Triple Bottom Line (TBL) Analysis of *Legionella* Mitigation in Domestic Hot Water (DHW) Systems

Logan B. Stone

Civil and Architectural Engineering and Construction Management Department

Milwaukee School of Engineering

Author Note

Logan B. Stone, Civil and Architectural Engineering and Construction Management Department, Milwaukee School of Engineering.

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Correspondence concerning this article should be addressed to Logan B. Stone, 1025 N Broadway, Milwaukee, WI 53202. E-mail: stonelb@msoe.edu

Abstract

The purpose of this report is to present the results of a capstone project investigation in which *Legionella* mitigation methods of temperature control and chlorine disinfection in domestic hot water building systems were compared based on the triple bottom line (TBL), which includes safety, sustainability, and cost. The research goal was to provide a recommendation as to which of these mitigation tactics a typical project in the United States should incorporate when the owner is looking to control *Legionella*. The methods employed include a review of relevant literature and a hypothetical case study of a small immediate care facility adapted to represent a typical project. The design analysis included safety considerations, a life cycle assessment (LCA), and a life cycle cost analysis (LCCA) of both mitigation methods. The main results from the analysis show the chlorine disinfection system provides a 19.34% decrease in life cycle costs, and between a 40-65% decrease in the negative environmental impacts when compared to the temperature control system. The report concludes that chlorine disinfection is the better *Legionella* mitigation method based on the TBL. Further research is recommended to compare the *Legionella* mitigation methods not focused on in this report in a similar manner.

Keywords: Legionella, domestic hot water (DHW), temperature control, chlorine disinfection, water quality, triple bottom line (TBL), hypothetical case study, life cycle assessment (LCA), life cycle cost analysis (LCCA), domestic hot water recirculation (DHR), qualitative risk assessment

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Nomenclature

ANSI……………………………………………………..American National Standards Institute

ASCE……………………………………………...…………American Society of Civil Engineers

ASHRAE..………...American Society of Heating, Refrigerating, and Air-Conditioning Engineers

ASPE……………………………………………...…….American Society of Plumbing Engineers

ASTM……………………………………………...American Society for Testing and Materials

CDC……………………………………………...……Centers for Disease Control and Prevention

DBP………………………………………………………………....Disinfection By-Product

DHR…………………………………..………..……….……..…Domestic Hot Water Recirculation

DHW…………………..………...……….…Domestic Hot Water

EPA……………………………………………………..………Environmental Protection Agency

FGI…………………………………………………………….……Facility Guidelines Institute

FPS……………………………………………………………………………...…Feet Per Second

HAA……………………………………………………………………………….Haloacetic Acid

HWSFU……………………………………………………….……Hot Water Supply Fixture Unit

ICC………………………………………………………….….……International Code Council

IECC………………………..………………………International Energy Conservation Code

IPC……………………………………………………..………..…International Plumbing Code

ISO……...……………………………………… International Organization for Standardization

LCA…………………..………..………Life Cycle Assessment

LCCA……...………….………..………Life Cycle Cost Analysis

LCIA……..……………………..Life Cycle Impact Assessment

MCL……………………………………………………...………Maximum Containment Level

NASEM……………………………..National Academies of Sciences, Engineering, and Medicine

NPV…………………………………………………………………………...Net Present Value

NSPE………………………………………….…………National Society of Professional Engineers

PPM……………………………………………………………….………..Parts Per Million

TBL………..…………………………………………………...….……..…Triple Bottom Line

THM……………………………………………………………………….………Trihalomethane

TMV……………………………………………………………...…Thermostatic Mixing Valve

TRACI……...Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts

UPC…………………………………………………..………..……Uniform Plumbing Code

USEEIO Model………………...…..United States Environmentally Extended Input-Output Model

USEIA………………………...……………..United States Energy Information Administration

WEDC………………………………………………Water, Engineering and Development Centre

Triple Bottom Line (TBL) Analysis of *Legionella* Mitigation in Domestic Hot Water (DHR) Systems

In any industry, it is imperative to comprehensively understand design options intended to support public safety as such an understanding allows for direct comparisons and the determination of the most appropriate solution(s). To form, use, and analyze this all-encompassing understanding, it is important to adopt a *triple bottom line* (TBL) approach, a sustainability framework which combines the social, environmental, and economical aspects of a company, a product, or a design (Kucukvar et al., 2014; Melles et al., 2011). Understandably, individuals often initially overlook environmental and cost dimensions when formulating designs for safety purposes, as designers are ethically obligated to hold public health and safety paramount (Gorp, 2005; International Code Council [ICC], 2018; National Society of Professional Engineers [NSPE], 2019). However, after accumulating enough research on safety related design options, industries should transition to promoting sustainability and cost reduction without compromising safety (Gorp, 2005).

The plumbing industry is beginning to reach this transition point in domestic hot water [DHW] *Legionella* mitigation, as many design tactics in this area have been under thorough investigation for many years. *DHW* refers to a piping system used to supply potable, or drinkable, hot water. Unfortunately, DHW also usually provides the elements needed to promote the growth of *Legionella,* a bacterial genus known to cause two human respiratory diseases (National Academies of Sciences, Engineering, and Medicine [NASEM], 2020). Of the tactics used to mitigate this dangerous bacterium from these systems, temperature control and chlorine disinfection have become the most heavily discussed and researched because historically, they have improved water quality, are well understood by owners, and present low upfront costs

(McGuire, 2013; NASEM, 2020). Therefore, determining which of these design options most appropriately balances the three factors presented in the TBL can improve designer, owner, and industry professional decision making when looking to mitigate *Legionella*.

The purpose of this report is to present the results of a capstone project investigation in which *Legionella* mitigation methods of temperature control and chlorine disinfection in domestic hot water building systems were compared based on the TBL, which includes safety, sustainability, and cost. The research goal was to provide a recommendation as to which of these mitigation tactics a typical project in the United States should incorporate when the owner is looking to control *Legionella*. In other words, this report aims to answer the following question: How do the DHW *Legionella* mitigation methods of temperature control and chlorine disinfection compare with respect to safety, sustainability, and cost in a typical project in the United States? There is also a secondary objective to determine the most concerning aspects of each method, with the goal of promoting continual industry improvement in these areas.

The research in this capstone project indicates that each method has various advantages over the other in terms of the TBL, which designers and owners need to align with their priorities to make informed decisions. The research also indicates that both methods feature specific areas for improvement. To reach these findings, a standard literature review paired with a hypothetical case study of a typical project was employed to produce specific qualitative results. The presentation of the design analysis in this report includes a comparative discussion featuring the analysis of the specific safety concerns, life cycle assessment (LCA), and a life cycle cost analysis (LCCA) for each method.

This research is important to the plumbing industry, as qualitative guidance can lead to large scale improvements of public policy affecting commercial buildings concerned with

Legionella control. This capstone report also introduces the topic of using the TBL for evaluating *Legionella* mitigation, which can provide broader perspectives to owners and designers.

Background

It is necessary to understand a significant amount of background information before appropriately analyzing and comparing temperature control and chlorine disinfection based on the TBL. Important subtopics include an overview of *Legionella*, the bacterium's impact on public policy, and the mitigation tactics in domestic water systems, specifically temperature control and chlorine disinfection. These subtopics uniquely integrate with temperature control and chlorine disinfection. One should understand the context of the relationships between them, as well as the basis of the mitigation methods themselves. Therefore, it is also helpful to describe the two methods in greater detail.

Overview of *Legionella*

The *Legionella pneumophila* bacterium currently stands alone as the most catastrophic microorganism within domestic hot water systems, and its effect on the United States' population has only increased since its first official identification in 1976 (Winn, 1988). It is important to note that this capstone report features the use of the term *Legionella* in the broad genus sense, but that in reaching the findings, the capstone project investigation relied primarily on data specifically associated with the *Legionella pneumophila* species. This is acceptable considering *Legionella pneumophila* contains "the most prevalent disease-causing variant" (Zhang et al., 2014, p. 1242) of *Legionella* in serogroup 1. However, it must be acknowledged that this narrow focus of studying the single species recently has been identified as a primary limitation that is restricting mitigation development--so much so, the NASEM's report (2020) recommends the industry undergoes urgent development to allow the identification of "pathogenic *Legionella* beyond… serogroup 1" (p. 5). While this limitation is important for the industry to overcome, this capstone project relied on previous research targeting the distinct species, of which *L. pneumophila* is the most well understood and is known to cause the most extreme outbreaks. The use of accumulated data on just the *L. pneumophila* species to develop broad conclusions for the overall genus is a conventional approach in the literature. Therefore, no specific consideration was given to other species or serogroups during research.

NASEM (2020) provides an in-depth overview of *Legionella* with claims that are important to highlight. First, *Legionella* is more concerning than other significant pathogens, especially in DHW systems, because it thrives at a high temperature range and is known to be more resistant to traditional disinfection methods. Also, other pathogens are most commonly mitigated before the water reaches the building occupants, while *Legionella* can naturally occur in individual building DHW systems. Furthermore, *Legionella* is known to cause two human diseases: Pontiac fever, and Legionnaire's disease. Both diseases, which together professionals refer to as legionellosis, cause harmful respiratory infections. Legionnaire's disease is the more extreme result as it includes pneumonia and is sometimes fatal. People, especially *at-risk* individuals, are susceptible to the effects of the bacteria if they inhale it through water mists, which often form from mechanical and plumbing equipment, such as faucets, showers, decorative fountains, and cooling towers. The term *at-risk* refers to individuals who statistically have a higher chance of being infected by the bacteria, most notably, those over the age of 50, the immunosuppressed, or those who have a history of smoking (NASEM, 2020). To determine the best methods to reduce the harsh impact of *Legionella*, there needs to be a broad understanding of both its historical context and its current impact on the industry.

History

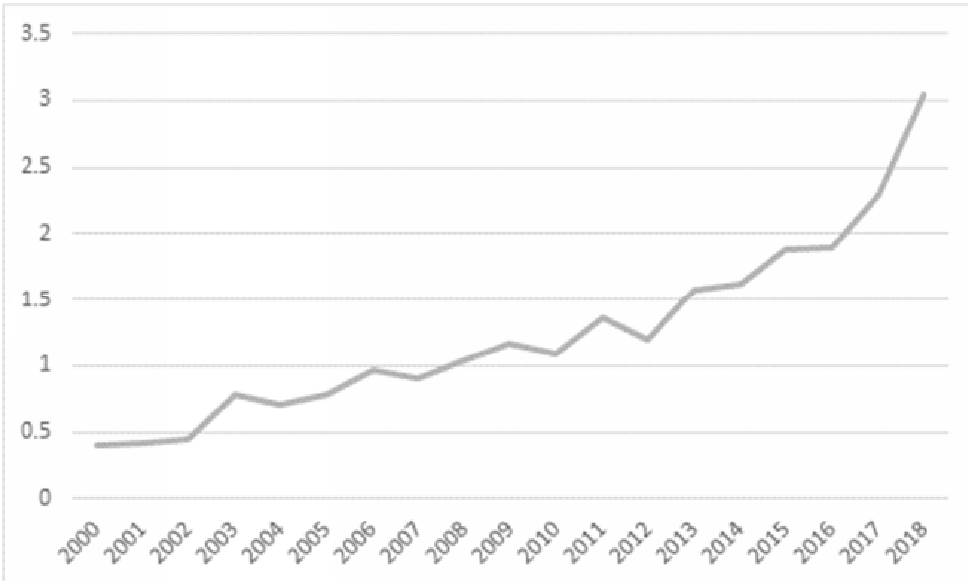
Winn (1988) provides useful historical information concerning *Legionella*. Health authorities have traced the history of *Legionella* to reported infection cases dating back to 1959. However, it was not until almost a decade after these initial cases that the first official case of Pontiac fever was reported in 1968, when multiple individuals were diagnosed with the newly discovered disease after being at a local health department in Pontiac, MI. Still, no one knew the direct cause of these seemingly spontaneous incidents until scientist Joseph McDade officially discovered the bacterium in 1976. This discovery came after the outbreak of Legionnaire's disease at the annual American Legion convention in Philadelphia, PA. The outbreak, due to cooling tower mist containing *Legionella*, infected 218 persons in total and caused the deaths of 29 of those individuals. Thus, research into mitigation tactics ensued (Winn, 1988).

Current Concern

Even with the evolving mitigation tactics across disciplines today, the incidence rate of Legionnaire's disease continues to increase. According to the Centers for Disease Control and Prevention, U.S. Department of Health and Human Services (2017), "The rate of reported cases of Legionnaires disease in the United States has increased more than four-fold since 2000" (p. [1]). This statistic is evident in Figure 1, which features information concerning the reported *incidence rate*, or total number of reported diagnoses per 100,000 individuals, of legionellosis in the United States. These reported statistics include cases resulting from all the previously listed mechanical and plumbing equipment responsible for exposing humans to the bacterium.

Figure 1

Incidence Rate of Legionellosis in the United States from 2000 to 2018



Note. Adapted from *Management of Legionella in Water Systems,* by the NASEM, 2020, National Academics Press, p. 2 (https://doi.org/10.17226/25474).

[a] Vertical axis portrays the annually reported incidence rate of legionellosis
[b] Horizontal axis portrays the years

Furthermore, between 2011 and 2012, *Legionella* was the cause of approximately two thirds of the infections associated with drinking water, making it the most concerning microorganism for domestic plumbing system designers by a substantial margin (Boppe et al., 2016, p. 230). Domestic water systems are crucial to consider because as *Legionella* mitigation activist, Janet Stout, states, “Potable drinking water systems, particularly warm water systems in building water systems is the most significant source of exposure for *Legionella*” (Doll, 2018, 2:00). While the plumbing industry has adopted many changes because of the concerns the bacterium poses, it is evident there is still much to do in terms of studying mitigation methods and implementing changes. As a result, DHW systems have drawn the attention of many researchers. Commercial DHW systems, specifically examples in the healthcare industry, are primary topics of this research because they are especially susceptible to bacterial growth and have the potential to affect large occupant populations with high risk levels (NASEM, 2020). Because of this large safety concern, *Legionella* has had a major impact on public policy relating to the commercial plumbing industry. Other public policies significantly affected by *Legionella* include those related to the HVAC, healthcare, manufacturing, and hospitality industries.

Plumbing Public Policy

This capstone report features a very heavy public policy component because of how *Legionella* research has impacted plumbing codes and standards. Plumbing codes and standards are the driving requirements and recommendations for plumbing designers to conform to in their designs. It is important in the context of this research to differentiate between them as they often have different requirements and may apply to projects differently. Legally adopted plumbing codes are the minimum plumbing system performance criteria that are required by law, and can be adopted statewide or locally. Code officials, or technical professionals, who aid in code adoption processes, often help the elected officials make informed decisions regarding building code selections. In terms of policy, it is crucial that professional opinions are what ultimately serve to develop the codes and standards, and therefore, design professionals often help aid in the process as well (Sauer, 2013). The extreme safety concern *Legionella* poses has led to changes in codes and formation of standards across the plumbing industry, and they continue to evolve based on research and experience (Ballanco, 2019). These changes have caused many *Legionella* mitigation DHW design methods to be developed with the goal of limiting the bacteria in these systems and maintaining proper code and standard compliancy (Cotruvo, 2020).

