BIM-based Automated Design and Drafting for Drainage Systems in Residential Buildings

by

Nan Zhang

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in
Construction Engineering and Management

Department of Civil and Environmental Engineering
University of Alberta

ABSTRACT

The development of building information modelling has facilitated the improvement of cost and time management in panelized construction, one of the most popular and efficient methods for constructing residential buildings. However, in most cases, the drainage system is currently still installed on site in a traditional manner and makes the design stage difficult and time-consuming due to the high level of design detail required. This research proposes an automated method to design and draft drainage systems in the BIM model, adapted for panelized construction of residential buildings. This proposed method can improve design efficiency, eliminate design errors, and reduce material waste. In order to improve production efficiency at the panelized construction plant, the drainage pipe network is separated into smaller components at the geometric boundaries of the plumbing panel which is a floor or wall panel through which pipes pass. Meanwhile, a bill of materials for each plumbing panel is generated for the purpose of further optimization of cutting list. A prototyped BIM extension application, an add-on to Autodesk Revit, is developed as a proof of concept. A case study of residential drainage system design and optimization is presented to illustrate the feasibility of the proposed framework. As the key contribution of this research, the integration of the BIM model with the automated design system, rule-based pipe route planning approach, and optimal cutting stock algorithm achieves the automation in drainage system design in the context of panelized construction to improve design and production efficiency.

PREFACE

This thesis is the original work by Nan Zhang who completes the thesis work under the supervision of Dr. Mohamed Al-Hussein. Three conference papers related to this thesis have been submitted or published and are listed below.

1. **Zhang, N.**, Tian, Y., and Al-Hussein, M. (2019). "A Case Study for 3D Modeling Process Analysis based on BIM Log File." Modular and Offsite Construction Summit 2019 (MOC), Banff, AB, Canada, May 21-24.

2. **Zhang, N.**, Tian, Y., Wang, J., and Al-Hussein, M. (2020). "BIM-based Automated Drainage System Design in Prefabrication Construction.", Construction Research Congress 2020 (CRC), Tempe, Arizona, United States, Mar. 8-10.

3. Tian, Y., Wang, J., **Zhang, N.**, and Al-Hussein, M. (2020). "BIM-based Automated Drafting System in Cabinet Manufacturing.", Construction Research Congress 2020 (CRC), Tempe, Arizona, United States, Mar. 8-10.

ACKNOWLEDGMENTS

Initially, I would like to express my sincere appreciation to my supervisor, Dr. Mohamed Al-Hussein, for his support, visionary direction, great patience and inspiration throughout my study. He always encourages me to do my best.

Also, I would like to express my thanks to Beda, Mahmud, Yichen, Yuan, Karen, Jon, Kristin and all other friends in our research group for their valuable suggestions and moral support during these two years.

Meanwhile, I am grateful to ACQBUILT Inc. in Edmonton, Canada, for their support and for granting access to observe panelized construction and collect data.

Finally, I would like to express my gratitude to my parents for their support, encouragement and love. They have always inspired me over the years without asking anything in return.

TABLE OF CONTENTS

LIST OF FIGURES

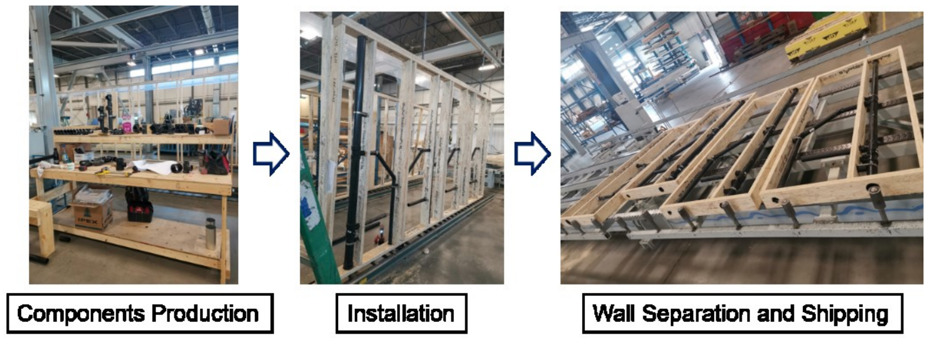
LIST OF TABLES

CHAPTER 1. INTRODUCTION

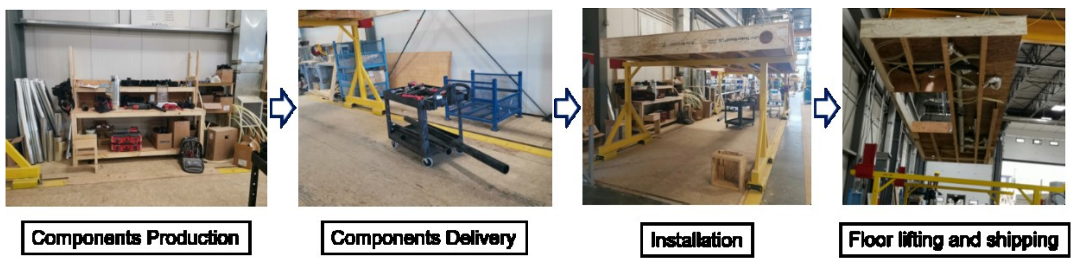
1.1 Background and Motivation

Building information modelling (BIM) can benefit almost all stages and processes involved in a construction project, especially the design and planning stage. In recent years, this information technology has been gradually implemented in the architecture, engineering, and construction (AEC) industry. It has been proven that BIM techniques can improve design efficiency and accuracy, and eventually improve the performance of industrialization and prefabrication in construction. Prefabrication can increase construction project performance (Li, Shen, & Xue, 2014), which has led to it being an increasingly popular construction method for home builders because of time and cost savings, the high level of quality control, and environmental friendly assembly process (Prefab Housing Canada, 2018). More recent studies show that the applications of prefabrication doubled in 2000 (Haas, O'Connor, Tucker, Eickmann, & Fagerlund, 2000). Prefabrication methods have been adopted worldwide and are well-developed in many countries, such as Japan, Sweden, Germany and the Netherlands (Steinhardt & Manley, 2016). In Sweden, in particular, around 80% of single-family homes were built using prefabricated timber construction methods (Knaack, Chung-Klatte, & Hasselbach, 2012).

As one classic type of prefab construction, panelized homes are assembled on site by installing the wall, floor and roof panels, which are designed and framed at a prefabrication plant and then shipped to the site for installation. However, in most cases, the mechanical, electrical and plumbing (MEP) components are installed on site in the traditional manner. Thus, there is a need for MEP components to be incorporated into the prefab panels in order to capitalize on the benefits of the prefab construction approach. The MEP installation process can be carried out while the framed panels are in queue at the plant for shipping to the construction site, as shown in Figure 1-1, which offers the potential to reduce total project time, the effect of weather outside and the garbage generated in on-site construction when cutting pipes and drilling holes in the framing members (i.e., stud, plate, and joist). Installing pipes in a framed wall in the context of industrialized panelized construction begins with producing pipe fittings by cold-welding fitting components at the material station of the plant. Then, the pipes that are cut to the desired length are installed in the framed walls with the pipe fittings. Figure 1-1(a) shows the drainage system prefabrication and installation process in the framed wall panels. The pipes are installed in the wall panels by passing pipes through the hole that is pre-drilled during the wall panel framing process. The pipes are cut and joined with the required plumbing fittings according to design drawings. After the pipe installation, the wall is separated into wall panels and prepared for shipping to the construction site. The installation process for the drainage system in framed floor panels is shown in Figure 1-1(b), and the process is the same as that of wall panels.



