Code**	**Simulated**	**Code**	**Simulated**	**Code**	**Simulated**
Water heater	0	21.12	26.88	21.12	26.88	16.63	25.46
Bathroom tap 1	5.63	15.40	26.15	17.20	26.56	15.29	25.43
WC 1	14.07	14.96	25.87	16.92	26.30	15.17	25.25
Shower 1	5.63	15.28	25.52	18.97	26.59	15.78	25.41
Kitchen sink	5.63	15.28	25.48	19.49	26.78	16.33	25.52
Washing machine	5.63	19.70	26.82	19.70	26.82	16.61	25.60
Shower 2	5.63	18.81	25.74	18.93	26.42	17.36	25.42
WC 2	14.07	18.22	25.83	18.36	26.57	17.16	25.74
Bathroom tap 2	5.63	18.44	26.36	17.66	26.61	18.94	26.10
Bathroom tap 3	5.63	17.83	26.06	17.61	26.59	18.25	25.88
Bathroom tap 4	5.63	17.85	26.65	15.01	26.27	20.04	26.82
WC 3	14.07	17.41	26.65	14.67	26.27	19.71	26.82
WC 4	14.07	17.69	26.64	15.50	26.32	20.53	26.87
Bathroom tap 5	5.63	17.69	26.40	15.37	26.01	20.40	26.56
Bathtub	14.07	16.49	26.40	15.15	26.29	20.19	26.84
Bathroom tap 6	5.63	17.15	26.63	15.96	26.48	20.99	26.97
Shower 3	5.63	15.95	26.61	16.32	26.56	21.09	26.98
Dish washer	5.63	18.43	25.15	19.98	26.10	15.47	24.58

B.2. Water age – Impact of Layout

B.2.1. house 1

Table B-4: Results summary for house 1 layouts, simulation 30 days, ages computed at the outlet nodes

Simulation time [day]		30				
Location		At the outlet				
		Layout				
		1	**2**	**3**	**4**	**5**
Cold	**Abs. max [hr]**	58.2	58.2	58.3	58.1	58.1
	Mean max [hr]	36.0	35.8	35.8	35.9	37.6
	Mean [hr]	9.0	8.7	9.0	8.8	9.2
Hot	**Abs. max [hr]**	68.7	68.7	68.7	68.7	68.7
	Mean max [hr]	55.4	55.4	56.2	55.8	56.6
	Mean [hr]	21.2	21.2	21.0	21.4	22.2

Table B-5: Results summary for house 1 layouts, simulation 90 days, ages computed at the outlet nodes

Simulation time [day]		90				
Location		At the outlet				
		Layout				
		1	**2**	**3**	**4**	**5**
Cold	**Abs. max [hr]**	86.9	86.9	87.1	86.9	86.9
	Mean max [hr]	46.8	45.9	42.1	50.5	51.6
	Mean [hr]	10.6	10.1	10.2	10.0	10.2
Hot	**Abs. max [hr]**	96.7	96.7	96.8	126.3	115.3
	Mean max [hr]	65.3	65.3	65.2	78.4	78.3
	Mean [hr]	24.2	24.2	24.0	25.3	26.1

Table B-6: Results summary for house 1 layouts, simulation 30 days, ages computed at the distribution pipe

Simulation time [day]		30				
Location		At the distribution pipe				
		Layout				
		1	**2**	**3**	**4**	**5**
Cold	**Abs. max [hr]**	58.2	19.9	21.0	58.1	58.1
	Mean max [hr]	22.7	13.0	13.6	31.1	23.8
	Mean [hr]	5.8	3.2	3.8	7.5	6.2
Hot	**Abs. max [hr]**	67.3	67.3	67.3	67.4	67.4
	Mean max [hr]	44.6	44.6	43.0	51.0	46.0
	Mean [hr]	16.6	16.6	16.0	18.5	17.7

Table B-7: Results summary for house 1 layouts, simulation 90 days, ages computed at the distribution pipe

	Simulation time [day]	90				
	Location	At the distribution pipe				
		Layout				
		1	**2**	**3**	**4**	**5**
Cold	**Abs. max [hr]**	86.9	21.0	24.3	86.9	86.9
	Mean max [hr]	31.3	15.3	16.1	44.7	34.1
	Mean [hr]	7.0	3.5	4.3	8.4	7.1
Hot	**Abs. max [hr]**	96.3	96.3	96.8	98.9	98.9
	Mean max [hr]	55.7	55.7	51.7	67.6	61.4
	Mean [hr]	19.8	19.8	19.2	21.3	20.3