Legionella Mitigation Tactics

The primary designs used to control *Legionella* in DHW systems are temperature control, chemical disinfection (primarily including chlorine, chlorine dioxide, monochloramine, and ozone as agents), copper-silver ionization, and UV irradiation (NASEM, 2020). Each of the methods has unique advantages, disadvantages, and integration complexities which plumbing designers must balance to determine the best solution for a particular project. Information on these methods, such as requirements, preferred water characteristics, and standards, can be seen in Appendix A.

Temperature control and chlorine (specifically, free chlorine) disinfection are the two most discussed methods and are often the first options building owners turn to. The popularity of temperature control is clear in Appendix A, as there are no negative byproducts and minimal restrictions, which provide simplicity and flexibility for designers and owners. Free chlorine, which for simplicity this report refers to as chlorine, is popular because of a historical reason, as life expectancy increased significantly after it was nationally introduced in municipal water in the United States (McGuire, 2013). Both temperature control and chlorine disinfection are also marketable to owners as featuring the lowest upfront cost solutions of all the methods (Cotruvo, 2020; NASEM, 2020). For these reasons, when considering all the mitigation options, comparing chlorine disinfection with temperature control has the greatest impact on the industry at this time, and therefore, is most beneficial to research. Elements which affect the design of both methods include preventive versus curative control, temperature maintenance, and dead leg mitigation.

Preventive versus Curative Control

Depending on their designs, temperature control and chlorine disinfection have varying preventive and curative capabilities when it comes to *Legionella*. Designers implement *preventive* control in new construction or renovation projects to maintain appropriate water quality with the goal of preventing *Legionella* from becoming present within the system. The purpose of *curative* control is to remove *Legionella* already detected within the system. Limiting the scope of this capstone report to preventive mitigation is important because the primary goal should be for designers to not allow *Legionella* to initially form in the system, rather than needing to react to the issues that arise (NASEM, 2020).

Temperature Maintenance

When looking to implement either temperature control or chlorine disinfection designs, it is important to first consider temperature maintenance, the most common solution being hot water recirculation. *Hot water recirculation* is the act of providing constant and steady flow of hot water in a piping system for the primary purpose of maintaining an appropriate water temperature at all points in the system. *Domestic* hot water recirculation [DHR] is simply hot water recirculation used in a DHW plumbing system (Polarczyk & Fijewski, 2017). DHR features the use of a circulation pump on the return line near the water heater to keep flow moving throughout the DHW system. To accomplish this, the pipe network is in a loop or multi-loop format. The loop(s) feed(s) into a recirculation main that sends the water back to the heater. There are many ways to design DHR, but commonly, the circulation pipe main or loops attach to the hot water pipe at a point that is less than a predefined maximum length from plumbing fixtures (Rhoads, 2017).

The other primary temperature control method, *heat trace*, is a legally acceptable substitute for DHR in many jurisdictions, as it maintains water temperature throughout the system by heating directly through the pipes by an electric coil (Silva, 2020). However, heat trace is less common as it is often more expensive and less effective at maintaining proper water quality because of minimizing flow in the pipe network. Therefore, this capstone project investigation considered only DHR for temperature maintenance, which is important when considering dead leg mitigation.

Dead Leg Mitigation

Dead legs are pipe runs where water does not continually flow, which are especially concerning in DHW because this stagnant water can cool to more beneficial *Legionella* growth temperatures resulting from natural heat loss (Rhoads, 2017). Industry professionals often misunderstand a dead leg as only being the developed length of pipe away from a hot water source, as described in codes (ICC, 2018, Section 607.2). However, one should better define a dead leg as any point in the plumbing system where the water becomes stagnant, or does not move for an extended period of time. This clarification becomes important when considering small pipe crevices or in fitting joints, which can create smaller dead legs that are less noticeable. Minimizing the number and lengths of dead legs, both large and small, is becoming more popular in plumbing design because of their recognized danger and this is especially important in mitigation tactics (George, 2019; NASEM, 2020). Both temperature control and chlorine disinfection require the consideration of factors such as dead legs, temperature maintenance, and preventive control, but it is also important to understand the unique characteristics in each method separately.

Temperature Control

Temperature control is arguably becoming the most widely used *Legionella* mitigation method in new construction projects (Caleffi Hydronic Solutions, 2020). This is primarily due to its effectiveness at limiting *Legionella* growth, and the general understanding of water temperature maintenance within the plumbing industry. Temperature control has many noteworthy factors, but the most unique include system temperatures and their scalding potential, and the temperature control location. These are the primary factors designers need to consider when looking to apply this method, as opposed to others, to a specific project (NASEM, 2020).

System Temperatures and Scalding

According to the NASEM (2020), preventive temperature control is the use of continually "elevated temperatures (greater than [131°F]) to limit colonization and growth of *Legionella* across hot-water systems" (p. 168). Designers can consider heat shocking, or a process of higher temperature elevation (between 140°F and 158°F) for a specific time period, to be a preventive measure if used consistently. However, the extreme temperature differential can cause issues such as pipe degradation, equipment damage, and scalding potential (NASEM, 2020). Therefore, in this capstone project investigation, this method was not evaluated.

As the NASEM (2020) suggests, designers can use elevated temperatures to accomplish preventive control as there is a fairly agreed upon relationship between the state of *Legionella* and the temperature of the DHW. Figure 2 features the relationship between water temperature and the state of *Legionella*. Information provided in the figure has been cross referenced with various sources to ensure values are representing industry agreement (Caleffi, 2020; George, 2019; NASEM, 2020).

Figure 2

Legionella State and Water Temperature Relationship

Above 158 F	•• Disinfection Range
151 F	•• Legionellae die within 2 minutes
140 F	•• Legionellae die within 32 minutes •• Risk of scalding
Above 122 F	•• Legionellae can survive but do not multiply
68 F – 122 F	•• Legionellae growth range •• Ideal growth range is 95 F-115 F
Below 68 F	•• Legionellae can survive, but are dormant. •• Ideal for cold water storage, piping, fountains, etc.

Note. Adapted from “Legionella Awareness”, by Corzan Piping Systems, first figure on the site (https://plumbing.corzan.com/health-safety/legionella-awareness/).

Often, sources also include 131°F as another temperature milestone on the basis that the bacteria have no growth potential and die over the span of several hours (NASEM, 2020). This is important as the NASEM (2020) recommends that “For all types of buildings, hot-water heater temperature should be maintained above [140°F], and the hot-water temperature to distal points should exceed [131°F]” (p. 6). However, in healthcare applications or other buildings with immunocompromised occupants, the risk of legionellosis is high enough to recommend at least a 140°F temperature at all points within the system (George, 2019). By only using heat, major components of the system are straightforward as such a system only requires a water heater and standard DHR components, both of which are standard in commercial applications. Nonetheless, it is also noteworthy that any water above 120°F has scalding, or burn, potential for occupants, especially immunosuppressed individuals. Table 1 exhibits the relationship between hot water temperatures, the time to typical occupant scalding, and *Legionella* growth potential.

Table 1

Water Temperature, Scalding Potential, and Legionella Growth

°F	°C	Time to First-degree Burn	Time to Second-degree Burn	*Legionella* Growth Potential
<77	<25			No
80	27			Low
90	32			Moderate
100	38			Very high
110	43			Very high
116	47	35 min	45 min	Moderate
122	50	1 min	5 min	Very low
131	55	5 sec	25 sec	No
140	60	2 sec	5 sec	No
149	65	1 sec	2 sec	No
154	68	instantaneous	1 sec	No

Note. Adapted from *Management of Legionella in Water Systems,* by the NASEM, 2020, National Academics Press, p. 175 (https://doi.org/10.17226/25474).

The *Legionella* growth potential in Table 1 does not refer to the complete mitigation of *Legionella* already present in the system, but only the prevention of their growth. Therefore, designers should use the temperatures in Figure 2 as temperature control recommendations in at-risk settings, as these temperatures represent the more complete preventive approach. However, designers need to be aware of the times to occupant scalding in Table 1 when using those temperatures. Hence, with water at or above the recommended 140°F serving every fixture, thermostatic mixing valves (TMVs)--valves that control the DHW temperature by appropriately mixing it with the domestic cold water--are required at every standard fixture using DHW to limit scalding potential (Caleffi, 2020; George, 2018; ICC, 2018).

Temperature Control Location

The final major point for temperature control designers to consider is whether to be more concerned with the temperature of the water at the heater and potential storage units, or throughout the piping network, such as fixture outlets or at the end of the recirculation loop. According to Polarczyk and Fijewski (2017), “Appropriately designed circulating system[s] should prevent water temperature decrease in DHW pipes” (p. [1]). Furthermore, the system “should also ensure appropriate water temperature at the outlet in the place of the point-of-use” (Polarczyk & Fijewski, 2017, p. [1]). Therefore, the typical method is to only be concerned with the temperature drop at the most distal fixture. This is often appropriate because the typical concern is to have hot water reach the user at an appropriate temperature to conserve water use. Yet, in high-risk applications such as healthcare, designers must minimize bacteria growth at all points in the system, even after the most distal fixture in DHR loop applications. Therefore, because of the concerning heat loss potential of the piping network, it is important to base the desired temperature at the end of the recirculation loop. However, since the water heater controls the temperature and is at the beginning of the recirculation loop, the temperature setpoint there needs to compensate for the heat losses for the entire system (Caleffi, 2020).

Chlorine Disinfection

Modern day evidence suggests that chlorine disinfection, the most common alternative to temperature control *Legionella* mitigation, continues to be the most popular water supply disinfection method in the United States (Abdel-Nour et al., 2013) as “it is convenient to use, effective against most waterborne pathogens, and continues disinfectant activity within the distribution system” (National Academy of Sciences, [NAS], 1980, p. 1). Because of this fact, “Chlorination is the standard disinfectant against which others are compared” (NAS, 1980, p. 1). One of the strongest benefits of chlorination versus other disinfection methods is its ability to continually disinfect the system through its residual that is detectable in the system (Water, Engineering and Development Centre [WEDC], 2011). *Legionella*, while not immune to this traditional disinfection method, has proven to be more resistive than most pathogens when determining appropriate residual levels (Cooper & Hanlon, 2010). For this system, it is especially important for designers to consider chlorine application, system components, and residual levels.

Chlorine Application Methods

The United States Environmental Protection Agency [EPA] (2016) states that "Chlorine [can be] added to drinking water as elemental chlorine (chlorine gas), sodium hypochlorite solution or dry calcium hypochlorite" (p. 25). Chlorine gas used to be the principal method, but safety concerns have caused the industry to recently switch to primarily using aqueous sodium hypochlorite (EPA, 2016). The most common means of acquiring sodium hypochlorite is by purchasing it as a twelve percent solution from a vendor and having it shipped directly to the building on a consistent schedule. This is the procedure that was assumed for this report. It is important to note that because of standard shipping time, it is typical to use ten percent in calculations as the disinfectant degrades over time. Having the solution be "generated onsite by the electrolysis of salt" (Cotruvo, 2020, p. 14) is possible, but it often has a higher upfront cost and more extensive maintenance, which most makes it less desirable (Rowe, 2013).

Chlorine System Components

The primary components of a sodium hypochlorite disinfection system, in addition to typical DHW components, include a sodium hypochlorite solution tank, chlorinator pump, injection line, retention tank, multi-media filter, and sodium hypochlorite (chlorine bleach) solution (Canature Water Group, 2019). In a DHW system application, the water heater can serve as the retention tank, with the setpoint temperature of the water at the heater being at the industry standard 120ºF. The sodium hypochlorite solution should be applied to the DHW to maintain the proper predefined residual.

Residual Levels

The Centers for Disease Control [CDC] (n.d.) refer to the official EPA (2020) website on the topic of maximum residual chlorine levels in drinking water, which states that the maximum contaminant level [MCL] of chlorine (as Cl_2) is 4.0 mg/L. This standard ensures no eye or nose irritation and no stomach discomfort resulting from chlorine intake and incorporates a proper safety factor established by the EPA. In terms of minimum recommended chlorination levels, the CDC (2014) states that there should be a chlorine residual concentration of 0.5 mg/L at fixture outlets to ensure normal disinfection. The CDC (2014) also recommends limiting residual chlorine concentration to at most 2.0 mg/L to preserve pleasant taste and odor, because for DHW, odor is the main concern. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) (2020) does not prescribe a specific residual concentration; however, they discuss the importance of both determining the appropriate residual level based on the present conditions, and understanding all the consequences that will ensue. Shock chlorination at much higher residuals is possible with appropriate flushing, but like heat shock, has many drawbacks in terms of pipe degradation and system maintenance (NASEM, 2020).

However, Lin et al. (1998) recommend that *Legionella* requires “subsequent maintenance concentrations of 2-4 mg/L” (p. 115). This range maintains the best disinfection efficacy possible while remaining below the standard safety limit of 4 mg/L. Nonetheless, some unintended effects of using this concentration continually could include changes in water taste and odor, as well as pipe degradation. The viability of this range assumes that there are no present *Legionella* bacteria within the system at the time the continual disinfection is initially implemented. It is also important to minimize water age (EPA, 2016), maintain water pH values between 6.0 and 7.0 (EPA, 2016; Kuchta et al., 1983), and monitor free chlorine levels due to its common degradation in high temperatures (EPA, 2016).

Disinfection By-products

When considering the use of sodium hypochlorite disinfection, it is also necessary to consider the effects of potentially harmful *disinfection by-products* (DBPs), which are the natural result of the disinfectant reacting to organic substances (CDC, 2016). The two most concerning DBPs for potable water chlorine disinfection are trihalomethanes (THMs) and haloacetic acids (HAAs), specifically chloroform and the five haloacetic acids, part of the group known as HAA5, which all have potential carcinogenic concerns when ingested (EPA, 2002). While none of the DBPs in question have sufficient evidence to prove their link to cancer, they are confined by legal limits to preserve public safety (CDC, 2016). The legal limit for THMs is in terms of the total THM (TTHM) concentrations as an annual average, which is 0.080 PPM. Chloroform is the most prevalent and concerning of these (EPA, 2002). Total HAAs are also limited in the same manner to 0.060 PPM (EPA, 2002). However, considering chloroform is the most harmful of all the DBPs in question, it can be representative of the harmful extreme that sodium hypochlorite can have on the water distribution. To appropriately consider DBPs in decision-making, it is important to quantify and compare carcinogenic and toxicity impacts.

Methods

The capstone project investigation presented in this report was based on information acquired from reliable secondary sources. Therefore, it is important to summarize the most important reference sources for this investigation and overall *Legionella* mitigation design before discussing specific methods used in this research. In addition to this review of relevant literature, the investigation involved an in-depth TBL analysis, which included a hypothetical case study, a qualitative risk assessment, a life cycle cost analysis (LCCA), and a life cycle assessment (LCA).