(a). Drainage system prefabrication on framed wall panels



(b). Drainage system prefabrication on framed floor panels

Figure 1-1: Drainage system prefabrication in panelized construction

The innovative production process increases the complexity of the development of the MEP design and the design stage requires more time and effort due to the higher level of design detail required and the need to consider potential clashes between the framed panels and MEP components. During the MEP preliminary design period, the most challenging aspect is the drainage system design due to the complexity of the pipe route design, which must take into account the respective design rules and the required gravity flow in drainage pipes. The gravity-based drainage system starts from the plumbing fixtures and ends at the connection to a municipal sewage pipe. To accomplish gravity flow, drainage pipes are designed at a slope which leads to a height difference when crossing floor panels. Furthermore, the holes drilled to allow pipes to pass through the framing members are designed to ensure the structural integrity of the framed panels according to the building code. Meanwhile, the vent pipes are designed to balance air pressure in order to ensure the proper draining of each plumbing fixture. All these designs are subject to the building and plumbing codes in the given jurisdiction.

In addition, the pipe route is normally rendered as a series of lines on a traditional floor plan drawing without specifying the pipe locations on the framing members, without an accurate schedule of pipes and plumbing fittings, and without the precise pipe height based on sloped pipe design. In most cases, these design details are improved by plumbers using their experience when the drainage system is installed on site. Fixing any details that were neglected in the production stage increases production time and cost. Taking the situation shown in Figure 1-2 as an example, the drainage pipe required a cut in the wall stud because of the lack of design details for the drilling location. It not only takes extra time and cost to cut and then reinforce the wall studs, but also generates construction wastes on site. However, this kind of rework can be avoided by providing supplementary details during the design stage, which will increase the level of design detail required and improve the construction accuracy in panelized construction. Therefore, both the accuracy and efficiency of panelized building design and drafting, especially for the drainage system, need to be improved to achieve high production performance while reducing material waste and cost.

Figure 1-2: Cutting and reinforcement of wall studs

This research thus proposes a rule-based system framework for automatically designing residential drainage systems to improve the assembly efficiency at the prefabrication plant. A planning algorithm and a rule-checking method are incorporated into the framework in order to identify the optimal drainage system design to minimize material waste. A prototyped BIM extension, an add-on to Autodesk Revit, is developed as a proof of concept. The add-on is built in the C# programming environment with the support of the application programming interface (API).

1.2 Research objectives

This research is built upon the following hypothesis:

"A BIM-based and gravity-based automated plumbing design system will improve the efficiency and accuracy of the drainage system design and manufacturing process in the residential panelized construction manufacturing facility."

This research aims to propose a framework that develops a rule-based BIM extension application that will automatically design and draft drainage systems for panelized buildings. To achieve this goal, the following objectives are pursued:

- to understand current panelized construction processes and technology;
- to develop a BIM-based automated design and drafting approach to improve the accuracy and efficiency of the drainage system design process;
- to separate the drainage system into smaller components adapted for panelized construction manufacturing;
- to automatically generate drainage system layouts and shop drawings that include detailed information for panelized construction;
- to generate cutting patterns for pipes based on the cutting stock algorithm to minimize material waste; and
- to develop a prototype system in a BIM environment to fulfill the above functions and proposed framework.

1.3 Thesis organization

This thesis consists of five chapters. Chapter 1 (Introduction) introduces the research background, objectives, and provides an overview of the thesis. Chapter 2 (Literature Review) presents a review of the literature pertaining to prefabrication construction design, optimization pipe route design, and cutting stock problem. Chapter 3 (Proposed Methodology) describes the proposed methodology framework, and consists of six sections including drainage system design overview, methodology overview, scenario-based vent pipe design, rule-based drainage pipe design, a heuristic approach for panelized drainage system, and pipe cutting optimization. Chapter 4 (Implementation and Case Study) is a validation of methodologies using a case study. Chapter 5 summarizes the validation results, and presents the discussion and conclusion of this research, as well as the challenges of applying existing BIM extensions and recommendations for future research.

CHAPTER 2. LITERATURE REVIEW

This chapter presents an overall review of the existing research related to prefabrication design, optimal pipe route design, and cutting stock problems to clarify the departure point of this research. For prefabrication design, the first section provides background information related to adapting mechanical, electrical and plumbing (MEP) design to prefabricated construction projects. The second section introduces the pipe routing design algorithms for identifying the shortest and free-obstacle path between two terminals. The last section summarizes the literature related to cutting stock problems and one-dimensional cutting stock algorithms.

2.1 Construction prefabrication

In many countries, construction waste is an increasing problem for the environment. In Australia, construction projects generate approximately 20-30% of total waste annually (Craven, Okraglik, & Eilenberg, 1994). Over 50% of landfill waste comes from construction sites in the UK (Ferguson, 1995). In the USA, 29% of solid waste comes from construction sites (Rogoff & Williams, 2012). In Hong Kong, construction waste is responsible for 40% of total waste, and is deposited in landfills areas, which will be at capacity in 10–15 years (Tam, Tam, Zeng, & Ng, 2007). Thus, prefabrication as one of the methods to reduce construction waste is of increasing interest in many countries. It is a “cleaner” production strategy, although many factors, including political, economic, social, and technological factors, affect the prefabrication adoption (Lu, Chen, Xue, & Pan, 2018).

As a manufacturing process, prefabrication generates the components that are joined together by various materials for final installation (CIRIA, 1999). Prefabrication has also been identified as the first degree of industrialization, followed by mechanization, automation, robotics and reproduction (Richard, 2005). There are two kinds of prefabrication, factory prefabrication, which is undertaken in a factory environment, and site-prefabrication, which is undertaken on site (Testa, 1972). In most cases, off-site prefabrication is more prevalent than site-prefabrication because of the lack of on-site space for producing components. Three categories of off-site fabrication were defined according to Gibb's research (1999), who classified off-site fabrication into non-volumetric (items that do not enclose usable space), volumetric (units that enclose useable space, but do not of themselves constitute the whole building), and modular building (units that form a complete building or part of a building, including the structure and envelope). Gibb also indicated the flexible boundary between these categories (1999).

In terms of approaches to constructing prefabricated homes, there are two main methods: panelized and modular construction. Modular construction is a construction process that uses volumetric units that are prefabricated and fully finished at the plant and then delivered to the construction site for final assembly to complete whole buildings (Lawson, Ogden, & Goodier, 2014). Panelized construction is a production process based on traditional framing construction that frames panelized components, such as wall panels and floor panels, in a climate-controlled and efficient manufacturing environment. The panelized building components are then shipped to the construction site and installed on the prepared project foundation (The Canadian Timber Company, 2007). The main difference between the modular construction method and the panelized construction method is that in the former the prefabricated unit is a box-like module including the completed structure and exterior finishes, and in the latter the prefabricated unit is a structural panel.

Prefabrication offers the potential for significant advantages, such as a stable working environment in the factory, repetitive work planned with more certainty, more efficient sequencing of the work by operators, working methods that can be analyzed at a detailed level to improve techniques, more efficient use of cranes on site, and less construction site waste (Neale, Price, & Sher, 1993).

2.1.1 Panelized construction

As one of the prefabrication methods, panelized construction produces pre-fabricated panels, which may include a pre-installed portion of a house system (such as an electrical system), pre-installed windows, doors, and skylights. In the production line, single panels can be merged into multi-panels and then travel through various workstations in the manufacturing facility (Altaf, Bouferguene, Liu, Al-Hussein, & Yu, 2018). To decrease permitting time and inspection delays, the panels are designed to meet the building code requirements of one or more jurisdictions.

Panelized construction offers some advantages compared to the modular construction approach. The first benefit presented by Lopez and Froese (2016) is with respect to transportation. In their research, in comparison with the transportation requirements for complete prefabricated modules, which require larger trucks and more of them, panels can be stacked and fit onto smaller trucks because of their flat rectangular structure. Lopez and Froese (2016) also mentioned that panelized construction components can be protected during transportation and there is a lower probability of damage as panels can be securely placed by strapping that is tightened to the flatbed truck to reduce or eliminate movement of the panels during transport; however, there is the potential risk of damage to modules during placement and transportation because strapping and tightening the fully assembled modules with walls and roof is a tough task. Furthermore, Lopez and Froese (2016) introduced another benefit of panelized construction, which is that the required equipment and machinery for on-site installation of panels can be smaller, which makes equipment transportation easier. In addition, the insulation technology for connecting panels provides a higher R-value and an airtight envelope to reduce heat losses in winter (Lopez & Froese, 2016).