B.2.2. house 2

Table B-8: Results summary for house 2 layouts, simulation 30 days, ages computed at the outlet nodes

	Simulation time [day]	30		
	Location	At the outlet		
		Configuration		
		1	**2**	**3**
Cold	**Abs. Max [hr]**	147.4	127.2	131.2
	Mean max [hr]	60.3	56.8	57.6
	Mean [hr]	24.0	24.6	24.4
Hot	**Max [hr]**	196.6	171.7	176.0
	Mean max [hr]	108.5	105.5	107.8
	Mean [hr]	61.2	57.9	59.6

Table B-9: Results summary for house 2 layouts, simulation 90 days, ages computed at the outlet nodes

	Simulation time [day]	90		
	Location	At the outlet		
		Configuration		
		1	**2**	**3**
Cold	**Abs. Max [hr]**	182.4	137.9	145.6
	Mean max [hr]	70.9	65.7	65.6
	Mean [hr]	25.4	25.9	25.8
Hot	**Max [hr]**	211.8	190.0	194.4
	Mean max [hr]	126.3	121.2	124.3
	Mean [hr]	65.4	61.4	62.9

Table B-10: Results summary for house 2 layouts, simulation 30 days, ages computed at the distribution pipe

	Simulation time [day]	30		
	Location	At the distribution pipe		
			Configuration	
		1	**2**	**3**
Cold	**Abs. Max [hr]**	147.4	37.5	40.3
	Mean max [hr]	39.7	17.8	18.7
	Mean [hr]	8.9	5.0	4.9
Hot	**Abs. Max [hr]**	134.2	86.7	87.2
	Mean max [hr]	68.3	59.3	61.0
	Mean [hr]	29.3	24.4	26.1

Table B-11: Results summary for house 2 layouts, simulation 90 days, ages computed at the distribution pipe

	Simulation time [day]	90		
	Location	At the distribution pipe		
			Configuration	
		1	**2**	**3**
Cold	**Abs. Max [hr]**	182.4	47.4	54.7
	Mean max [hr]	45.6	19.4	19.8
	Mean [hr]	9.4	5.2	5.0
Hot	**Abs. Max [hr]**	162.4	131.4	131.6
	Mean max [hr]	83.4	75.1	77.5
	Mean [hr]	30.9	25.7	27.2

B.3. Water age – Impact of Heater type

B.3.1. house 1

Table B-12: Results for different water heaters at fixtures, house 1, 30-day simulation

Simulation time [day]		30				
Location		At the outlet				
		Layout				
		1	**2**	**3**	**4**	**5**
Traditional	**Max [hr]**	68.7	68.7	68.7	68.7	68.7
	Mean max [hr]	55.4	55.4	56.2	55.8	56.6
	Mean [hr]	21.2	21.2	21.0	21.4	22.2
Instant	**Max [hr]**	66.0	66.0	66.0	66.1	66.1
	Mean max [hr]	44.7	44.7	44.5	45.3	45.5
	Mean [hr]	12.2	12.2	12.0	12.4	12.9
Variation	**Max [%]**	-3.9	-3.9	-3.9	-3.9	-3.9
	Mean max [%]	-19.3	-19.3	-20.8	-18.9	-19.7
	Mean [%]	-42.4	-42.4	-42.8	-42.2	-41.9

Table B-13: Results for different water heaters at fixtures, house 1, 90-day simulation

Simulation time [day]		90				
Location		At the outlet				
		Layout				
		1	**2**	**3**	**4**	**5**
Traditional	**Abs. Max [hr]**	96.7	96.7	96.8	126.3	115.3
	Mean max [hr]	65.3	65.3	65.2	78.4	78.3
	Mean [hr]	24.2	24.2	24.0	25.3	26.1
Instant	**Abs. Max [hr]**	94.1	93.9	93.9	112.3	100.8
	Mean max [hr]	61.9	61.9	61.3	64.8	63.9
	Mean [hr]	14.6	14.6	14.4	14.9	15.6
Variation	**Abs. Max [%]**	-2.7	-2.9	-3.0	-11.1	-12.6
	Mean max [%]	-5.2	-5.3	-5.9	-17.3	-18.3
	Mean [%]	-39.5	-39.5	-39.9	-41.1	-40.1

Table B-14: Results for different water heaters at the distribution pipe, house 1, 30-day simulation