TBL analyses, hypothetical case studies, risk assessments, LCAs, and LCCAs are well endorsed methods for research. The primary evidence used to validate these methods include previously performed, well regarded studies, which use the methods separately. Therefore, to provide an appropriate understanding of each method, this report provides scholarly examples to accompany the methods' basic descriptions and specific requirements. To validate the use of all these methods in the capstone project, this report presents a brief overview of each, beginning with the relevant literature.

Important Reference Sources

Plumbing codes and standards are the driving requirements and recommendations for plumbing designers to conform to in their designs. It is important in the context of this research to differentiate between plumbing codes and plumbing standards. Legally adopted plumbing codes are the minimum plumbing system performance criteria required by law while standards are professionally reviewed recommendations for best practices. Guidelines are similar to standards but they undergo a less stringent review process. Depending on location, building type, and priorities, projects can have their own unique set of codes and standards applicable to the designer.

Applicable Codes

There are two primary sets of plumbing standards within the United States, known as the model plumbing codes, which municipality and state codes often reference or entirely adopt. The two model plumbing codes are the International Plumbing Code [IPC], written by the International Code Council [ICC], and the Uniform Plumbing Code [UPC], written by the

International Association of Plumbing and Mechanical Officials [IAPMO]. Most of the United States use one of these two models for at least a basis in their plumbing codes with the IPC being the most frequently adopted, but a few states and areas maintain entirely independent building codes. For perspective, the IPC is currently either in use or fully adopted in 35 states, and it has three requirements that are specifically applicable to this study. First, the maximum developed length of a dead leg, or the length between the plumbing fixture and the DHR, is 50 feet (ICC, 2018, Section 607.2). The second is that the tempered water running to the fixture through a temperature limiting device, must be no greater than 110°F (ICC, 2018, Section 607.1.2). Finally, pipe sizing is based on required fixture pressures, and hot water supply fixture units (HWSFU) tables and figures found throughout the code.

Another applicable code is the International Energy Conservation Code [IECC]. Currently, this code is administered at the local or state level within 48 states and is therefore necessary to consider. There are multiple applicable sections including aspects such as recirculation pump usage, pipe insulation, and acceptable dead leg lengths from fixtures. According to the IECC, for a circulation system, “The controls shall automatically turn off the pump when the water in the circulation loop is at the desired temperature and when there is not a demand for hot water” (ICC, 2018, Section C404.6.1). This is concerning to many professionals when considering *Legionella* control because while the temperature is met, the flow in the system stops when the hot water demand is met, which could allow *Legionella* to grow. However, since the IECC is adopted as code in most cases, it should be followed in this study to represent a typical example. IECC pipe insulation requirements are also applicable to this project. The last major applicable aspect the ICC (2018) has written in the IECC is the maximum pipe lengths from the fixture to the nearest heat source (i.e., domestic hot water loop). It requires that a public lavatory served by a half-inch nominal pipe size needs to be within two feet of a heat source, and any other fixture served by a half-inch pipe needs to be within forty three feet of the heat source.

Applicable Standards and Guidelines

Currently, there are three primary guidelines and one primary standard, which prioritize the management of *Legionella*. Municipalities most often do not reference these four documents as codes, but most of the language is presented in a way to easily transition the documents to code status in the future. ASHRAE (2000) Guideline 12-2000 was the first *Legionella* guideline implemented and provides a broad list of recommendations to control the bacterium. The organization recently released the current version of the guideline, ASHRAE (2020) Guideline 12-2020, which further discusses important considerations for potable water *Legionella* control. The American National Standards Institute (ANSI) and ASHRAE (2018) Standard 188 is a recently released formalized standard that describes the best practices for water management program implementation. This source is not as important to this capstone project report as it is primarily concerned with system water quality monitoring, which does not impact system comparisons. Another important guideline is the Facility Guidelines Institute's (FGI) (2018) *Guidelines for Design and Construction of Outpatient Facilities*, section 2.1-8.4.2.5 Heated potable water distribution systems. This guideline indicates the need for outpatient facilities to design DHW systems for *Legionella* control and promotes dead leg mitigation. The final and most substantial guideline to consider is NASEM (2020). Though it is not an official standard, this report extensively references NASEM's document as it is currently the most extensive and up to date *Legionella* resource based on viable research. This document includes many specific recommendations and example studies relating to both temperature control and chlorine disinfection, which formed the basis of the designs presented in this report. The use of these guidelines and standard form the basis for the methods of this report.

TBL Analysis

The discussion presented in Guest et al. (2010) helps to reiterate the point that a TBL analysis includes the integrated consideration of social, environmental, and economic aspects in decision-making, and specifically study its use in wastewater management. Tseng et al. (2020) agree that the TBL method has significantly improved since its first public introduction by Elkington (1998), but they argue the TBL needs to begin including aspects such as engineering, technology, and operations to properly analyze the entire concept of sustainability. It is still appropriate, however, to use the current TBL method in broad comparisons, such as its use in this capstone project investigation.

It is common for researchers to test a TBL analysis using a hypothetical case study. Janjua et al. (2020) used a literature review to form key performance indicators of residential buildings based on the TBL and then used a hypothetical case study to test these indicators. Lim and Biswas (2017) used the same methods to assess the Malaysian palm oil production and test their results. This capstone project investigation involved the use of a reverse process by first applying data from a literature review to a hypothetical case study (the design of the *Legionella* mitigation methods), and then analyzing decisions using the TBL. Reversing the typical process is beneficial because the use of appropriate assumptions can allow for the informative generalization of data inherently specific to the hypothetical case study. In the case of this capstone project investigation, the data were generalized to represent a typical project in the United States.

Hypothetical Case Study

Hypothetical case studies are applicable in a wide range of research topics and are becoming more applicable as modeling software and techniques improve (Bricker et al., 2012). Researchers often use hypothetical case studies to estimate environmental and cost impacts, similar to the methods employed in this capstone project investigation. Bricker et al. (2012) use a hypothetical CO_2 injection in a specific groundwater source to simulate its environmental impacts. Fan et al. (2000) use a hypothetical design of a stormwater harvesting system to simulate its cost effectiveness in industrial applications. This capstone project investigation combines the methods used in the example literature (environmental impact and cost evaluations) and adds the use of a risk assessment to assess safety. This comprehensive approach allows for a full TBL comparison of the two *Legionella* mitigation methods.

Hypothetical Case Study Parameters

The capstone project conducted for this report used a reference building design as the hypothetical case study for the comparative TBL analysis. The reference building is a one story, immediate care outpatient facility assumed to be in Wheaton, IL. While it is an actual building, this report omits certain project specifics, including its specific location, to preserve client confidentiality. Wheaton is the assumed location because it is close to the original location and is in DuPage County, IL, which adopts the IPC 2015 without amendments. It is important to consider the entire IPC 2015 as the acting code because it helps make the project most applicable to the broader United States. This report cites the 2018 edition of the IPC at points because it is more readily available and there are minor changes from the 2015 edition. Wheaton has also adopted the 2018 IECC as required by Illinois, which again, coincides with the broader United States.

Some information needed to complete the hypothetical system designs was known or derived through an analysis of the existing building and system designs completed by a plumbing professional. The following bulleted list summarizes the key known or derived information used in the hypothetical case study.

- The original DHW system design does not factor *Legionella* mitigation.
- Appendix B (not to scale) is the original DHW system designed by the plumbing professional.
- The pressure available for uniform pressure drop is 2.9 PSI per 100 linear feet of pipe.
- The total DHW flow demand is 38.5 HWSFU, as calculated per Table 2.
- The total water heater supply demand is 46.5 gph, and the necessary storage demand is 27.9 gal as calculated per Table 3.

Table 2

Hot Water Supply Fixture Unit Calculation

Tag	Decription	Quantity	HWSFU Per Fixture	Combined HWSFU
P-3	Lavatory	7	1.5	10.50
P-5	Sink, service, floor mount	1	2.0	2.00
P-6	Sink, general use	1	1.0	1.00
P-6A	Sink, exam	18	1.0	18.00
P-6B	Sink, lab	2	1.5	3.00
P-6C	Sink, service, free standing	2	2.0	4.00
			Total Combined HWSFU	38.5

Note. By the author of this report, HWSFU = hot water supply fixture unit values obtained from the 2018 IPC, Table E103.3(2) Load Values Assigned to Fixtures. (https://codes.iccsafe.org/content/IPC2018/appendix-e-sizing-of-water-piping-system)

Table 3

Water Heater Demand and Storage Calculations

BUILDING TYPE			Hospital
Fixture	**Number of Fixtures**	**Hot Water Demand Per Fixture [gph]**	**Total Hot Water Demand [gph]**
1. Lavatory, general, P-6	**1**	**2**	**2**
2. Sink, exam, P-6A	**18**	**4**	**72**
3. Lavatory, public, P-3	**7**	**6**	**42**
4. Sink, Laboratory, P-6B	**2**	**5**	**10**
10. Service Sink, P-5, P-6C	**3**	**20**	**60**
Sum			**186**
Demand Factor			**0.25**
Total Demand (GPH)			**46.5**
Storage Capacity Factor			**0.6**
Necessary Storage (GAL)			**27.9**

Note. By the author of this report following protocol in the *Plumbing Engineering Design Handbook: A Plumbing Engineer's Guide to System Design and Specifications*, Volume Two, by the American Society of Plumbing Engineers (ASPE), 2014, Table 6-1, p. 106.

The capstone project investigation also needed appropriate assumptions to complete the hypothetical system designs. The following bulleted list summarizes these assumptions.

- It is assumed that the primary objective of the hypothetical DHW designs is to prevent *Legionella* growth within the system (i.e., it is more important than cost, and sustainability considerations).
- It is assumed that only the DHW system and items pertaining to it are to be designed.
- It is assumed that the water heater, recirculation pump, and piping are in conditions not suitable for re-use.
- It is assumed that the project is a heavy renovation from the existing design, which is equivalent to new construction.
- It is assumed that no architectural changes are required.
- It is assumed that the building is designed for a 50-year lifespan.

- It is assumed that the municipal water entering the building is 50ºF.
- It is assumed that the difference in shipping, trucking, and warehousing of materials between the systems is negligible for both cost and environmental impacts.
- It is assumed that there are no coordination concerns between the DHW designs and other building systems.

Design and Qualitative Risk Assessment

A designer's top priority should be to minimize the risk in their systems, especially risk to the public and building occupants (National Society of Professional Engineers [NSPE], 2019). With that, minimizing risk is often costly and requires more resources, which may increase the environmental impact of a system. Therefore, risk assessment is important in system decision making, especially when analyzing options pertaining to public safety such as *Legionella* mitigation. There are many examples of this method being employed in research successfully. Barberio et al. (2014) used both an LCA and a qualitative risk assessment to compare emerging technologies in nanofluid production. Gormley et al. (2017) used secondary data to formulate a qualitative risk assessment for pathogen transmission via sanitary plumbing systems. The success of these examples provides evidence of the viability of the use of this method for this capstone project investigation.

Design and Qualitative Risk Assessment Parameters

The capstone project investigation used the previously listed known, derived, and assumed components in conjunction with plumbing industry standards and other typical assumptions prominent in the United States to design the DHW temperature control and chlorine disinfection systems used for further analysis. The designs of both systems appropriately prevent *Legionella* based on relevant literature, so the risk assessment does not factor potential harm caused by the bacteria as a potential risk. However, both systems do have risks associated with their functionality, which are important considerations in the risk assessment. Functionality risks include items such as proper temperature balancing for the temperature control system or proper chlorine concentration for the chlorine disinfection system. Both systems also have inherent safety risks associated with high temperature and chemical usage, respectively, which need to be qualitatively compared.

LCCA

The purpose of an LCCA is to improve decision making based on economic factors. The American Society of Civil Engineers (ASCE) (2018, July 13) "recommends the appropriate use of Life-Cycle Cost Analysis (LCCA) principles in the planning and design processes to evaluate the total cost of projects" (para. 1). The society goes further to say in its policy statement that while the analysis is important, it should not be the only project consideration. Today's owners and design professionals often overlook this point as overall cost is such a driving factor. Therefore, this method is greatly enhanced by acting as a portion of the TBL analysis, and specifically being paired with LCA. An LCCA is often the easiest portion of the TBL to quantify as costs are well known, especially in engineered systems, but there are important requirements that should not be neglected (Guest et al., 2010).

The American Society for Testing and Materials (ASTM) standard E917 governs the means of properly conducting life cycle cost analyses. An important requirement that the standard discusses is to normalize the costs using the net present value (NPV) method to allow direct comparisons between systems (ASTM, 2017). The project investigation presented in this report employed the NPV method to normalize the values and allow for appropriate comparisons, as taught by Milwaukee School of Engineering Professor D. Jackman in her class entitled Life Cycle Assessment of Building and Infrastructure Systems (personal communication, October 2019). In this case, the NPV method transforms all the costs to the time of building construction.

LCCA Parameters

The capstone project LCCA investigation includes data derived from various commercial sources. There is not enough data available to determine average industry prices across the United States for all the materials incorporated into the construction of the system designs. It is important, however, to use the same, or similar, cost data for the two systems to ensure accurate comparisons. Both the upfront and usage cost data are important in this analysis. Upfront costs primarily include construction materials, labor, and space considerations while usage costs include items such as electricity and natural gas usage, maintenance requirements, and the continual purchasing of sodium hypochlorite (for the chlorine disinfection system only).

Assumptions and Limitations

Like the LCA, the assumptions of the LCCA are related to the assumptions made in the hypothetical case study to represent a typical commercial project in the United States. Primarily, the investigation assumes a 50-year building lifespan and only includes construction, maintenance, and usage of items specifically related to the DHW system. As many of the component costs as possible are from Supply House (n.d.), as it was recommended by plumbing industry temperature control supply professional, K. Freidt, as being industry standard (personal communication, February 5, 2021) and it has a wide range of products. For the sake of this project investigation, it is more important that the prices be accurately comparable between the systems rather than accurate to industry standard. Piping pricing is from Ferguson (n.d.) and was verified as industry standard pricing. Specific equipment is from specified manufacturers and suppliers that are cited later in this report. The differences between the two mitigation systems in terms of prices associated with transportation, warehousing, shipping, and soft costs of equipment and components are assumed to be negligible and are therefore not included in the analysis. Furthermore, the construction of the systems assumes no coordination concerns with other building systems.

Having this project represent a typical project in the United States is also a primary assumption that affects system costs. In terms of energy usage, there are national average prices for electricity and natural gas collected by the United States Energy Information Administration (USEIA) (n.d.a; n.d.b). These costs vary month to month; therefore, an average for all the months in 2020 was calculated to determine an annual average unit cost. The analysis does not consider inflation and assumes a conservative 4% interest rate (Blank & Tarquin, 2014). Having an all-encompassing labor cost factor of 1.43 for the material costs, which is based on previous experience of Milwaukee School of Engineering Professor D. Nelson (personal communication, February 12, 2021), is also a substantial LCCA assumption.