Panelized construction also has some other notable features. This construction method reduces the effect of weather on the construction schedule, improves the uniformity of wall construction, improves the performance of components because they are manufactured in a controlled environment, reduces storage and traffic conflicts due to just-in-time delivery, reduces the staging area as panel materials are not stored on site, and shortens the construction time required for interior finishes since that process can start as soon as the building is enclosed due to the excellent quality of framed interior walls (Lindow & Jasinski, 2003). Moreover, panelized construction reduces the labour cost on site, requires a low skill set for the on-site construction, and improves building quality control management (Mousa, 2007). These advantages are important to the improvement of the performance of panelized houses and preventing maintenance issues in the future.

Three classes of panel implementation are defined by Morse-Fortier (1995), namely Class I, Class II, and Class III. In Class I, the whole building design is translated into discrete panels, which is based on using traditional production methods in a factory environment before shipping panels to the construction site for assembly. This class of panel implementation is common among some manufacturers and builders. For Class II, panels are used as secondary or even non-structural elements to enclose or fill in a structural frame. In this class, for example, applying standardized foam-core panels to the outside of the frame provides the building's insulation but does not form primary structural system of the finished building in some timber-frame building industries. Class III is a panel system that consists of whole building systems (building envelope and structural system) that are formed by fully standardized and interchangeable panels supported by system flexibility of house designs.

2.1.2 MEP prefabrication

The current practice of installing plumbing systems in the context of prefabrication is fraught with challenges and barriers. The main contributing factors include the lack of policies to encourage and promote plumbing prefabrication when following the building codes related to prefabricated building and green building, the lack of availability of plumbing fittings designed to be installed on site, the low level of design standardization, and low-skilled workers (Li, Li, & Wu, 2017). Furthermore, successful implementation requires the full cooperation from all stakeholders in a project, such as the owners, the designers, the general contractor, the MEP sub-contractors, and the fabricator (Lavikka, Chauhan, Peltokorpi, & Seppanen, 2018).

The numerous challenges involved in the successful application of plumbing in prefabrication, specifically in panelized construction projects, cannot dampen the research enthusiasm on this topic. Researchers from Taiwan and the US provided a spatial planning algorithm, which separated complex facilities of an MEP room into smaller fabricated components to improve the loading and shipping efficiency (Tserng, Yin, Jaselskis, Hung, & Lin, 2011). An efficient modularization algorithm was developed for reducing the cost of the assembly and handling of MEP modules (Samarasinghea, Gunawardenaa, Mendisa, Sofia, & Aye, 2019). Moreover, to shorten project duration, the project's activities can be re-organized by adding offsite coordination activities for prefabrication (Jang & Lee, 2018). In addition, a simulation-based approach was developed to test and evaluate lean production principles in order to improve the value stream in pipe spool fabrication (Wang, Mohamed, Abourizk, & Rawa, 2009). In terms of identifying the challenges of practicing prefabrication, preassembly, modularization, and off-site fabrication (PPMOF) in MEP construction, a systematic method was developed by the Construction Industry Institute (CII) (2004) during conceptual design phases.

2.2 Pipe route design optimization algorithms

The pipe route design (PRD) problem has become a popular research topic in the past few decades in various industrial applications, such as chemical plant layout design (Burdorf, Kampczyk, Lederhose, & Schmidt-Traub, 2004), ship pipe system design (Park & Storch, 2002), and aero-engine pipe route design (Yin, Xu, Bi, Chen, & Zhou, 2013). The PRD problem is generally defined as the problem of planning the shortest path connecting the start point and the target point in a limited workspace, to satisfy all the constraints that affect the pipe system.

Many researchers have put effort into creating algorithms and enabling a computer to solve the PRD problem. In an early study, Lee (1961) proposed a search and trace algorithm for path problem in a grid, a type of maze routing problem, to find the shortest free-obstacle path between two points. This algorithm divided the workspace into cells and labeled all adjoining cells continuously with positive integers from the start cell until reaching the target cell or until no unlabeled cells are left. After this search approach, a trace method was developed to find all possible paths. From the target cell, a neighbor cell with the lower mark was added to a cell list until reaching the start cell, and this list was reorganized from minimal mark to maximal mark to comprise a path from start point to the target point. The maze algorithm guarantees a solution, but it requires a long calculation time and a significant amount of memory space (Kai-jian & Zhu, 1987).

A* (A Star) algorithm, proposed by Hart et al. (1968), extends Lee's maze algorithm and uses cell decomposition and connectivity graphs to find an optimal solution. This algorithm is widely used in pathfinding and graph traversal to find a path between multiple points, which are also called nodes. In Hart's research, there was a formula to evaluate available nodes to determine which one was expanded next from the start point. The evaluation function $f(n)$ was the sum of two parts, the cost $g(n)$ from the start point to the node (n) and the cost $h(n)$ from the node (n) to the target point. The cost, $g(n)$ and $h(n)$, may be the length between two points or the time traveled from one point to another, which is defined by the objective of the pathfinding problem. The node with minimum $f(n)$ was selected and then $f(n)$ of its neighbor nodes was calculated and filtered, which was repeated until the path reached the target node. The cost of an optimal path was equal to the cost of the target node.

Dijkstra's (1959) algorithm is a computer algorithm that is used in the pathfinding problem. This method aims to produce the shortest path tree from the start node to all other nodes in the graph, as well as to find the shortest path between two nodes. In his research, the distance between the start node and its neighbors is calculated and the closest node will be the new start node. This process is repeated until reaching the goal node. As one of the most famous pathfinding methods, Dijkstra's algorithm always determines the best solution, but it takes a long calculation time, occupies more memory space, and only considers the shortest solution (Nguyen, Kim, & Gao, 2016). Dijkstra's algorithm was improved by Nguyen et al. (2016) for solving the ship pipe route design problem by finding the shortest path with a minimum number of bends and elbows.

Some other algorithms were also implemented in solving the PRD problem. The escape algorithm (or linear expansion algorithm) generates a perpendicular line as an escape line from the starting point to find an escape point avoiding obstacles, then this process is repeated by setting the escape point as a new start point until the line crosses the target point (Hightower, 1969). This algorithm is fast and uses less memory space, but it cannot guarantee to find the shortest path (Kai-jian & Hong-e, 1987). Furthermore, the robot-path planning algorithm is an approach that regards the pipe as the trace left behind by a rigid object moving in the workspace for pipe route design in ships (Zhu & Latombe, 1991). In their research, backtracking happens if the "robot" fails to search a channel using an improved chronological backtracking strategy that changes routes in the reverse chronological order of their generation and finally considers all the possible orderings on the pipes without looping.

A genetic algorithm (GA) was applied to find an appropriate pipe route (Ito, 1999). This algorithm generated a route path through the evolution of genes, which stood for pipe routes by using a crossover method to test possible free-obstacle paths. In Ito's research, the working space for pipe routing planning was divided into cells, and a route was a combination of cells connecting a start cell and a destination cell. A unit vector set presented the direction of a route path with a character string corresponding to each vector or direction. Thus, each path can be coded as a character set, which was the chromosome genotype in GA. To find a new route, a crossover operation between parents (initially generated route paths) was conducted to generate vector arrays. The child paths were set as parents and then continued to generate new genes until there was one route path that met the objective function. This path is the optimal path, which may be the shortest path or the path with the minimum number of turns.