	Simulation time [day]	30				
	Location	At the distribution pipe				
				Layout		
		1	**2**	**3**	**4**	**5**
Traditional	**Abs. Max [hr]**	67.3	67.3	67.3	67.4	67.4
	Mean max [hr]	44.6	44.6	43.0	51.0	46.0
	Mean [hr]	16.6	16.6	16.0	18.5	17.7
Instant	**Abs. Max [hr]**	66.0	66.0	66.0	66.0	66.0
	Mean max [hr]	29.7	29.7	27.5	39.2	31.6
	Mean [hr]	7.8	7.8	7.2	9.7	8.7
Variation	**Abs. Max [%]**	-2.0	-2.0	-2.0	-2.0	-2.0
	Mean max [%]	-33.3	-33.3	-36.0	-23.1	-31.3
	Mean [%]	-52.7	-52.7	-55.1	-47.8	-50.7

Table B-15: Results for different water heaters at the distribution pipe, house 1, 90-day simulation

	Simulation time [day]	90				
	Location	At the distribution pipe				
				Layout		
		1	**2**	**3**	**4**	**5**
Traditional	**Abs. Max [hr]**	96.3	96.3	96.8	98.9	98.9
	Mean max [hr]	55.7	55.7	51.7	67.6	61.4
	Mean [hr]	19.8	19.8	19.2	21.3	20.3
Instant	**Abs. Max [hr]**	87.0	87.0	87.0	87.0	87.0
	Mean max [hr]	40.7	40.7	37.9	52.8	43.4
	Mean [hr]	9.0	9.0	8.4	11.0	10.0
Variation	**Abs. Max [%]**	-9.6	-9.6	-10.1	-12.0	-12.0
	Mean max [%]	-26.9	-26.9	-26.7	-21.9	-29.2
	Mean [%]	-54.6	-54.6	-56.5	-48.3	-50.6

B.3.2. house 2

Table B-16: Results for different water heaters at the outlet, house 2, 30-day simulation

	Simulation time [day]	30		
	Location	At the outlet		
			Layout	
		1	**2**	**3**
Traditional	**Abs max [hr]**	196.6	171.7	176.0
	Mean max [hr]	108.5	105.5	107.8
	Mean [hr]	61.2	57.9	59.6
Instant	**Abs max [hr]**	179.7	154.6	159.2
	Mean max [hr]	92.9	91.0	93.7
	Mean [hr]	49.0	45.4	46.9
Variation	**Abs max [hr]**	-8.6	-10.0	-9.5
	Mean max [%]	-14.3	-13.8	-13.1
	Mean [%]	-19.9	-21.7	-21.3

Table B-17: Results for different water heaters at the outlet, house 2, 90-day simulation

	Simulation time [day]	90		
	Location	At the outlet		
			Layout	
		1	**2**	**3**
Traditional	**Abs max [hr]**	211.8	190.0	194.4
	Mean max [hr]	126.3	121.2	124.3
	Mean [hr]	65.4	61.4	62.9
Instant	**Abs max [hr]**	203.2	168.6	168.0
	Mean max [hr]	106.7	100.6	103.3
	Mean [hr]	51.7	47.5	49.0
Variation	**Abs max [hr]**	-4.0	-11.3	-13.6
	Mean max [%]	-15.6	-17.0	-16.9
	Mean [%]	-20.9	-22.6	-22.0

Table B-18: Results for different water heaters at the distribution pipe, house 2, 30-day simulation

	Simulation time [day]	30		
	Location	At the distribution pipe		
			Layout	
		1	**2**	**3**
Traditional	**Abs max [hr]**	134.2	86.7	87.2
	Mean max [hr]	68.3	59.3	61.0
	Mean [hr]	29.3	24.4	26.1
Instant	**Abs max [hr]**	120.9	78.2	78.3
	Mean max [hr]	52.0	44.0	46.9
	Mean [hr]	16.5	11.5	13.0
Variation	**Abs max [hr]**	-9.9	-9.8	-10.2
	Mean max [%]	-23.8	-25.8	-23.1
	Mean [%]	-43.8	-52.7	-50.2

Table B-19: Results for different water heaters at the distribution pipe, house 2, 90-day simulation

	Simulation time [day]	90		
	Location	At the distribution pipe		
			Layout	
		1	**2**	**3**
Traditional	**Abs max [hr]**	162.4	131.4	131.6
	Mean max [hr]	83.4	75.1	77.5
	Mean [hr]	30.9	25.7	27.2
Instant	**Abs max [hr]**	138.2	128.5	129.2
	Mean max [hr]	62.6	48.7	51.7
	Mean [hr]	17.1	11.8	13.2
Variation	**Abs max [hr]**	-14.9	-2.2	-1.8
	Mean max [%]	-24.9	-35.2	-33.3
	Mean [%]	-44.7	-54.1	-51.3

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