LCA

Since the late 1990s, International Organization for Standardization (ISO) standard 14040 *Standard for Life Cycle Assessment* has standardized the way to conduct life cycle assessments to allow direct comparisons between the environmental impact results of different studies (Pryshlakivsky & Searcy, 2013). Nowadays, companies and researchers in most industries utilize research results from official LCAs in some form to influence their environmental management and decision making (Mathews et al., 2014). While this capstone project investigation abides by ISO 14040 in as many ways possible, it is not required to abide by all aspects required for an extensive LCA, as it is only intended for scholarly graduate level research to allow broad comparisons between *Legionella* mitigation systems (D. Jackman, personal communication, December 18, 2020). There are many successful examples of LCAs to research in the plumbing industry alone. Arpke and Hutzler (2008) use LCA to compare the energy usage for different domestic water applications in different building types. Asadi et al. (2016) use both LCA and LCCA to compare the environmental and cost impacts of PEX and copper tubing.

LCA Parameters

As previously noted, standards require LCA reports to specifically include and discuss many aspects pertaining to the analysis. For this report, these primarily include the necessary discussions of goal statements, product systems, functional units, system boundaries, allocation processes, impact categories, data and data quality requirements, software programs, assumptions, limitations, and critical reviews used as stipulated in the International Organization for Standardization (ISO) standard 14040 (ISO, 1997).

Goal Statement and Intended Use

The goal of the LCA was to compare the environmental impacts of two domestic hot water *Legionella* mitigation methods, temperature control and chlorine disinfection, as they are typically designed in the United States. The results of this comparative assessment were intended for use in academic research, acting as the environmental analysis portion of a graduate level project, which compares the two mitigation methods based on the TBL. The capstone project, including this assessment, aims to aid plumbing designers and commercial building owners in comprehensive *Legionella* control decision making. Specifically, the LCA results are intended to be a *comparative assertion*, a definitive comparison between the two methods, used to specifically aid environmental decision making that will be disclosed to the public (ISO, 2006). A proper comparative assertion requires that the analysis of each system includes the same goal and scope, functional unit, system boundary, sensitivity analysis, and peer review when released to the public (ISO, 2006).

Product System, Functional Unit, and System Boundaries

The first product system is the construction and use of a typical commercial project DHW temperature control *Legionella* mitigation system in the United States. The second is the construction and use of a typical commercial project DHW chlorine disinfection *Legionella* mitigation system in the United States. The functional unit of both systems is the same as they both analyze the environmental impacts per one US gallon of domestic hot water supplied to the facility fixtures. The system boundary for each product system includes both the embodied energy needed to manufacture and construct the system, as well as the operational energy to continually use the system over the building's lifespan. The boundary does not consider the deconstruction or repurposing of the systems at the end of its life cycle as there are limited data available in this area, and results would be dependent on each project. This boundary restriction aligns to the cost analysis as there would be little salvage value due to the labor required for demolition (D. Nelson, personal communication, April 5, 2021).

Allocation Process and Impact Categories

DHW water production is a stand-alone process with no co-product generation; therefore, allocation between various products is unnecessary. The method used for the *life cycle impact assessment* (LCIA), the means of quantifying environmental impact from inputs and outputs, is the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI), version 2.1. The project analysis used TRACI instead of other LCIA methods, because it includes an appropriate variety of impact categories and continually updates to reflect the most up to date LCIA research (EPA, 2016, December 9). The five impact categories evaluated were carcinogenics, ecotoxicity, global warming, non carcinogenics, and ozone depletion. The investigation evaluated these impact categories because they represent a balance between the anticipated strengths and weaknesses of each system. The chlorine system's disinfection byproducts were anticipated to increase the carcinogenics and ecotoxicity impacts, while the extra natural gas usage of the temperature control system was anticipated to increase global warming, non-carcinogenics, and ozone depletion. Analyzing the other impact categories produces redundant results, which are omitted from this report for simplicity.

Data Requirements and Software Used

Proper system comparisons require extensive data on the construction and usage of each system. Construction data documents the inputs and by-products of manufacturing processes such as pipe, fitting, insulation, valve, and equipment manufacturing. Usage data include the manufacturing of continually used materials, such as sodium hypochlorite used in chlorine disinfection, as well as the fuel usage to supply energy to the systems, such as natural gas expenditure to heat water. With the analyzed project being a representative hypothetical case study, all the data are secondary from similar projects and appropriate databases. The primary data interpretation method used in the LCA investigation was Carnegie Mellon University's economic input-output life cycle assessment. Carnegie Mellon University (2018) accurately states that the method "estimates the materials and energy resources required for, and the environmental emissions resulting from, activities in our economy" (para. 1). The method is set up to use the United States environmentally extended input-output (USEEIO) model, documented by Yang et al. (2017), as its data source. This source was beneficial for this capstone project because it has the most extensive data on the processes used in the construction and usage of the *Legionella* mitigation systems and uses economic data in US dollars as inputs and primary outputs. It is important to note that this analysis does not use the NPV from the LCCA because the method requires primary costs not including interest rate factors. There were also instances in the investigation that required the use of the traditional mass or volume input and output values. This traditional method was particularly necessary in areas that required the use of data from the US Life Cycle Inventory Database by the National Renewable Energy Laboratory (2012) to fill data gaps in the USEEIO model. Using the Carnegie Mellon University calculation method in conjunction with the tradition method within *openLCA* software allowed the efficient use of cost data accumulated for the LCCA and typical measurements as the base values in the LCA.

According to GreenDelta, the creator of openLCA, the software "is a free, professional [LCA] and Footprint software with a broad range of functions and available databases" (GreenDelta, 2021b, para. 1). The capstone project investigation used openLCA instead of other LCA software programs because it is free, is open source, has the capacity to use large systems and databases, and has the flexibility to identify impacts and primary concerns (GreenDelta, 2021c, paras. 4-5). Additionally, openLCA accounts for different life cycle inventory assessment methods, and the openLCA Nexus provides free databases which align with the program (GreenDelta, 2021a, paras. 1-3).

Assumptions, Limitations, and Critical Review

The assumptions of the LCA are related to the assumptions made in the hypothetical case study that allow the investigation to represent a typical commercial project in the United States. However, it is also important to note the assumptions specific to the environmental data as many of the specific *LCA flows* and *processes* required assumed equivalency to available data. LCA flows are the most basic elements that make up the LCA model. Several flows make up an LCA process, which uses flows as input and output parameters (D. Jackman, personal communication, October 2019). To illustrate this relationship, an example of a flow in this project is electricity that is consumed by a consumer. This flow acts as one of many inputs in the process of pipe fabrication, which produces many output flows such as a certain dollar amount of fabricated pipe as well as emissions. Nealer (2013) agrees with most LCA professionals when she states assumptions, such as those regarding LCA flows and processes, are often necessary to produce results and are appropriate as long as they are “justified and well-documented” (para. 11). Appendix E summarizes the assumed equivalencies used in this capstone project analysis. The primary limitations of this LCA are that it does not consider the demolition and deconstruction of the systems, and that the assumed data equivalencies may not be completely accurate in representing the actual flows and processes. It is also assumed that the systems have negligible impact differences resulting from material transportation, warehousing, and shipping; therefore, they are not considered. These minor limitations are acceptable considering the assessment is for broad level academic research. Finally, to ensure comparative assertion standards are met, the LCA requires a critical review. In the case of this graduate level capstone project investigation, the capstone committee presentations at the Milwaukee School of Engineering will serve as an appropriate critical review.

Results and Discussion

To allow proper reviewing of and analysis of the results based on the TBL, the independent results of each method incorporated into the TBL analysis are first analyzed separately based on each system, and then compared. These comparisons are then evaluated to determine which is more sustainable for the project owner.

Design and Qualitative Risk Assessment Results

The temperature control and the chlorine disinfection systems were designed to mitigate *Legionella* with preventive control, but through their design, both systems introduce unique hazards and risks that need to be properly compared from a safety perspective. Appendix C is the temperature control system design plan and Appendix D is the chlorine disinfection system design plan for reference.

Temperature Control

The temperature control system design starts at the water heater that raises the water temperature to 147°F. The water is then distributed to the fixtures through routing that includes four separate system loops to minimize heat loss through pipes and to allow proper balancing of water velocities to about 4.5 feet per second (FPS). Each loop required an automatic balancing valve controlled by the loop temperatures to ensure proper flow, velocity, and temperature balancing. The temperature setpoint is just upstream of the circulation pump and is set to a minimum of 147°F to ensure *Legionella* mitigation. The system also included point-of-use TMVs at every fixture to ensure scalding mitigation.

Scalding is the primary safety concern for temperature control systems because the routing water temperature is above 120°F. However, the use of point-of-use TMVs properly mitigates this safety risk at the fixtures.

Chlorine Disinfection

The chlorine disinfection system begins with 12.5% sodium hypochlorite being stored in a five-gallon drum in the mechanical room and is set to input a maximum of 2 PPM free chlorine residual upstream of the water heater. The water heater acts as the residual tank, set at a 120°F setpoint at the heater, and the circulation pump distributes the DHW to the fixtures. The system has only a single recirculation loop to minimize construction complexity as temperature loss is not a primary concern in this system. The system has minor carcinogenic risk pertaining to the DBPs that form in the water supply from the decomposition of sodium hypochlorite, but the most concerning factor THM, chloroform, is assumed to be at or below the legal limit of 0.080 PPM at all times. It also needs to represent the HAA carcinogenic contribution, so the maximum concentration for calculation purposes should add the 0.060 PPM HAA limit, which makes it total 0.14 PPM. For the hypothetical case study, this equates to 0.0720 kg of chloroform supplied through the DHW annually, which can then be evaluated as a part of the LCA. The sodium hypochlorite solution is also a direct eye hazard for those working within the mechanical space. It is easy to tie the chlorine disinfection system into the domestic cold water distribution to disinfect that as well if so desired. This is an advantage in certain applications, such as when there is high *Legionella* concern for the project.

Direct Comparison

While both systems present risks associated with their functionalities, chlorine disinfection poses the greater risk to the building occupants based on the reviewed literature and data. The most concerning risk for the chlorine disinfection system is the supply of carcinogenic DBPs to the building occupants. The other risks are not substantial as proper safety measures are included in each system. The disinfection byproducts may be concerning to the health of building occupants, but they must remain below the required legal limit, which preserves safety to a sufficient level.

LCCA Results

The LCCA results are primarily dependent on manufacturer and supplier price values, energy usage, spreadsheet calculations, and the NPV analysis. As stated previously, values from the LCCA also need to be easily transformable to the LCA; therefore, a second analysis involves calculating values without interest. Equipment replacement at different points during the system lifespan is included in the material construction costs and as part of the NPV analysis. A material replacement factor for each subtotal is used to represent how many times the material is expected to be fully replaced throughout the 50-year lifespan.

Temperature Control

Appendix F provides detailed estimating information for the temperature control system construction costs. A summary of the subtotal costs and a calculation of life cycle material costs is given in Table 4.

Table 4

Temperature Control Construction Costs

Subtotals Designations	Upfront Cost ($)	Material Replacement Factor for 50-Year Lifespan	Life Cycle Material Costs ($)
Pipe Subtotal	$ 6,602.07	1	$ 6,602.07
Pipe Insulation Subtotal	$ 7,253.76	2	$ 14,507.52
Fittings Subtotal	$ 545.66	1	$ 545.66
Valves Subtotal	$ 5,365.08	3	$ 16,095.24
Hangers Subtotal	$ 2,537.50	1	$ 2,537.50
Equipment Subtotal	$ 4,350.06	2	$ 8,700.12
		Life Cycle Material Cost	$ 48,988.11
		Labor Factor	1.43
		Total Life Cycle Construction Cost	$ 70,053.00

Note. By the author of this report following guidance regarding equipment replacement requirements from Milwaukee School of Engineering Professor D. Nelson, February 28, 2021. Other data are derived from Appendix F.

To allow portions of the LCCA to act as inputs for the LCA, it was important to separate costs based on the LCA flows documented in Appendix E. Therefore, life cycle material costs from Table 4 were adjusted based on assumed cost designations as presented in Table 5. The annual costs did not require any assumed adjustments, so they are provided in Table 6 without any post calculation changes.

Table 5

Adjusted Temperature Control Construction Costs for LCA Integration

Actual Flow for LCA Integration	Life Cycle Material Cost ($)	Notes
Pipe Manufacturing	$ 5,281.66	Assumed 80% of pipe material
Fitting Manufacturing	$ 436.53	Assumed 80% of fitting material
Pipe and Fitting Fabrication	$ 1,429.55	Assumed 20% of pipe and fitting material costs
Pipe Insulation Manufacturing	$ 14,507.52	
Valve Manufacturing	$ 16,095.24	
Water Heater Manufacturing, not including controls	$ 1,799.74	Assumed 80% of water heater
Circulation and Chlorinator Pump Manufacturing, not including controls	$ 3,870.26	Assumed 60% of pump costs
Controls Manufacturing	$ 3,030.11	Assumed 40% of pump costs, 20% of water heater costs, and 30% of ventillation fan costs
Emergency Eyewash Manufacturing	N/A	
Ventillation Ductwork	N/A	
Ventillation Equipment	N/A	Assumed 70% of venitllation fan
Hanger Manufacturing	$ 2,537.50	
Health Care Building Construction	N/A	
Construction Labor	$ 21,064.89	
Total	$ 70,053.00	

Note. By the author of this report, material costs derived from values presented in Table 4.

Table 6

Temperature Control Annual Operations Costs

Equipment	Electric Energy (kwh)	Natural Gas (Cubic Feet)	Unit Energy Cost ($/kwh or $/thousand cubic feet respectfully)	Annual Usage Cost ($)
Circulation Pump	7008.0	N/A	$ 0.1063	$ 744.95
Water Heater	N/A	169.1	$ 7.73	$ 1,306.94
			Total Annual Cost	$ 2,051.89

***Assumed electric energy for controls and monitoring difference is negligible between the systems.

Note. By the author of this report, electricity and natural gas requirements calculated from equipment information presented by the manufacturers. Circulation pump information retrieved from (https://documentlibrary.xylemappliedwater.com/wp-content/blogs.dir/22/files/2014/09/A-165C-ecocirc-XL-curves.pdf), water heater information retrieved from AO Smith cutsheet. (https://www.hotwater.com/Water-Heaters/Residential/Gas/ProLine/XE/ProLine-XE-Power-Vent-Gas-Tank-Water-Heater-GPVL-50/).

Appendix H includes the cash flow diagram and NPV calculations for the temperature control system derived from information presented in Table 4, Table 5, and Table 6. The material replacement factors are defined as evenly spaced, one-time future costs in the cash flow diagram. The calculations conclude that this system had an NPV of $90,111.30. About 42.3% of the total NPV was dedicated to its upfront construction costs and about 48.9% was dedicated to its annual operational costs.