In recent studies, an ant colony optimization algorithm (ACO) was improved with a co-evolution mechanism for ship multi and branch pipe route design (Jiang, Lin, Chen, & Yu, 2015). ACO is a method to find the shortest path, and this method mimics ants of the artificial colony generating shorter feasible tours by using the accumulated pheromone deposited on the paths (Dorigo & Gambardella, 1997). Jiang et al. (2015) developed the conventional ACO based on the pheromone direction information and pheromone extension process to enhance the calculation performance.

As another approach discovered from artificial life, particle swarm optimization (PSO) was initially used to mimic the movement of the organisms in bird flocking and fish schooling, and then developed for continuous nonlinear function optimization and neural network training (Kennedy & Eberhart, 1995). PSO was implemented to find the optimal pipe route with minimal length and minimal turns closely following around the obstacle contours in constrained aero-engine 3D rotational space (Liu & Wang, 2010).

To summarize, the genetic algorithm, ant colony algorithm, and particle swarm optimization algorithm are the methods using a stochastic process to find the optimal path, but they may not guarantee the best solution even if it exists, especially in a complex environment with many obstacles (Nguyen, Kim, & Gao, 2016).

2.3 Cutting stock problem

The cutting stock problem (CSP) is a type of optimization problem that cuts standard-sized stock material into pieces of specified sizes to meet the production demand for these pieces. The main objective of solving cutting stock problems is to minimize the total waste, minimize the costs of the used objects, or maximize the profit.

Cutting stock problems can be classified according to the dimensions of the cutting object, i.e., one-dimensional, two-dimensional, and three-dimensional problems. One-dimensional problems usually occur when cutting pipes, cables, and steel bars. Two-dimensional problems are generally applicable in the case of cutting paper, clothing, furniture, and in glass production. Three-dimensional problems are commonly related to 3D packing problems, such as packing objects into shipping containers. In this research, cutting pipes belongs to a one-dimensional problem. Therefore, this section gives a brief review of research studies focused on the one-dimensional cutting stock problem.

The one-dimensional cutting stock problem addresses the issue of cutting the standard-length stock to fit the required length in a project to minimize the total cutting waste. It commonly assumes the standard-length stock as an unlimited supply. In general, the methodology for solving a cutting stock problem can be classified as being one of two types, analytical method or heuristic method, to generate the best cutting patterns with the least cutting waste (Zheng, Yi, & Lu, 2019).

2.3.1 Analytical approach

For the analytical approach, Gilmore and Gomory (1961) applied linear programming (LP) to find the solution of the cutting stock problem. The objective they considered was to minimize the cost and the total amount of required stock with an assumption of a unique price for each object. They introduced a column generation technique to generate the cutting patterns by using a constraint matrix. In the typical LP approach, the LP relaxation model obtained by relaxing the integrality constraints on variables is considered and solved. Then, a rounding procedure is used to get an integer solution. However, the LP relaxation approach generates massive cutting patterns that are rarely enumerated. Thus, Gilmore and Gomory (1961) developed the column generation method to overcome this difficulty. Their approach starts with a set of cutting patterns generated through an auxiliary problem to form the initial basis, then the solution is improved by removing a cutting pattern (as the leaving variable) and generating a new one (as the entering variable). The new cutting pattern is generated as the new column of the matrix in a manner that results in the most possible solutions based on the same concept as choosing the entering variable to be the non-basic variable with the most negative reduced cost in the simplex method. Gilmore and Gomory's approach is relatively efficient because it does not require the generation of all the possible cutting patterns but it may not achieve the optimal solution (Salem, Shahin, &

Khalifa, 2007). To improve their work, Dyckhoff (1981) proposed a dynamic model to structure the cutting patterns in a more simple manner. This method has been adapted to deal with a large number of stock lengths and order lengths (Zheng, Yi, & Lu, 2019).

2.3.2 Heuristic approach

In terms of an heuristic approach, in earlier studies, Haessler (1975) and Roodman (1986) developed a set of heuristic procedures to control cutting waste and generate good solutions for one-dimensional CSP. A sequential heuristic procedure (SHP) was proposed by Gradišar et al. (1999) to solve the one-dimensional CSP when all stock lengths were different, and this solution was done in the context of rebar. In Gradišar's research, an item-oriented solution was raised through a combination of approximations and heuristics in order to reduce the influence of rebar ending conditions leading to near-optimal solutions.

In recent decades, some researchers still put efforts into solving CSP through a heuristic approach, a faster and more efficient method. Salem et al. (2007) developed a method based on genetic algorithm (GA) combining linear programming (LP) and integer programming (IP) to solve the optimization problem of minimizing the steel rebar trim losses in a steel workshop. The generated cutting schedules by applying GA-based methodology were compared to the cutting schedules in a real-world workshop, and the results showed a high potential of cost savings that could be achieved using such techniques (Salem, Shahin, & Khalifa, 2007). Moreover, an improved heuristic approach was proposed to redesign the non-used material in the cutting patterns if the unused portions were large enough to be used in the future (Cherri, Arenales, & Yanasse, 2009).

CHAPTER 3. PROPOSED METHODOLOGY

3.1 Overview

3.1.1 Basic definitions

The basic definitions of terms used in the research are illustrated in Figure 3-1. The detailed descriptions of the terms are as follows:

(1) Drainage system: a system to drain wastewater from a residential building to the municipal sewage network, including plumbing fixtures, pipe fittings, and pipes.

(2) Plumbing panel: a floor or wall panel installed drainage systems, like pipes and pipe fittings.

(2) Element: the smallest and most basic item in the drainage system, such as elbows, pipes, and valves.

(3) Combo fitting: the combination of three or more elements ending with a pipe fitting that will be connected to a pipe segment. All the combo fittings are designed before planning the drainage system and can be selected as a type of pipe fitting.

(4) Assembly: it involves the connection of two pipe fittings, or one pipe fitting and a pipe segment, by cold-welding the connections.

(5) Connector: the joint connecting one element to another element, one combo fitting to another combo fitting, or one element to one combo fitting.

(6) Panelized package: a package including the pipes, pipe fittings, and related plumbing fixtures required for a given plumbing panel.