Chlorine Disinfection

Appendix G provides detailed estimating information for the chlorine disinfection system construction costs. A summary of the subtotal costs and a calculation of life cycle material costs is given in Table 7.

Table 7

Chlorine Disinfection Construction Costs

Subtotals Designations	Upfront Cost ($)	Material Replacement Factor for 50-Year Lifespan	Life Cycle Material Costs ($)
Pipe Subtotal	$ 6,925.20	1	$ 6,925.20
Pipe Insulation Subtotal	$ 3,658.90	2	$ 7,317.80
Fittings Subtotal	$ 540.14	1	$ 540.14
Valves Subtotal	$ 235.26	3	$ 705.78
Hangers Subtotal	$ 2,037.45	1	$ 2,037.45
Equipment Subtotal	$ 9,317.80	2	$ 18,635.60
Architecture Subtotal	$ 6,956.00	1	$ 6,956.00
		Life Cycle Material Cost	$ 43,117.97
		Labor Factor	1.43
		Total Life Cycle Construction Cost	$ 61,658.70

Note. By the author of this report following guidance regarding equipment replacement requirements from Milwaukee School of Engineering Professor D. Nelson, February 28, 2021. Other data are derived from Appendix G.

As with the temperature control system, portions of the LCCA results need to be able to act as inputs for the LCA and so the costs were adjusted to align with the LCA flows documented in Appendix E. Therefore, life cycle material costs from Table 7 were adjusted based on assumed cost designations as presented in Table 8. As with the temperature control system, the annual costs did not require any assumed adjustments, so they are provided in Table 9 without any post calculation changes.

Table 8

Adjusted Chlorine Disinfection Construction Costs for LCA Integration

LCA Flow	Life Cycle Material Cost ($)	Notes
Pipe Manufacturing	$ 5,540.16	Assumed 80% of pipe material costs
Fitting Manufacturing	$ 432.11	Assumed 80% of fitting material costs
Pipe and Fitting Fabrication	$ 1,493.07	Assumed 20% of pipe and fitting material costs
Pipe Insulation Manufacturing	$ 7,317.80	
Valve Manufacturing	$ 705.78	
Water Heater Manufacturing, not including controls	$ 1,630.06	Assumed 80% of water heater costs
Circulation and Chlorinator Pump Manufacturing, not including controls	$ 7,265.29	Assumed 60% of pump costs
Controls Manufacturing	$ 5,355.44	Assumed 40% of pump costs, 80% of water heater costs, and 30% of ventillation fan costs
Emergency Eyewash Manufacturing	$ 3,608.70	
Ventillation Ductwork	$ 532.50	
Ventillation Equipment	$ 243.60	Assumed 70% of venitllation fan costs
Hanger Manufacturing	$ 2,037.45	
Health Care Building Construction	$ 6,956.00	
Construction Labor	$ 18,540.73	
Total	$ 61,658.70	

Note. By the author of this report, material costs derived from values presented in Table 7.

Table 9

Chlorine Disinfection Annual Operations Costs

Equipment	Electric Energy (kwh)	Natural Gas (Cubic Feet)	12.5% Sodium Hypchlorite (Gal)	Unit Energy Cost ($/kwh or $/thousand cubic feet respectfully)	Annual Usage Cost ($)
Circulation Pump	902.3	N/A	N/A	$ 0.1063	$ 156.44
Water Heater	N/A	122.0	N/A	$ 7.73	$ 943.15
Chlorinator	N/A	N/A	5	$ 15.00	$ 75.00
				Total Annual Cost	$ 1,174.59

***Assumed electric energy for controls and monitoring difference is negligible between the systems.

Note. By the author of this report, electricity and natural gas requirements calculated from equipment information presented by the manufacturers. Circulation pump information retrieved from (https://documentlibrary.xylemappliedwater.com/wp-content/blogs.dir/22/files/2014/09/A-165C-ecocirc-XL-curves.pdf), water heater information retrieved from AO Smith cutsheet. (https://www.hotwater.com/Water-Heaters/Residential/Gas/ProLine/XE/ProLine-XE-Power-Vent-Gas-Tank-Water-Heater-GPVL-50/). Chlorinator information from personal communication with Mulcahy Shaw Water.

Appendix I includes the cash flow diagram and NPV calculations for the chlorine disinfection system. The material replacement factors are again defined as one-time future costs in the cash flow diagram at the same time periods used in the temperature control analysis. This system had an NPV of $72,685.88. About 58.4% of the total NPV was dedicated to its upfront construction costs and about 34.7% was dedicated to its annual operational costs.

Direct Comparison

Choosing the chlorine disinfection system would save the owner $17,425.42 in this hypothetical case study when considering all the previously stated necessary assumptions. This results in an approximate 19.34% decrease in life cycle NPV costs over the assumed 50-year life span.

LCA Results

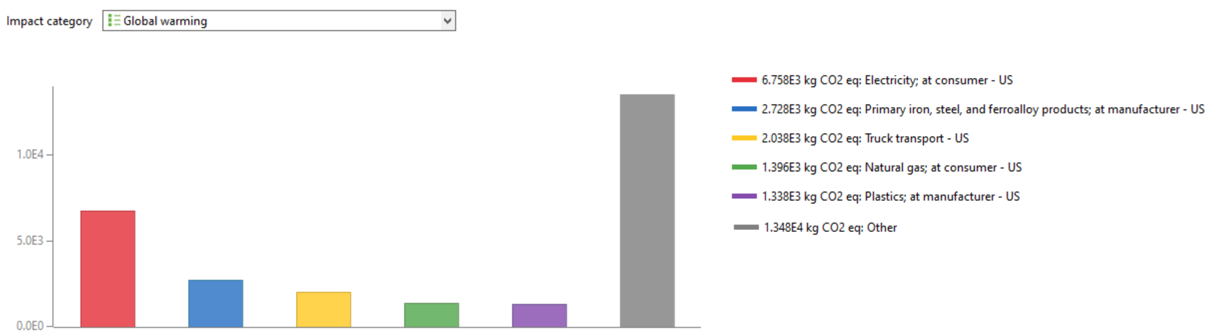
As stated previously, the five impact categories of carcinogenics, ecotoxicity, global warming, non-carcinogenics, and ozone depletion were all evaluated for each system. OpenLCA presents environmental impact results in two primary ways. The first way is a comparison of the specified impact of independent flows within the specific product system. Analyzing these results satisfies the secondary goal of this report to determine the most concerning factors in each system.

Temperature Control

Beginning with an example of comparing the impact of independent flows within the temperature control system, Figure 3, Figure 4, and Figure 5 provide flow comparisons of construction, annual usage, and life cycle usage, respectfully. The global warming impact is the one given in this example, as it most aligns with the overall concerns of all five impacts, which are not all shown to minimize confusion.

Figure 3

Temperature Control Construction Flow Global Warming Impact Comparison



Note. By the author of this report using OpenLCA software, impacts are derived from values presented in Table 5 as they pertain to flows provided in Appendix E.

[a] Vertical axis depicts the global warming impact in terms of equivalent CO_2

[b] Horizontal axis depicts the LCA flows

Figure 4

Temperature Control Annual Usage Flow Global Warming Impact Comparison

Note. By the author of this report using OpenLCA software, impacts are derived from values presented in Table 6 as they pertain to flows provided in Appendix E.

[a] Vertical axis depicts the global warming impact in terms of equivalent CO_2

[b] Horizontal axis depicts the LCA flows

Figure 5

Temperature Control Life Cycle Flow Global Warming Impact Comparison

Note. By the author of this report using OpenLCA software, impacts are derived from values presented in Table 5 and Table 6 as they pertain to flows provided in Appendix E. These values are combined using a 50-year lifespan.

[a] Vertical axis depicts the global warming impact in terms of equivalent CO_2
[b] Horizontal axis depicts the LCA flows

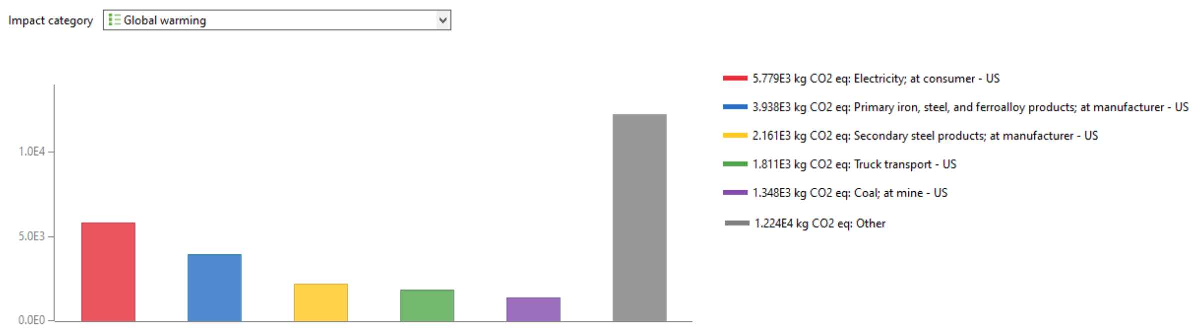
It is evident, after analyzing and comparing the results presented in Figures 3, 4, and 5, that electricity usage is the flow that provides the greatest global warming environmental impact in all stages of the temperature control system. When looking at the other impact categories, electricity usage was the most contributing flow in all impacts on an annual basis, while the manufacturing of steel, copper, and plastic products (representing pipe insulation) were most concerning during the construction phases. The life cycle impact comparison aligns much more with the annual impact comparison with electricity usage being the dominating factor.

Chlorine Disinfection

Next, the impact of independent flows associated with chlorine disinfection are shown in Figures 6, 7, and 8.

Figure 6

Chlorine Disinfection Construction Flow Global Warming Impact Comparison



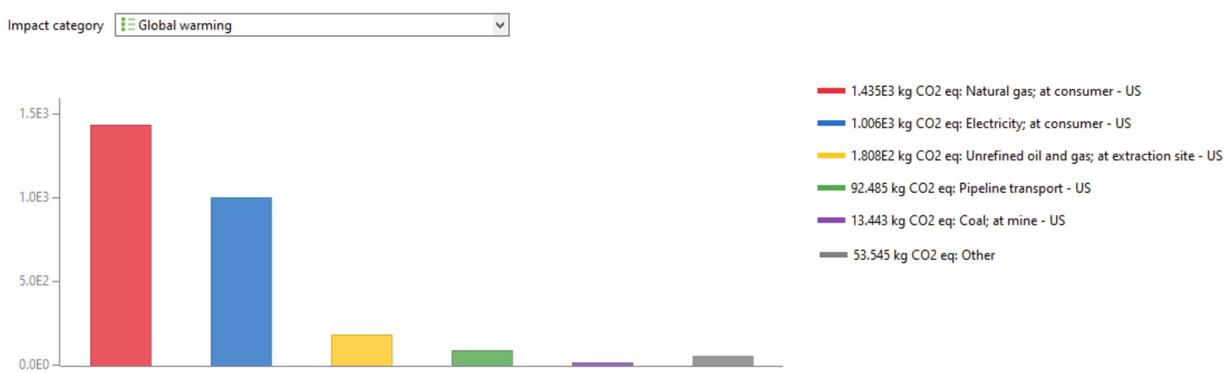
Note. By the author of this report using OpenLCA software, impacts are derived from values presented in Table 8 as they pertain to flows provided in Appendix E.

[a] Vertical axis depicts the global warming impact in terms of equivalent CO_2

[b] Horizontal axis depicts the LCA flows

Figure 7

Chlorine Disinfection Annual Usage Flow Global Warming Impact Comparison



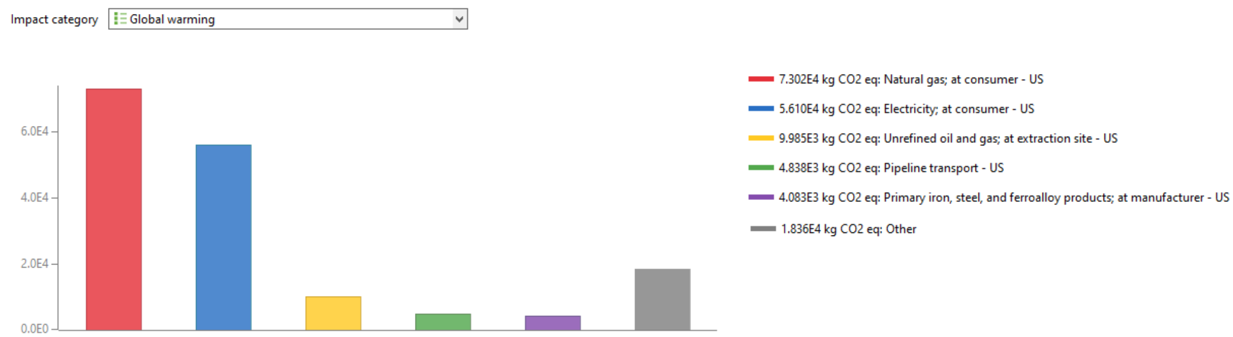
Note. By the author of this report using OpenLCA software, impacts are derived from values presented in Table 9 as they pertain to flows provided in Appendix E.

[a] Vertical axis depicts the global warming impact in terms of equivalent CO_2

[b] Horizontal axis depicts the LCA flows

Figure 8

Chlorine Disinfection Life Cycle Flow Global Warming Impact Comparison



Note. By the author of this report using OpenLCA software, impacts are derived from values presented in Table 7 and Table 8 as they pertain to flows provided in Appendix E. These values are combined using a 50-year lifespan.

[a] Vertical axis depicts the global warming impact in terms of equivalent CO_2
[b] Horizontal axis depicts the LCA flows

It is evident, after analyzing and comparing the chlorine disinfection results presented in Figures 6, 7, and 8, that natural gas usage is the flow that provides the greatest global warming environmental impact annually, but electricity provides the greatest impact through construction of the system. When looking at the other impact categories, either electricity or natural gas usage were the top contributors, with the latter being the second. Again, the life cycle impact comparison aligns much more with the annual impact comparison in all flows.

Direct Comparison

When comparing the results of the individual flow impacts between the systems, focusing on just the construction portion of the project indicates that it is most important to reduce steel, copper, and plastic (pipe insulation) materials. While this is beneficial, the overall results show more accurately that it is more important to minimize recurring annual usage rather than upfront construction impacts as it has a greater influence on the life cycle impact of the system.

Therefore, electricity usage is the most important flow to minimize when looking to minimize environmental impact, followed by natural gas usage. This point is true for both systems, but electricity usage is more extreme in the temperature control system.

Next, it is important to analyze the primary goal of the LCA analysis, which is to directly compare the environmental impacts of both systems. The second way in which OpenLCA comprises results are shown in Table 10 and Figure 9, which provide the comparison of the construction and maintenance impacts of both systems based on percentage of the most impactful system.