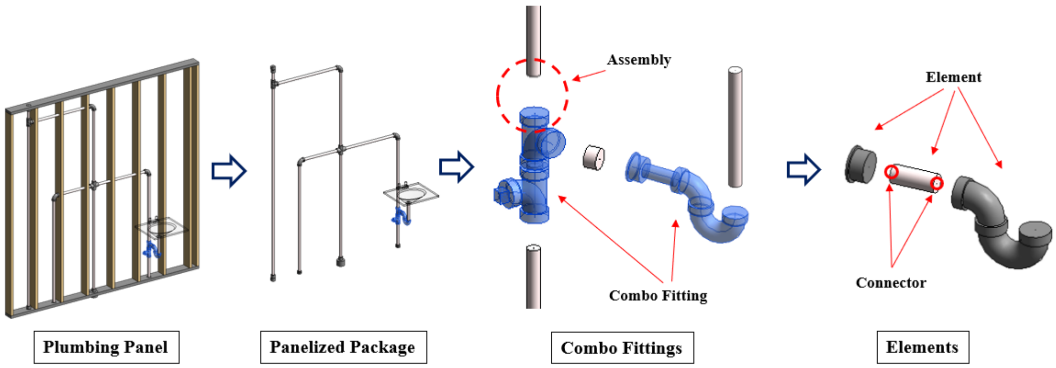


Figure 3-1 Basic definitions of terms used in the research

3.1.2 Drainage system design

This section presents the basic knowledge of residential drainage system design to assist in understanding what is included in the system. A drainage system (Sys_{dr}) typically consists of drainage pipes and vent pipes based on the pipe function. The drainage pipe (P_{di}) is designed to discharge wastewater from a plumbing fixture to the city sewer. The vent pipe (P_{vi}) is designed to balance air pressure in the drainage pipe to maintain smooth water flow by removing gas and odors and allowing fresh air into the pipe. The number of drainage systems (Sys_{dr}) depends on the MEP engineering design. In the context of a townhouse, for example, the number of drainage systems is usually the same as the number of units, because drainage system independence can improve the efficiency of checking and maintenance, as well as avoid damaging other units because of a clog in one unit. In a residential building, the pipe network of a drainage system (Sys_{dr}) is like a tree that comprises the trunk pipes and many branch pipes, as shown in Figure 3-2. The trunk pipes include soil-or-waste stack (Sta_{sw}) and main vent stack (Sta_{ve}). The term soil-or-waste stack (Sta_{sw}) is referred to in the Canadian National Plumbing Code (NPC) (2015) and represents a vertical waste pipe that passes through two or more successive floors. The soil-or-waste stack (Sta_{sw}) includes a drainage pipe (P_{di}) that discharges wastewater to the city sewer and a vent pipe (P_{vi}) that connects to a vent header or outside fresh air. The main vent stack (Sta_{ve}), which is referred to in the NPC (2015), is a vertical vent pipe (P_{vi}) that is upward to the vent pipe of the soil-or-waste stack (Sta_{sw}) and downward to the lower end of the soil-or-waste stack (Sta_{sw}). As another indispensable part of the drainage system (Sys_{dr}), the branch pipes include the drainage pipes (P_{di}) and vent pipes (P_{vi}) from plumbing fixtures to the trunk pipes. The relationship of components in one drainage system (Sys_{dr}) is also shown in Eq. (3-1).

$$Sys_{dr} = Sta_{sw} + Sta_{ve} + \sum P_{vi} + \sum P_{di} \tag{3-1}$$

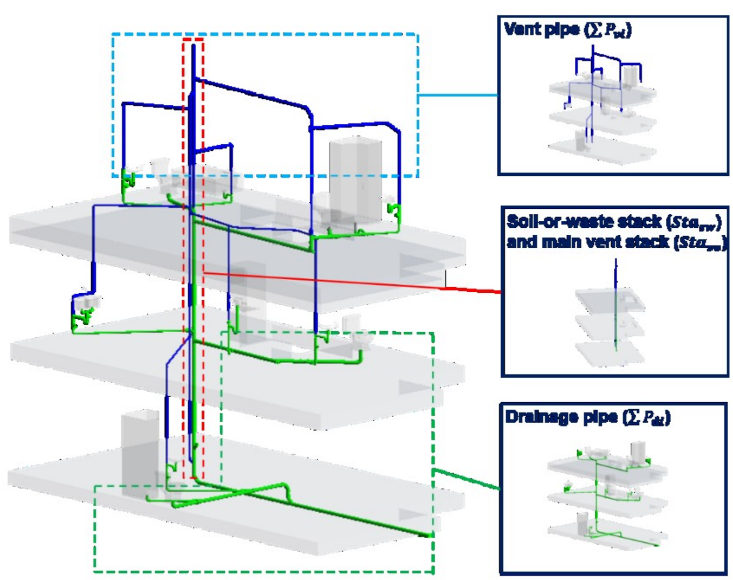


Figure 3-2: Drainage system (DS) 3D view

One important attribute of a drainage system (DS) is the pipe slope (S_i) which is shown in Figure 3-3. There is an obvious height difference (h_i) between one end of the pipe and the other through corresponding floor panels in a light-frame building. The slope (S_i) is calculated in Eq. (3-2) by using pipe fall distance (h_i), pipe horizontal length (m_i), and pipe gradient (α_i). Thus, in this research, the pipe length (L_i) can be calculated using Eq. (3-3) based on the pipe slope (S_i) and pipe horizontal length (m_i).

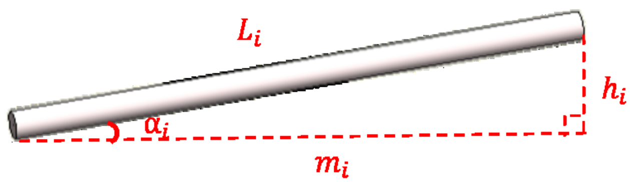


Figure 3-3: Pipe slope (S_i) calculation

$$S_i = tan\alpha_i = h_i/m_i \tag{3-2}$$

$$L_i = \sqrt{{h_i}^2 + {m_i}^2} = \sqrt{(m_i \times tan\alpha_i)^2 + {m_i}^2} = \sqrt{(m_i \times S_i)^2 + {m_i}^2} = m_i \times \sqrt{{S_i}^2 + 1} \tag{3-3}$$

According to the integrated consideration of residential building code (IRC, 2006) and plumbing code (NPC, 2015), the threshold value of slope (S_i) depends on the diameter (D_i) of the pipe. For a pipe with a diameter (D_i) equal to or less than 3 in (76 mm), the slope (S_i) must satisfy Eq. (3-4):

$$1/50 \leq S_i \leq 1/24 \tag{3-4}$$

For a pipe with a diameter that is equal to or greater than 4 in (101 mm), the slope (S_i) must satisfy Eq. (3-5):

$$1/100 \leq S_i \leq 1/24 \tag{3-5}$$

Based on real cases at the panelized construction manufacturing facility, the gravity-based pipe for a drainage system is normally less than 4 in (101 mm) in diameter for residential use, since 3 in (76 mm) is usually sufficient for the hydraulic loading from relatively small scale units in a residential building (such as single-family house, townhouse, or condo). Thus, in this research, the calculation of slope (S_i) is based on Eq. (3-4), which is for pipes of 3 in (76 mm) in diameter or less. Figure 3-4 shows the effect of pipe slope (S_i) in a discharging process. A drainage pipe slope (S_i) of less than $1/50$ or even no slope may cause an accumulation of soil and wastewater and constant drain clogs. A slop (S_i) of more than $1/24$ may allow the liquid waste to drain away and leave the soil waste behind to stick to the pipe.

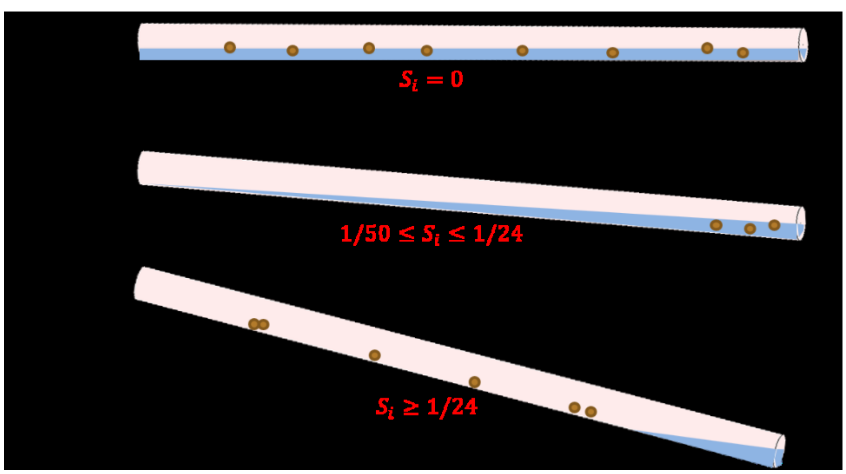
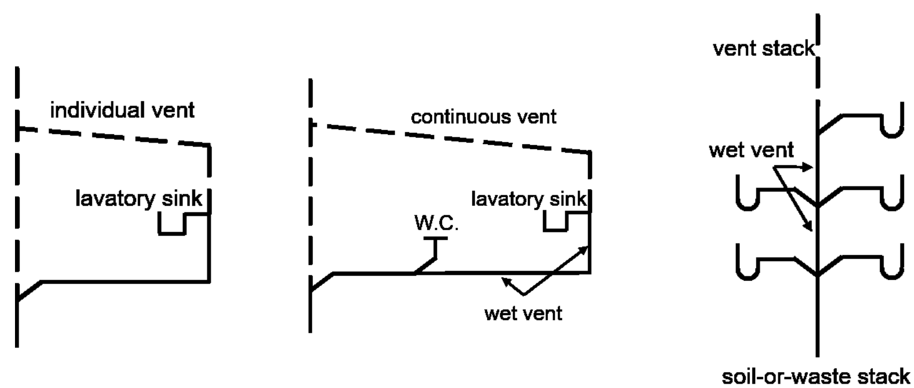