Table 10

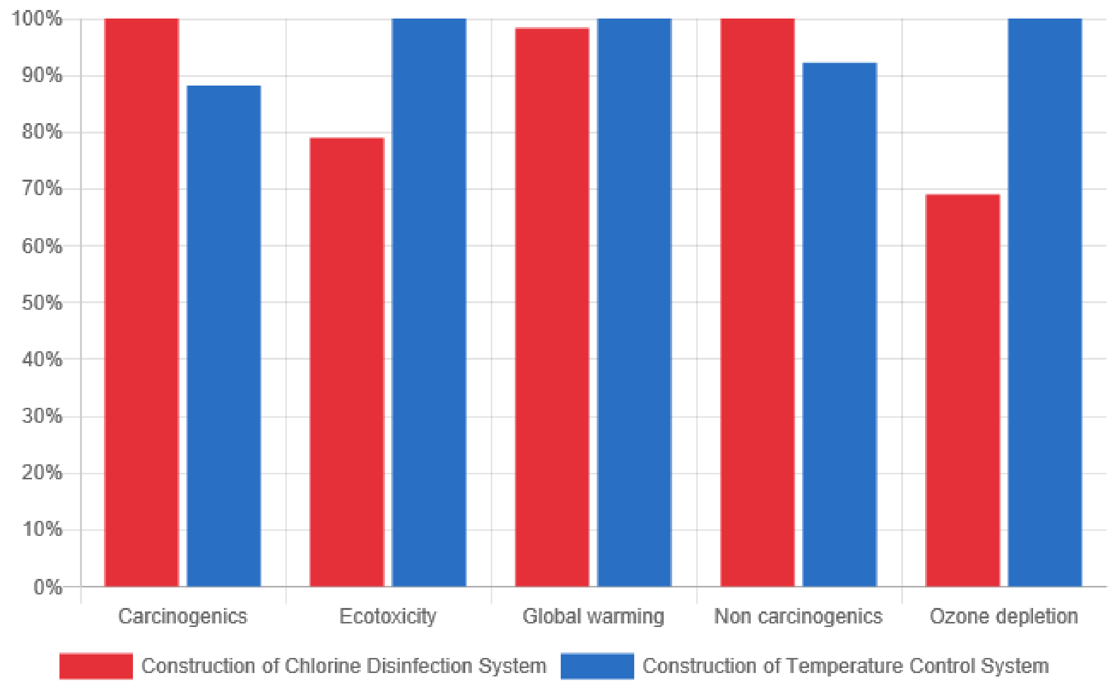
System Construction and Maintenance LCIA Comparison

Indicator	Construction of Chlorine Disinfection System	Construction of Temperature Control System	Unit
Carcinogenics	6.33232e-5	5.58834e-5	CTUh
Ecotoxicity	3.58243e+3	4.53233e+3	CTUe
Global warming	2.72824e+4	2.77411e+4	kg CO2 eq
Non carcinogenics	1.56235e-3	1.44087e-3	CTUh
Ozone depletion	5.94774e-3	8.60773e-3	kg CFC-11 eq

Note. By the author of this report using OpenLCA software.

Figure 9

System Construction and Maintenance LCIA Comparison



Note. By the author of this report using OpenLCA software.

[a] Vertical axis depicts environmental impact as a percentage of the more impactful system

[b] Horizontal axis depicts the LCA impact indicators

Based on the results presented in Table 10 and Figure 9, the temperature control system construction is substantially more impactful in ecotoxicity and ozone depletion. This difference between the systems is due to the increased pipe insulation requirements for the 140ºF water distribution. The chlorine disinfection system is more impactful in carcinogenics and non-carcinogenics because of the added square footage of building construction required for the added chlorine equipment and emergency eye wash. The systems are very similar in their construction global warming impacts. Moving past system construction, Table 11 and Figure 10 compare the annual usage environmental impact of the two systems.

Table 11

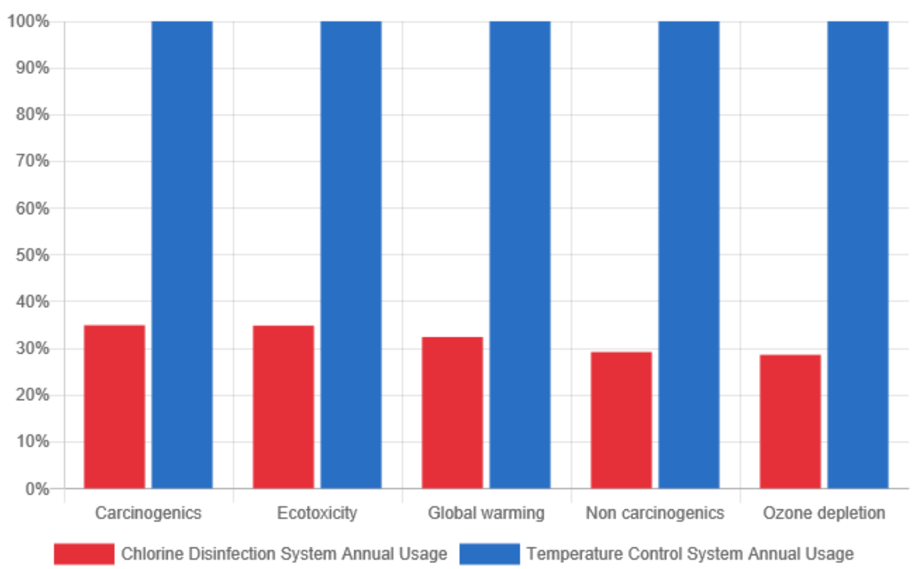
Annual System Usage LCIA Comparison

Indicator	Chlorine Disinfection System Annual Usage	Temperature Control System Annual Usage	Unit
Carcinogenics	1.12568e-6	3.21985e-6	CTUh
Ecotoxicity	2.46645e+1	7.07093e+1	CTUe
Global warming	2.78208e+3	8.57446e+3	kg CO2 eq
Non carcinogenics	2.58674e-5	8.84147e-5	CTUh
Ozone depletion	8.55228e-5	2.98485e-4	kg CFC-11 eq

Note. By the author of this report using OpenLCA software.

Figure 10

Annual System Usage LCIA Comparison



Note. By the author of this report using OpenLCA software.

[a] Vertical axis depicts environmental impact as a percentage of the more impactful system

[b] Horizontal axis depicts the LCA impact indicators

Based on the results presented in Table 11 and Figure 10, the temperature control system construction is significantly more impactful in all the environmental impact categories. This difference between the systems is primarily due to the increased electricity and natural gas usage requirements for the 140ºF water distribution.

It is important to note, however, that the emissions from producing and distributing electricity and natural gas do not directly impact the building occupants initially. On the other hand, the carcinogenics and ecotoxicity impacts may be more impactful to the building occupants in the chlorine disinfection system because of the chlorine by-products being formed in the direct water supply. However, the DHW is not intended for drinking purposes, and the concentration of disinfection by-products is maintained below the legal limit so there is not a major concern.

While these annual results may be appropriate for this specific hypothetical case study, they are not easily applied to other projects as they are not in terms of the functional unit defined previously, which is the environmental impacts per one US gallon of domestic hot water supplied to the facility fixtures. This is easy to determine from the results as they just need to be divided by the number of DHW gallons used by the facility in a given year, which is estimated to be 137,780 gallons. Assuming the DHW usage of the added emergency eye wash chlorine is negligible to the annual amount, the percentage comparison from Figure 10 remains the same between the two systems. However, the amounts in Table 11 need to be updated as shown in Table 12.

Table 12

One Gallon of DHW LCIA System Usage Comparison

Indicator	Chlorine Disinfection System Annual Usage	Temperature Control System Annual Usage	Unit
Carcinogenics	8.17013E-12	2.33695E-11	CTUh
Ecotoxicity	1.79014E-04	5.13204E-04	CTUe
Global Warming	2.01922E-02	6.22330E-02	kg CO2 eq
Non Carcinogenics	1.87741E-10	6.41709E-10	CTUh
Ozone Depletion	6.20720E-10	2.16639E-09	kg CFC-11 eq

Note. By the author of this report.

Lastly, combining the impact results from the system construction, maintenance, and the assumed 50 years of annual operation, Table 13 and Figure 11 provide the life cycle comparisons.

Table 13

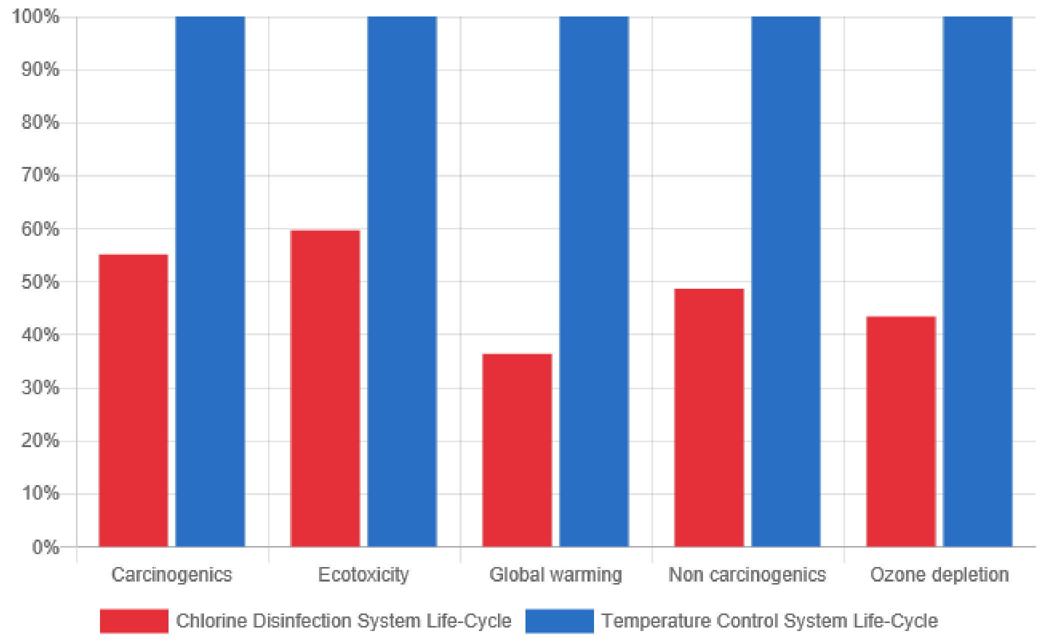
Life Cycle LCIA Comparison

Indicator	Chlorine Disinfection System Life-Cycle	Temperature Control System Life-Cycle	Unit
Carcinogenics	1.19607e-4	2.16876e-4	CTUh
Ecotoxicity	4.81566e+3	8.06780e+3	CTUe
Global warming	1.66386e+5	4.56464e+5	kg CO2 eq
Non carcinogenics	2.85572e-3	5.86160e-3	CTUh
Ozone depletion	1.02239e-2	2.35320e-2	kg CFC-11 eq

Note. By the author of this report using OpenLCA software.

Figure 11

Life Cycle LCIA Comparison



Note. By the author of this report using OpenLCA software.

[a] Vertical axis depicts the environmental impact as a percentage of the more impactful system
[b] Horizontal axis depicts the LCA impact indicators

Based on the results presented in Table 13 and Figure 11, the temperature control system construction is much more impactful in all the environmental impact categories. Again, this difference between the systems is primarily due to the increased electricity and natural gas usage requirements for the 140ºF water distribution. These results confirm the results of the individual flow analysis that the annual usage is more representative of the life cycle than construction impacts. Like the annual usage portion, the life cycle impacts can be put in terms of the functional unit to allow its use on other projects, as shown in Table 14. Similar to the annual usage, the percentage results in Figure 11 are still applicable, but it is important to note that the results of Table 14 consider construction, maintenance, and usage while Table 12 only considers system usage.

Table 14

One Gallon of DHW LCIA Life Cycle Comparison

Indicator	Chlorine Disinfection	Temperature Control	Unit
Carcinogenics	8.68101E-10	1.57407E-09	CTUh
Ecotoxicity	3.49518E-02	5.85557E-02	CTUe
Global Warming	1.20762E+00	3.31289E+00	kg CO2 eq
Non Carcinogenics	2.07267E-08	4.25432E-08	CTUh
Ozone Depletion	7.42045E-08	1.70794E-07	kg CFC-11 eq

Note. By the author of this report.

Conclusions

The results of this report, which are based on a TBL analysis, provide sufficient evidence that chlorine disinfection is better than temperature control for *Legionella* mitigation in a typical United States project. The main concern with this finding is that there is the possibility for more safety concerns using the chlorine disinfection system, but these are easily avoidable with proper system monitoring and educated staff. In terms of cost and environmental impact, the LCCA and LCA both favor the chlorine disinfection system, as it costs less and has less environmental impact over its life cycle. The LCA portion may be surprising because of concerns revolving around disinfection byproducts, especially when considering carcinogenics and ecotoxicity. However, with the assumptions present in this analysis, the results show that the increases in required electricity and natural gas in the temperature control system constitute a far worse environmental impact than the disinfection byproducts caused using sodium hypochlorite in the chlorine disinfection system. These results also provide evidence to suggest that either reducing electricity and natural gas usage, and/or improving the electric grid would provide the greatest improvements to both mitigation systems in terms of reducing cost and environmental impact.

Limitations

Even with the scholarly valid results presented, there are a few limitations in this research that are important to note. The main limitation of this project is its dependance on accurate assumptions. While all the assumptions are justifiable, natural variance associated with some factors may skew the results in scenarios involving actual applications. The costs of the system components, for example, are widely variable depending on manufacturer selection and the status of the economy at the time of purchase. These assumed costs are then affecting both the LCCA and the LCA through the economic input-output analysis. This project is also limited by the qualitative risk assessment, as it is difficult to make solid comparisons without quantitative data. The final noteworthy limitation is the assumption that the water heater uses natural gas, which may reflect the current normality, but may change as the United States is trending towards more electric equipment. However, as previously stated, this would only substantially affect the results presented in this report if great improvements were made to the electric grid.

Improvements and Further Research

Considering areas of improvement for this project is necessary if the industry is to move towards using similar research methods in the future. First and foremost, a sensitivity analysis of all the factors would greatly improve this project, as it would quantify the error caused by all of the assumptions. Specifically, this analysis would likely produce stronger results for the LCCA and LCA, which in turn, would produce more sound comparative findings.

Another improvement would be to quantify the risk assessment. While the qualitative risk assessment in this project was beneficial, quantifying the results would make the safety comparisons between the systems stronger and more reliable. More small-scale improvements could include comparing more pricing resources and performing the research on different scale projects.

This investigation also offers many avenues for further research on the topic of *Legionella* mitigation and the TBL. For example, based on methods in this project, a similar TBL analysis for all known *Legionella* mitigation systems could be undertaken (refer to Appendix A for the different systems). This would allow for a more comprehensive comparison that could provide more decision-making benefits, considering that temperature control and chlorine disinfection are only two possible options. This potential study could even be made broader by not limiting it to *Legionella*, but evaluating all water quality management methods. Another potential research opportunity that is less similar is the possibility of quantifying the bacterial risk of *Legionella*, which this project did not address.