Figure 3-4: Effect of pipe slope on drainage

The vent pipe design is also crucial for a proper drainage system. The vent pipe is designed to balance the air pressure in a pipe when discharging the wastewater from a plumbing fixture. The maximum and minimum total length of the pipe path from fixture to vent stack is constrained by the plumbing code. All plumbing fixtures should be protected by a vent pipe. There are various methods to vent a plumbing fixture. The types of vent pipe considered in this research are individual vent and continuous vent, as shown in Figures 3-5(a) and (b), respectively. The individual method provides venting for an individual fixture. The continuous method is an extension of an individual method, and it is designed for the case of one vent connected by two or three fixtures in a room. In the continuous method, there is a type of vent, named a wet vent, which acts both as a waste pipe for an upstream fixture and a vent for a downstream fixture. The wet vent is designed to save cost and space as reducing the number and length of vent pipes. The soil-or-waste pipe between drainage branch pipes on different floors is also a wet vent, as illustrated in Figure 3-5(c).



(a) Individual vent method

(b) Continuous vent method

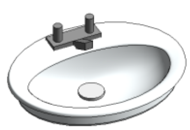
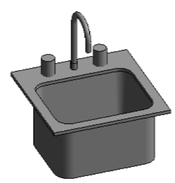
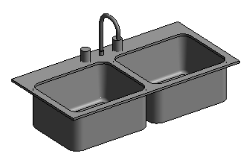
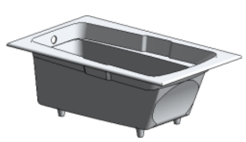
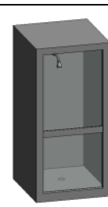
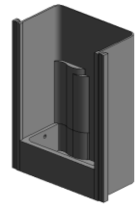
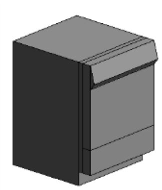
(c) Wet vent in soil-or-waste stack

Figure 3-5: Methods of venting a plumbing fixture

3.1.3 Plumbing fixtures and fittings

As the start point of a drainage system, a plumbing fixture is a type of device that is connected to a plumbing system, including a water supply system and drainage system, to deliver and drain water in a building. The plumbing fitting is the connection of pipes in two directions or sizes. The plumbing fixtures listed in Table 3-1 are normally used in a residential building include sinks, showers, bathtubs, water closets, clothes washers, and dishwashers. From a plumbing fixture, the wastewater is drained through a fixture outlet pipe, trap, and trap arm in sequence to a branch drainage pipe. An example of drainage pipes for a lavatory sink is presented in Figure 3-6.

Table 3-1: Plumbing fixtures in a house

Lavatory sink	Kitchen sink with single basin	Kitchen sink with double basins
		
Bathtub	Shower stall	Bathtub and shower combo
		
Water closet	Clothes washer	Dishwasher
		

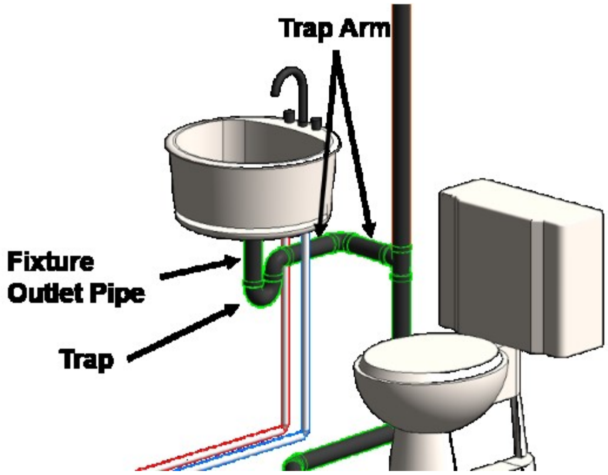
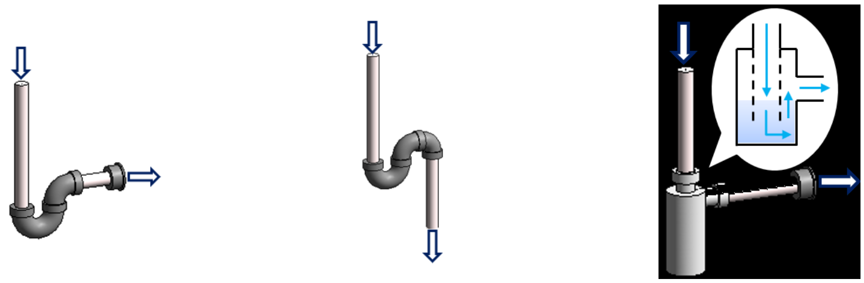


Figure 3-6: An example of a lavatory sink drain

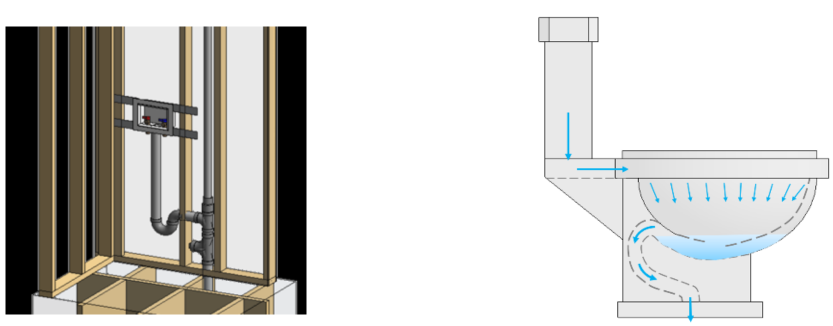
There are three types of sink normally used in residential buildings, including the kitchen sink with a single basin, kitchen sink with double basins, and lavatory sink. The sink needs a trap to hold a liquid seal that prevents the passage of sewer gas but allows the liquid to flow. There are two traditional types of traps, S-shaped trap (S-trap) and P-shaped trap (P-trap), which are shown in Figures 3-7(a) and (b), respectively. The "S" and "P" are the shape of the fittings in the side elevation view. The arrows shown in Figure 3-6 indicate the wastewater flow directions. In some regions of North America, the S-trap is prohibited by the plumbing code since liquid can be siphoned from the trap and returns sewer gas back to homes (NPC, 2015). Thus, the P-trap is most commonly applied for sinks. Furthermore, the bottle trap which is shown in Figure 3-7(c) is an extension of the P-shaped trap and has the same structure to seal water but saves room under the basin.



(a) P-trap (b) S-trap (c) Bottle trap

Figure 3-7: P-trap, S-trap and bottle trap examples

The trap is also used for other plumbing fixtures, including bathtub, shower stall, clothes washer, and dishwashing machine. The dishwasher and kitchen sink share the same trap by directly connecting into the sink outlet pipe with a hose from the dishwasher. The hose is not involved in this research since it comes with the dishwasher. For clothes washers or a stacked combination of washer and dryer, there is an outlet box recessed into the wall of the laundry room, shown in Figure 3-8(a). The outlet box provides shutoffs for both hot water and cold water supply lines, and a wastewater drain connection to connect a hose to the clothes washer. The hose is outside the scope of this research because it is a flexible pipe and considered part of the washing machine.

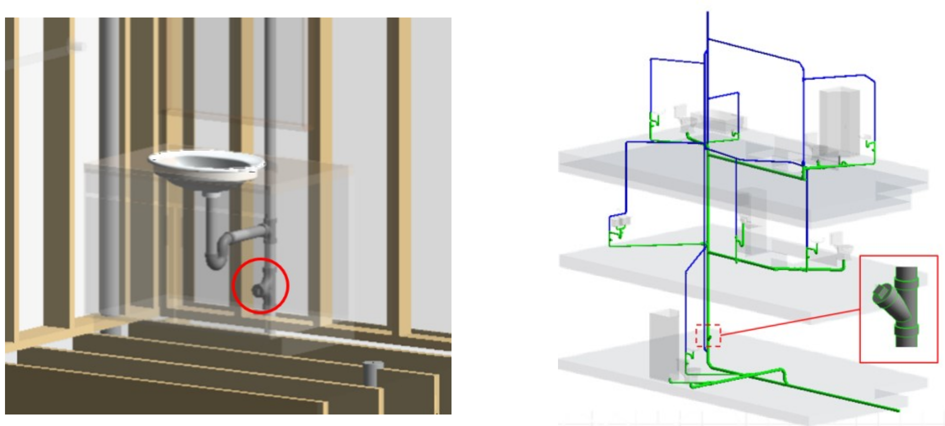


(a) 3D view of clothes washer outlet box (b) Elevation view of water closet's integrated trap

Figure 3-8: Clothes washer outlet box and water closet

All the plumbing fixtures should be protected by a trap except the water closet and some customized fixtures with an inside trap. A water closet is a common type of plumbing fixture that has a trap integrated within the structure, as shown in Figure 3-8(b). There is no need to apply an extra trap for drainage system design since the water can be sealed at the bottom of the toilet bowl against sewer gas.

Another special plumbing fitting is cleanout. A cleanout is a type of pipe fitting that provides access for cleaning and inspection services. It is commonly installed at the drainage vertical pipe of a sink hidden in the wall and near the base of every vertical soil-or-waste stack as shown in Figure 3-9.



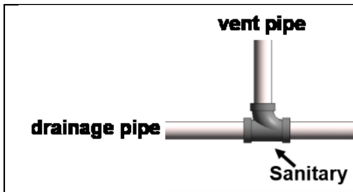
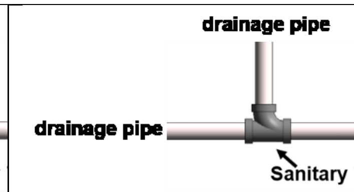
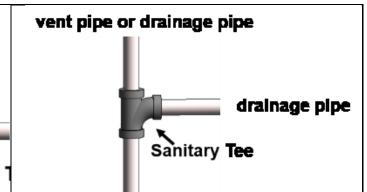
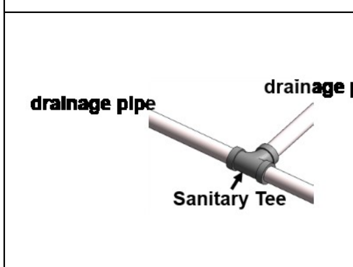
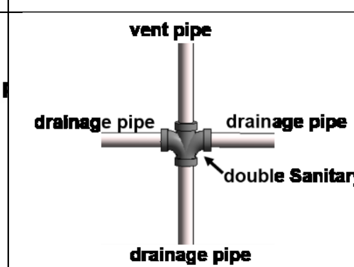
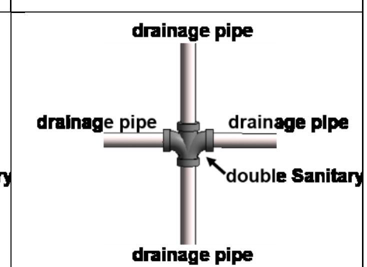
(a) sink cleanout

(b) system cleanout

Figure 3-9: 3D view of cleanouts in a house

According to the plumbing code, there are some special requirements for a 90-degree connection for plumbing fittings. These requirements are listed in Table 3-2. First, it should use a Sanitary Tee fitting or combination Wye with 1/8 bend where a horizontal drainage pipe is connecting to a vertical drainage pipe. However, it is only permitted to use combination Wye with 1/8 bend instead of a standard Tee fitting when the vertical drainage pipe is connecting to a horizontal drainage pipe. Also, Sanitary Tee fitting and combination Wye with 1/8 bend are used for connecting two horizontal drainage pipes on the floor plan. Moreover, it only allows the use of a 90-degree elbow when changing the direction of fixture trap arms or the direction of a vent, otherwise it is required to use a bend that has a larger radius of curvature to create a smoother flow of wastewater. Lastly, the cross fitting is only allowed when connecting four vents.

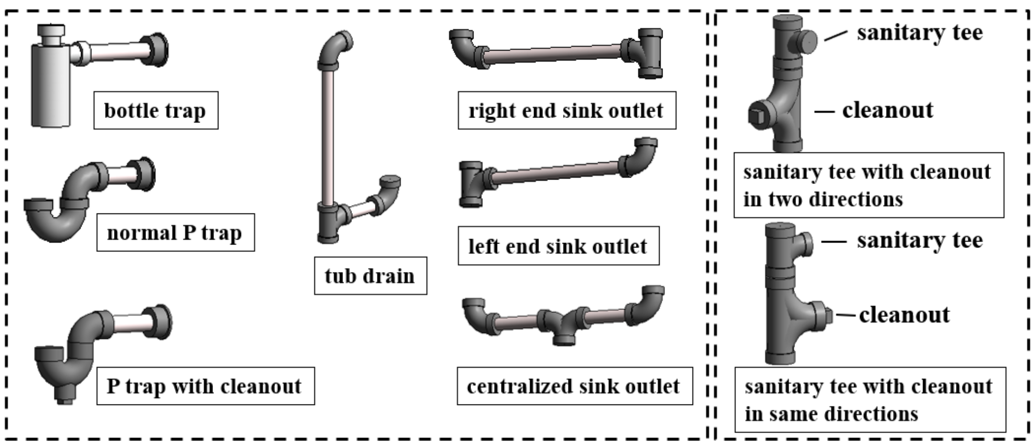
Table 3-2: 90-degree connection rule for drainage pipes and vent pipes

		
permitted, also can use combination Wye with 1/8 bend 	not permitted, use combination Wye with 1/8 bend 	permitted, also can use combination Wye with 1/8 bend 
		
permitted, also can use combination Wye with 1/8 bend ; same to connecting vent pipes	permitted, also can use combination double Wye with 1/8 bend ; the cross fitting  is only allowed for connecting vents	not permitted, use combination double Wye with 1/8 bend 

3.1.4 Plumbing combo fitting design

This section introduces the combo fitting design in a drainage system. All the combo fittings are designed before planning the drainage system. The design of this type of component aims to improve installation efficiency and standardization since plumbers can prepare a set of standard components before installing pipes in framed panels. In this research, a combo fitting is defined as a combination of three or more elements (i.e., pipes and pipe fittings) ending with a pipe fitting which will be connected to a pipe segment.

The combo fitting design should consider the applicability for various fixtures and installation feasibility in the space between framing members. Thus, there are two types of combo fittings, as shown in Figure 3-10, which are designed in this research, including the combo fitting for fixtures and combo fitting in framed panels. For the first type, the fixture comb fitting (FCF) is designed for plumbing fixtures discharging wastewater and being replaced for maintenance. The FCF can be purchased and replaced directly if there is a leak or erosion at a pipe or pipe fitting in one FCF. Therefore, the design of the FCF is based on readily available products in the plumbing market. Three kinds of drain products are involved in this type of combo fitting for plumbing fixtures: (1) the trap is an essential part of plumbing fixtures, and typically it can be one of three types, a normal P trap, P trap with cleanout, and bottle trap, and it is made from commonly available materials, including plastic and chrome-plated brass; (2) the tub drain, which connects the tub overflow opening and bottom drain opening; (3) for a kitchen sink with double basins, the outlet combo fitting can be one of two types, the end-outlet type that connects two sink basins with the drain at one side and the centralized-outlet type that connects two sink basins together with a drain in the middle. In this research, the end-outlet type is defined in two directions, right end and left end, for further calculation. Figure 3-10(b) shows the other type of combo fitting, which is designed for pipe installation in framed panels. The combination comprises a Sanitary Tee and a cleanout, and the fitting directions may be different. The Sanitary Tee can also be replaced by a reducing Sanitary or a Wye fitting.