The Future of DHW *Legionella* Mitigation

While there is still much research to be done on the different *Legionella* mitigation systems and how they relate, this research has proven to be worthwhile because it has resulted in a credible comparison between the two most common mitigation methods. The project entailed the consideration of all the different advantages and disadvantages in each system, which was rendered possible by the LCCA, LCA, and TBL methods employed in the study. The findings of this study help to demonstrate that moving forward, it is essential for the plumbing industry to use a more comprehensive decision-making approach, such as the TBL. The broader perspective associated with a comprehensive approach helps to produce the best products, systems, or designs possible.

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Appendix A

Legionella Mitigation Tactics Summary

Table 2-1: Summary of *Legionella* Management Disinfection Processes and Characteristics

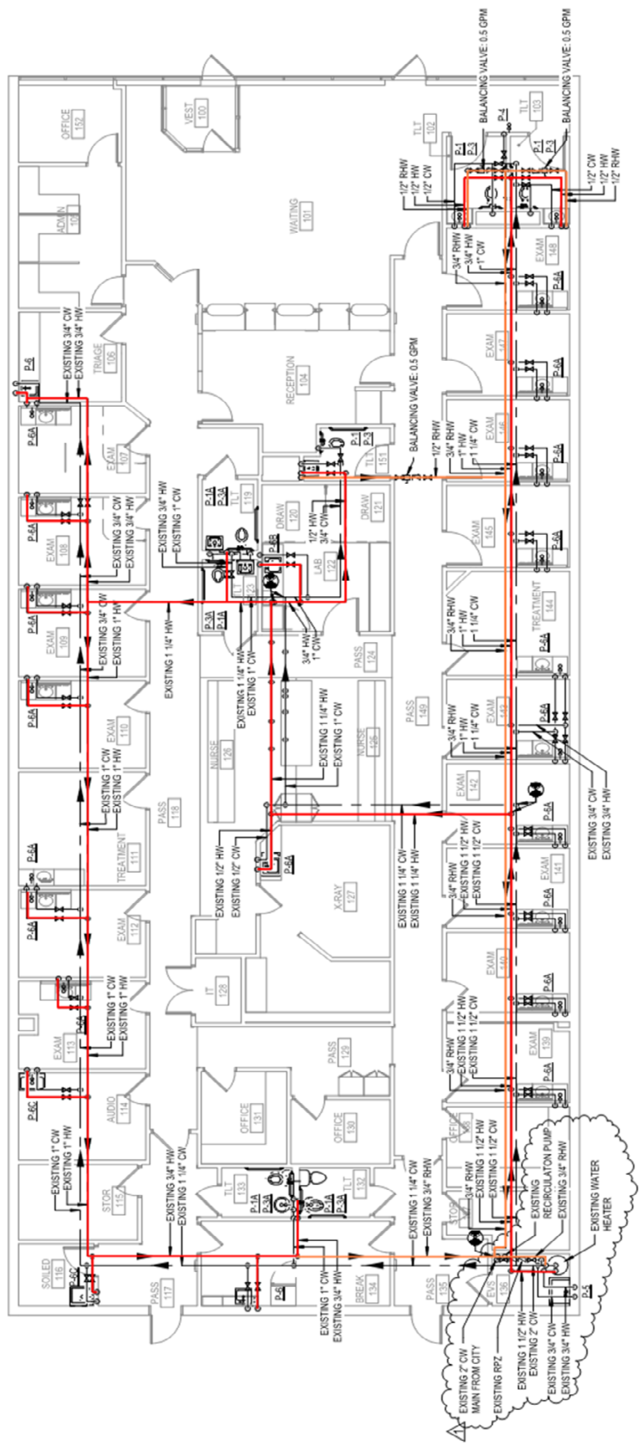
	Free Chlorine	Monochloramine	Chlorine Dioxide	Copper-Silver	Thermal (°C)	Ozone	UV Light
Typical Concentrations (mg/L)	2–4, initial	2–4, initial	0.1–0.8	Cu: 0.2–0.8 Ag: 0.02–0.08	55–77	Low dosage ranges	Varied
pH Effect on Efficacy	Reduced above 8–9	None in 7–9 range	None in 6–10 range	pH >8.5	None	Not at normal pH	None expected
Temperature	Increased decay rate	Minimal	Increased decay rate	None	>55	Increased decay rate	None expected
Major Byproducts	Halogenated DBPs (THMs and HAAs)	Less THMs	Chlorite and chlorate	None besides Cu and Ag residues	None	Transient oxygenated organics	None expected
Standards and Guidelines (mg/L)	**USEPA:** 4 THMs: 0.08 HAAs: 0.06 **WHO:** 5 **Can:** No guideline THM: 0.1 HAAs: 0.08	**USEPA:** 4 as Cl_2 **WHO:** 3 as Cl_2 **Can:** 3 as Cl_2	**USEPA:** ClO_2: 0.8 ClO_2-: 1 **WHO:** ClO_2: 0.7 ClO_3-: 0.7 **Can:** ClO_2-: 1 ClO_3-:1	**USEPA:** Cu: 1.3 Ag: 0.1 (SMCL) **Can:** Cu: 2 Ag: No guideline	None	None	None

Where: Ag = silver; Can = Canadian Drinking Water Guideline; Cl_2 = chlorine; ClO_2 = chlorine dioxide; ClO_2- = chlorite; ClO_3- = chlorate; Cu = copper; HAAs = haloacetic acids; SMCL = secondary MCL; THMs = trihalomethanes; UV = ultraviolet light; USEPA = U.S. Environmental Protection Agency maximum residual disinfectant level; WHO = World Health Organization Guideline. Note: all concentrations are reported in mg/L (ppm).

Note. Adapted from *Legionella Management in Building Water Systems: The Role of Chlorine Products,* by J. Cotruvo, 2020, American Chemistry Council, p. 19 (https://www.chlorine.org/legionella/).

Appendix B

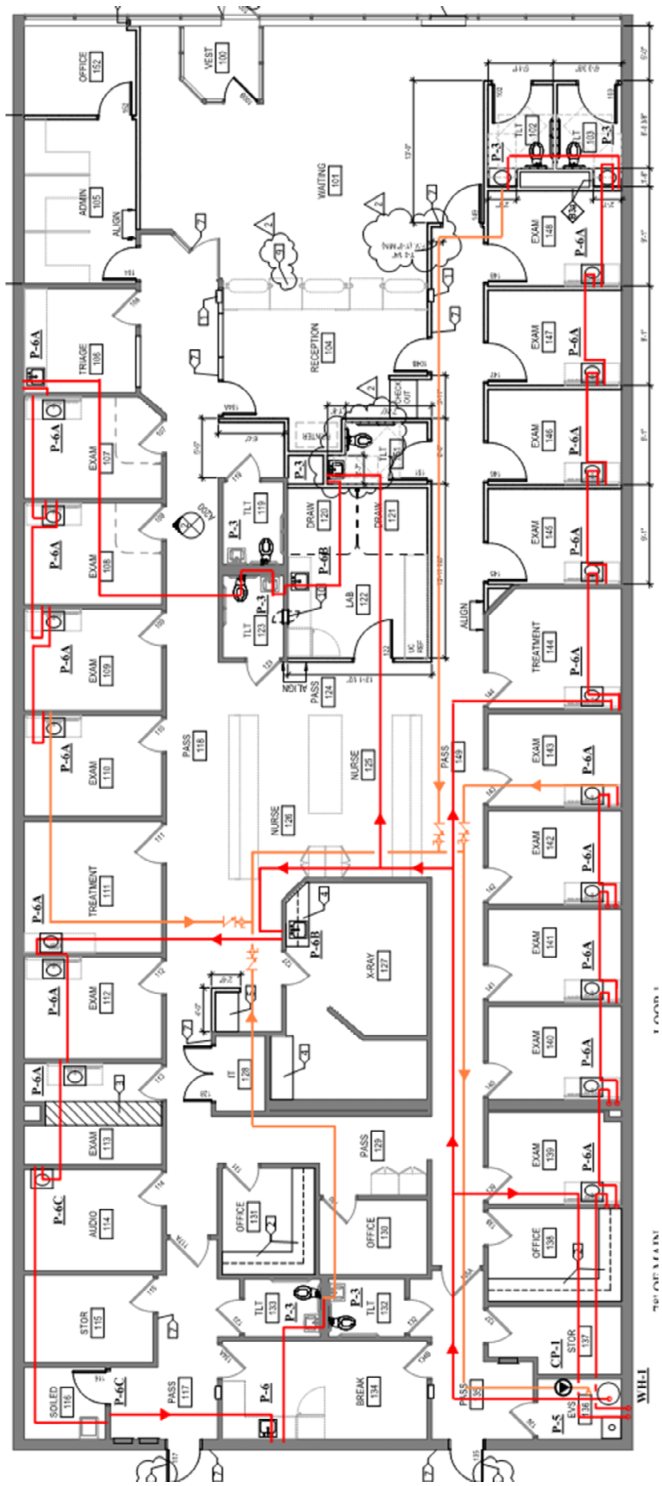
Existing DHW System Design



Note. Created by the author of this report. Not to scale.

Appendix C

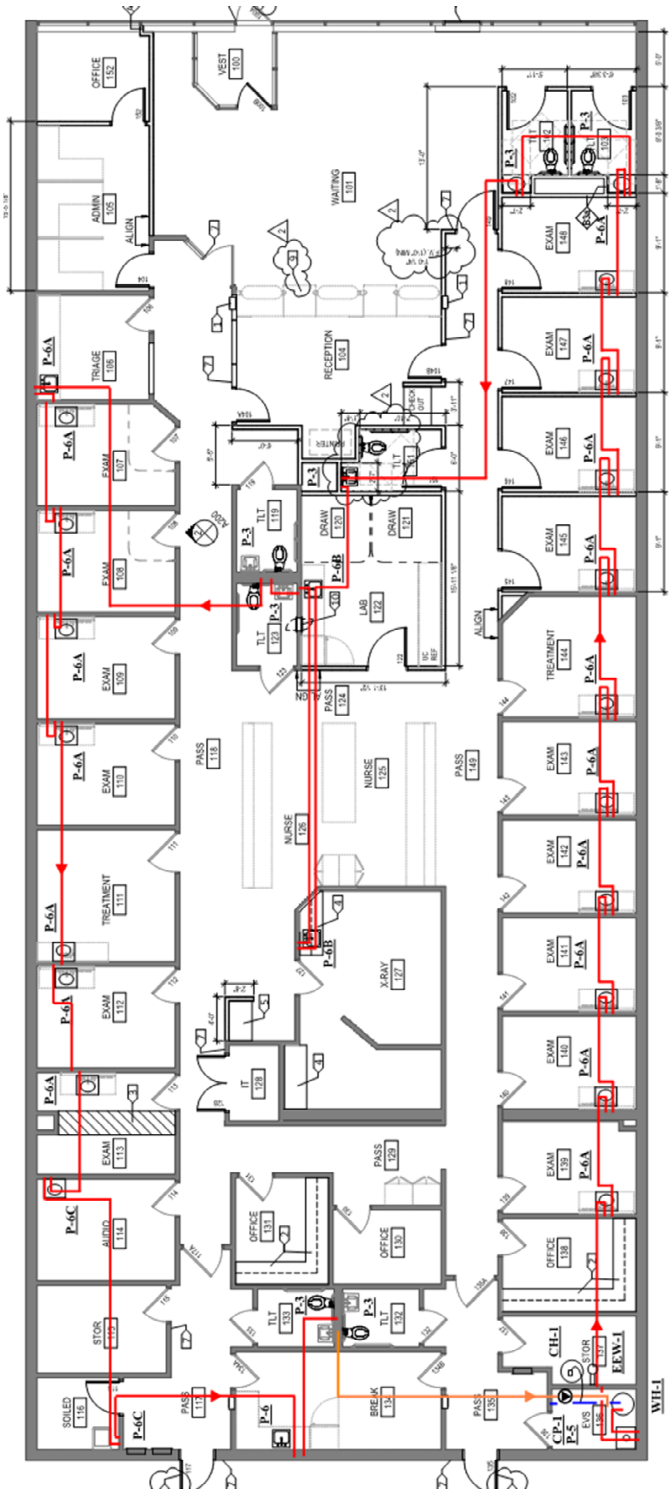
New Temperature Control System Design



Note. Created by the author of this report. Not to scale.

Appendix D

New Chlorine Disinfection System Design



Note. Created by the author of this report. Not to scale.

Appendix E

LCA Equivalent Flows/Processes and Product System Designations

Actual Flow/Process	Assumed Equivalent LCA Flow/Process in USEEIO Data	Product System Designation(s)
Pipe Manufacturing	Secondary copper products; at manufacturer - US	Temperature control construction, chlorine disinfection construction
Fitting Manufacturing	Metal pipe fittings, ball and roller bearings, industrial patterns, metal bath fixtures, other misc. fabricated metals; at manufacturer - US	Temperature control construction, chlorine disinfection construction
Pipe and Fitting Fabrication	Fabricated pipe and pipe fittings; at manufacturer - US	Temperature control construction, chlorine disinfection construction
Pipe Insulation Manufacturing	Other plastic products; at manufacturer - US	Temperature control construction, chlorine disinfection construction
Valve Manufacturing	Metal plumbing drains, faucets, valves, and other fittings; at manufacturer - US	Temperature control construction, chlorine disinfection construction
Water Heater Manufacturing, not including controls	Heavy gauge metal tanks; at manufacturer - US	Temperature control construction, chlorine disinfection construction
Circulation Pump Manufacturing, not including controls	Secondary steel products; at manufacturer - US	Temperature control construction, chlorine disinfection construction
Controls Manufacturing	Automatic controls for HVAC and and refrigeration equipment; at manufacturer	Temperature control construction, chlorine disinfection construction
Construction Labor	Commercial machinery repair - US	Temperature control construction, chlorine disinfection construction
Emergency Eye Wash Manufacturing		
Hanger Manufacturing	Secondary steel products; at manufacturer - US	Chlorine disinfection construction
Ventilation Ductwork		
Ventilation Equipment	Air conditioning, refrigeration, and warm air heating equipment; at manufacturer - US	Chlorine disinfection construction
Healthcare Building Construction	Health care buildings - US	Chlorine disinfection construction
Sodium Hypochlorite Manufacturing	Chlorine, production mix, at plant - US	Chlorine disinfection usage
Electricity Generation, Transmission, and Distribution	Electricity; at consumer - US	Temperature control usage, chlorine disinfection usage
Natural Gas Extraction, Transmission, and Distribution	Natural gas; at consumer - US	Temperature control usage, chlorine disinfection usage

Note. Tables created by the author of this report. Equivalent flows and processes adapted from *USEEIO: A New and Transparent United States Environmentally-Extended Input-Output Model*, by Yang et al., 2017, Journal of Cleaner Production, pp. 308-318 (https://doi.org/10.1016/j.jclepro.2017.04.150).

Appendix F

Temperature Control Upfront Construction Cost Estimate

Material	Unit Prices ($)		Material Amount (LF of pipe or item count)	Cost ($)		Manufacturer, Model	Supplier
Pipe							
1/2" Copper Pipe Type L	$	2.32	0	$	-	Mueller Industries, 1/2 in. x 10 ft.	Ferguson
3/4" Copper Pipe Type L	$	3.79	195	$	739.05	Mueller Industries, 3/4 in. x 10 ft.	Ferguson
1" Copper Pipe Type L	$	5.50	930	$	5,115.00	Mueller Industries, 1 in. x 10 ft.	Ferguson
1 1/4" Copper Pipe Type L	$	7.45	0	$	-	Mueller Industries, 1 1/4 in. x 10 ft.	Ferguson
1 1/2" Copper Pipe Type L	$	9.59	78	$	748.02	Mueller Industries, 1 1/2 in. x 10 ft.	Ferguson
2" Copper Pipe Type L	$	15.20	0	$	-	Mueller Industries, 2 in. x 10 ft.	Ferguson
			Pipe Subtotal	$	6,602.07		
Pipe Insulation							
1 1/2" Insulation for 1/2" Pipe	$	6.91	0	$	-	K-Flex, 6RXLO148058	Supply House
1 1/2" Insulation for 3/4" Pipe	$	6.17	195	$	1,203.15	K-Flex, 6RXLO148078	Supply House
1 1/2" Insulation for 1" Pipe	$	6.02	930	$	5,598.60	***Interpolated Cost	
1 1/2" Insulation for 1 1/4" Pipe	$	5.87	0	$	-	K-Flex, 6RXLO148138	Supply House
1 1/2" Insulation for 1 1/2" Pipe	$	5.80	78	$	452.01	***Interpolated Cost	
			Pipe Insulation Subtotal	$	7,253.76		
Fittings							
1 1/2" 90 Elbows	$	6.39	4	$	25.56	Elkhard, 31314	Supply House
1 1/4" 90 Elbows	$	4.09	0	$	-	Elkhard, 31306	Supply House
1" 90 Elbows	$	2.78	129	$	358.62	Elkhard, 31296	Supply House
3/4" 90 Elbows	$	1.04	30	$	31.20	Elkhard, 31288	Supply House
1/2" 90 Elbows	$	0.45	0	$	-	Elkhard, 31272	Supply House
1 1/2" Tee	$	14.89	6	$	89.34	Elkhart, 32910	Supply House
1 1/2" - 1" Reducer Coupling	$	6.89	4	$	27.56	Elkhart, 30768	Supply House
1 1/2" - 3/4" Reducer Coupling	$	6.69	2	$	13.38	Elkhart, 30772	Supply House
			Fittings Subtotal	$	545.66		
Valves							
1 1/2" Isolation Ball Valves	$	39.21	4	$	156.84	Watts, 88005695	Supply House
3/4" Automatic Thermosetter	$	209.33	4	$	837.32	Caleffi, 116250AC	Supply House
1/2" TMV	$	137.92	28	$	3,861.76	Watts, 1/2" LFL1170M2-UT	Supply House
3/4" TMV	$	169.72	3	$	509.16	Watts, 3/4" LFL1170M2-UT	Supply House
			Valves Subtotal	$	5,365.08		
Hangers							
1/2" Black Clevis	$	0.97	0	$	-	Bluefin, BLCH050	Supply House
3/4" Black Clevis	$	0.96	49	$	46.85	***Interpolated Cost	
1" Black Clevis	$	0.96	233	$	223.20	Bluefin, BLCH100	Supply House
1 1/4" Black Clevis	$	1.04	0	$	-	Bluefin, BLCH125	Supply House
1 1/2" Black Clevis	$	1.05	20	$	20.48	Bluefin, BLCH150	Supply House
Rods	$	2.49	902	$	2,246.98	Cooper B-Line, B3213	Supply House
			Hangers Subtotal	$	2,537.50		
Equipment							
Water Heater	$	1,124.84	1	$	1,124.84	AO Smith, GPVT50 Model	Supply House
Circulation Pump	$	3,225.22	1	$	3,225.22	Bell and Gossett, 65-130 model	Supply House
			Equipment Subtotal	$	4,350.06		
Architecture							
Sq Ft. For Equipment	$	278.24	0	$	-	DCR Costbook 2017	
			Architecture Subtotal	$	-		
			Total Upfront Material Cost	$	26,654.13		
			Labor Factor		1.43		
			Total Upfront Cost	$	38,115.40		

Note. Created by the author of this report. Unit prices derived from either the Supply House (http://supplyhouse.com) or Ferguson (https://www.ferguson.com/) websites respectfully by material supplier. All values from electronic sources were derived on March 28, 2021.

Appendix G

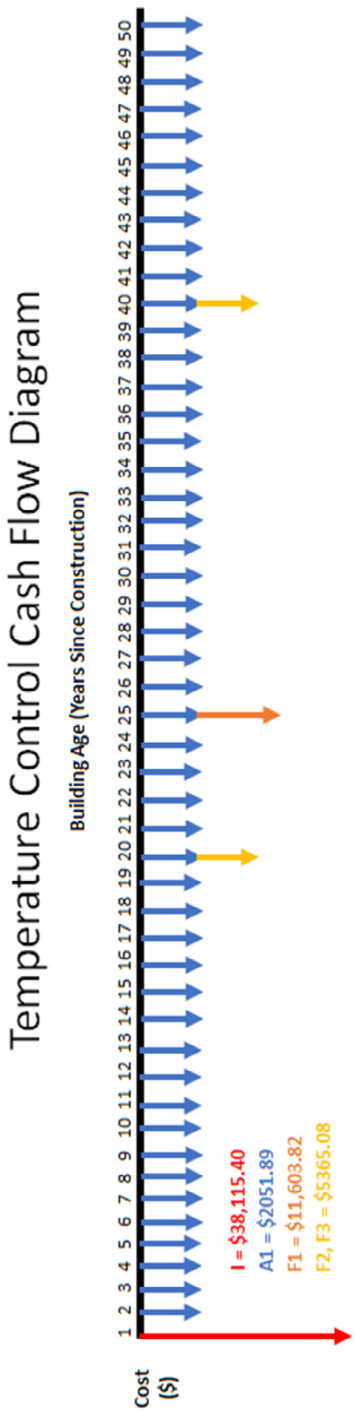
Chlorine Disinfection Upfront Construction Cost Estimate

Material	Unit Prices ($)	Material Amount (LF of pipe or item count)	Cost ($)	Manufacturer, Model	Supplier
Pipe					
1/2" Copper Pipe Type L	$ 2.32	0	$ -	Mueller Industries, 1/2 in. x 10 ft.	Ferguson
3/4" Copper Pipe Type L	$ 3.79	50	$ 189.50	Mueller Industries, 3/4 in. x 10 ft.	Ferguson
1" Copper Pipe Type L	$ 5.50	220	$ 1,210.00	Mueller Industries, 1 in. x 10 ft.	Ferguson
1 1/4" Copper Pipe Type L	$ 7.45	510	$ 3,799.50	Mueller Industries, 1 1/4 in. x 10 ft.	Ferguson
1 1/2" Copper Pipe Type L	$ 9.59	180	$ 1,726.20	Mueller Industries, 1 1/2 in. x 10 ft.	Ferguson
2" Copper Pipe Type L	$ 15.20	0	$ -	Mueller Industries, 2 in. x 10 ft.	Ferguson
		Pipe Subtotal	$ 6,925.20		
Insulation					
1" Insulation for 1/2" Pipe	$ 2.75	0	$ -	K-Flex, 6RXLO100058	Supply House
1" Insulation for 3/4" Pipe	$ 3.26	50	$ 163.00	K-Flex, 6RXLO000078	Supply House
1" Insulation for 1" Pipe	$ 3.42	220	$ 752.40	***Interpolated Cost	
1" Insulation for 1 1/4" Pipe	$ 3.95	510	$ 2,014.50	K-Flex, 6RXLO100138	Supply House
1" Insulation for 1 1/2" Pipe	$ 4.05	180	$ 729.00	***Interpolated Cost	
		Insulation Subtotal	$ 3,658.90		
Fittings					
1 1/2" 90 Elbows	$ 6.39	24	$ 153.36	Elkhard, 31314	Supply House
1 1/4" 90 Elbows	$ 4.09	64	$ 261.76	Elkhard, 31306	Supply House
1" 90 Elbows	$ 2.78	35	$ 97.30	Elkhard, 31296	Supply House
3/4" 90 Elbows	$ 1.04	18	$ 18.72	Elkhard, 31288	Supply House
1/2" 90 Elbows	$ 0.45	20	$ 9.00	Elkhard, 31272	Supply House
1 1/2" Tee	$ 14.89	0	$ -	Elkhart, 32910	Supply House
1 1/2" - 1" Reducer Coupling	$ 6.89	0	$ -	Elkhart, 30768	Supply House
1 1/2" - 3/4" Reducer Coupling	$ 6.69	0	$ -	Elkhart, 30772	Supply House
		Fittings Subtotal	$ 540.14		
Valves					
1 1/2" Isolation Ball Valves	$ 39.21	6	$ 235.26	Watts, 88005695	Supply House
3/4" Automatic Thermosetter	$ 209.33	0	$ -	Caleffi, 116250AC	Supply House
1/2" TMV	$ 137.92	0	$ -	Watts, 1/2" LFL1170M2-UT	Supply House
3/4" TMV	$ 169.72	0	$ -	Watts, 3/4" LFL1170M2-UT	Supply House
		Valves Subtotal	$ 235.26		
Hangers					
1/2" Black Clevis	$ 0.97	0	$ -	Bluefin, BLCH050	Supply House
3/4" Black Clevis	$ 0.96	13	$ 12.00	***Interpolated Cost	
1" Black Clevis	$ 0.96	55	$ 52.80	Bluefin, BLCH100	Supply House
1 1/4" Black Clevis	$ 1.04	128	$ 132.60	Bluefin, BLCH125	Supply House
1 1/2" Black Clevis	$ 1.05	45	$ 47.25	Bluefin, BLCH150	Supply House
Rods	$ 2.49	720	$ 1,792.80	Cooper B-Line, B3213	Supply House
		Hangers Subtotal	$ 2,037.45		
Equipment					
Water Heater, GPVL 40	$ 1,018.79	1	$ 1,018.79	AO Smith	Supply House
Circulation Pump, 20-35	$ 1,131.41	1	$ 1,131.41	Bell and Gossett	Supply House
Chlorinator Pump	$ 4,923.00	1	$ 4,923.00	Verder	Mulcahy Shaw
Ventilation Fan	$ 174.00	1	$ 174.00	fantech	Supply House
Emergency Eyewash and Shower	$ 1,804.35	1	$ 1,804.35	Guardian Equipment	Grainger
Galvanized Ductwork	$ 10.65	25	$ 266.25	Lambro Industries	Supply House
		Equipment Subtotal	$ 9,317.80		
Architecture					
Sq Ft. For Equipment and EEW	$ 278.24	25	$ 6,956.00	DCR Costbook 2017	
		Architecture Subtotal	$ 6,956.00		
		Total Upfront Material Cost	$ 29,670.75		
		Labor Factor	1.43		
		Total Upfront Cost	$ 42,429.17		

Note. Created by the author of this report. Unit prices derived from either the Supply House (http://supplyhouse.com) or Ferguson (https://www.ferguson.com/) websites, respectfully, by material supplier. All values from electronic sources were derived on March 28, 2021. Materials with other, or no listed suppliers were derived directly from supplier or manufacturer cut sheets.

Appendix H

Temperature Control Cash Flow Diagram and Calculations



Temperature Control

I

I = $38,115.40

A1

PA1 = A(P/A, 4%, 50) = 2,051.89(21.4822) = $44,079.12

F1

PF1 = F(P/F, 4%, 25) = 11,603.82(0.3751) = $4,352.60

F2

PF2 = F(P/F, 4%, 20) = 5,365.08(0.4564) = $2,446.63

F3

PF3 = F(P/F, 4%, 40) = 5,365.08(0.2083) = $1,117.55

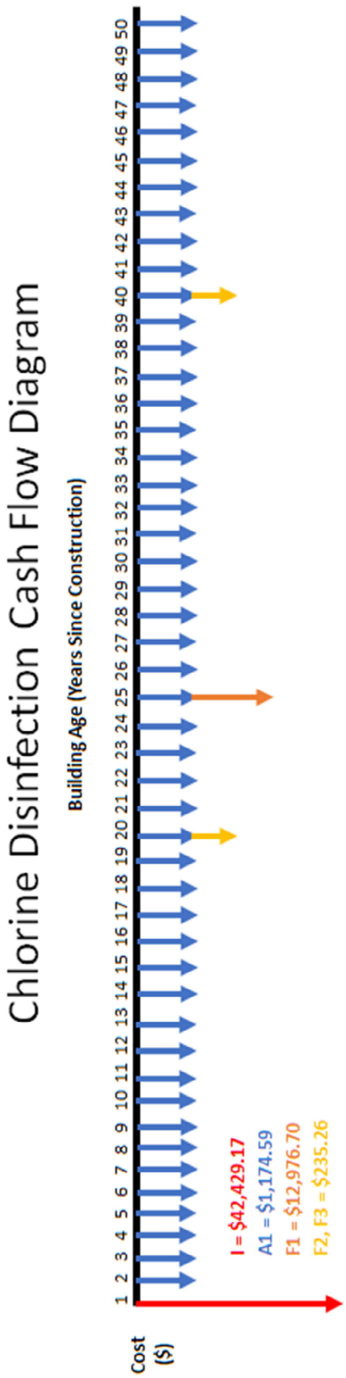
NPV

NPV = Σ(I, PA1, PF1, PF2, PF3) = $90,111.30

Note. Created by the author of this report. Cash flow diagram not to scale. Pre-calculated values in calculations adapted from *Basics of Engineering Economy, Second Edition*, by L. Blank and A. Tarquin, 2014, McGraw-Hill, p. 447.

Appendix I

Chlorine Disinfection Cash Flow Diagram and Calculations



Chlorine Disinfection

I

I = $42,429.17

A1

PA1 = A(P/A, 4%, 50) = $1,174.59(21.4822) = $25,232.78

F1

PF1 = F(P/F, 4%, 25) = 12,976.70(0.3751) = $4,867.56

F2

PF2 = F(P/F, 4%, 20) = 235.26(0.4564) = $107.37

F3

PF3 = F(P/F, 4%, 40) = 235.26(0.2083) = $49.00

NPV

NPV = Σ(I, PA1, PF1, PF2, PF3) = $72,685.88

Note. Created by the author of this report. Cash flow diagram not to scale. Pre-calculated values in calculations adapted from *Basics of Engineering Economy, Second Edition*, by L. Blank and A. Tarquin, 2014, McGraw-Hill, p. 447.