(a) Combo fittings for fixtures (b) Combo fittings in framed panels

Figure 3-10: 3D view of combo fittings

The combo fittings are specified by the designers to implement in a project. The above combinations are suitable for most residential panelized constructions, but the customized combo fittings are also permitted. Figure 3-11 illustrates an example of combo fitting selection for a kitchen sink with double basins. In this figure, three combo fittings (i.e., sink outlet, trap, and Sanitary Tee with cleanout) are used to drain wastewater. The outlet combo fitting is the first device connected to the sink followed by the trap and Sanitary Tee combo fittings. For these three type of combo fittings, alternatives are provided for users and are involved in a prototype system which will be validated by a case study in Chapter 4.

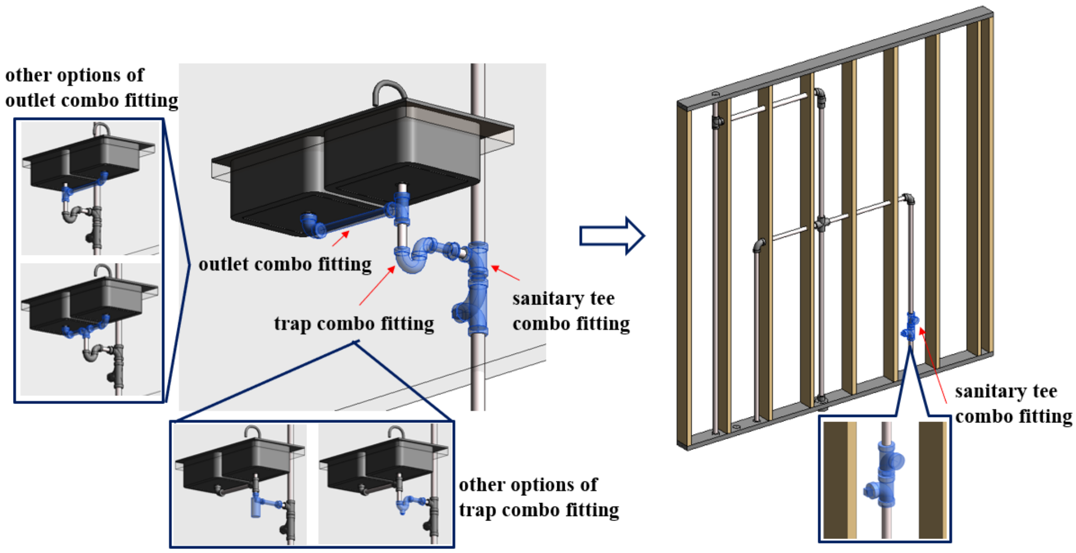


Figure 3-11: Combo fitting design for a kitchen sink with double basins

3.1.5 Methodology overview

This section presents the overview of a framework for the automated design and drafting of a drainage system in a BIM environment The framework includes inputs, criteria, main process, and outputs, and is illustrated in Figure 3-12.

The main process of the research methodology comprises four sections, including scenario-based vent pipe design, rule-based drainage pipe design, pipe network separation into panels, as well as pipe cutting pattern generation. The automated design system extracts from the BIM model the information that will be used in these four steps. First, a scenario-based planning process for the vent pipes provides three options typically used to place vent pipes. After that, the drainage pipe from plumbing fixtures to the soil-or-waste stack is designed automatically using rule-based planning algorithms. Next, the whole drainage system is separated into smaller pieces at the panel boundaries, and the shop drawing and bill of materials (BOM) for each plumbing panel are produced. At last, the optimal cutting list is generated using the pipe schedule and stock pipe length.

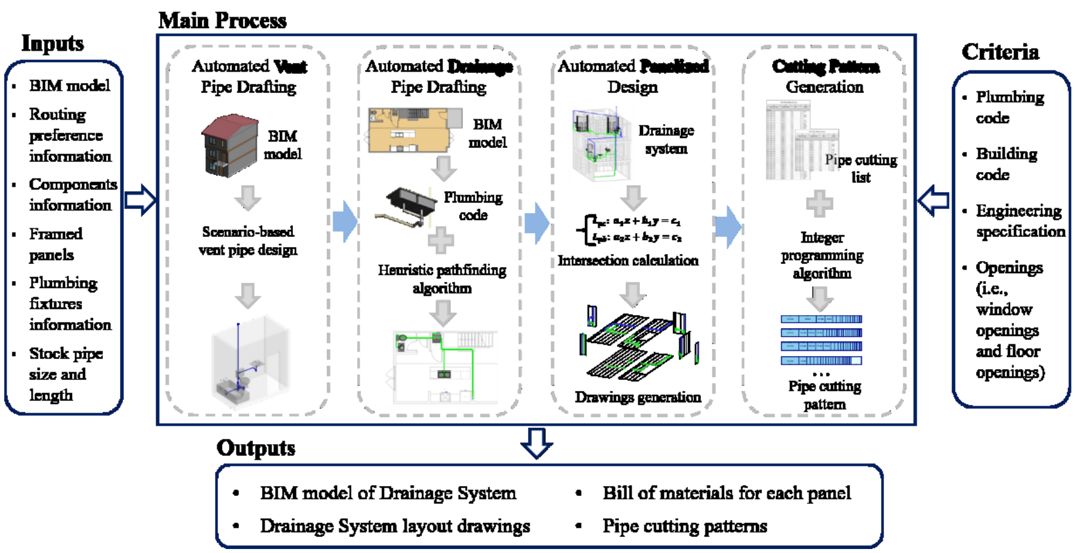


Figure 3-12 Overview of proposed framework

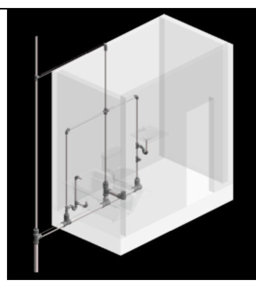
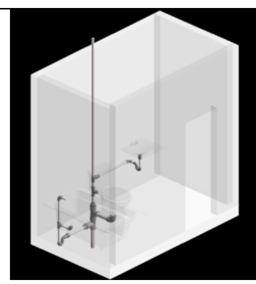
The inputs of the automated design system include a BIM-based 3D model, user-defined routing preference, pre-designed combo fittings, framed panels, plumbing fixtures, as well as stock pipe size and length. The detailed BIM model should, at minimum, comprise wall panels, floor panels, windows, doors, and plumbing fixtures to facilitate planning the drainage system. The wall and floor panels should be framed by studs and plates within a clear panel boundary. The user-preferred fixtures should be loaded into the BIM model and placed according to an architectural design layout. The routing preferences set by the user define the priority list of pipes and different types of pipe fittings, and the automated design system applies a pipe fitting according to the order in the priority list. The fitting with lower priority will be used only if the fitting with higher priority cannot meet the design rules. The combo fittings are designed by the engineer and applied either in one project or to various different projects. The size and length of stock pipes are needed for optimizing cutting patterns. To set up the constraints of the drainage system generation process, criteria are used such as the plumbing and building codes, engineering specifications, and opening (i.e., window opening and floor opening) information.

The outputs of the proposed research methodology are BIM 3D drainage system models, drainage piping layout, shop drawings, optimal cutting patterns of pipes, and a bill of materials (BOM) of the panelized package, which includes the combo fittings, pipes, and pipe fittings for each framed plumbing panel.

3.2 Scenario-based vent pipe design

Any residential drainage system includes one main soil-or-waste stack and one main vent stack, which are located together in a wall or shaft and pass through different floors of a building. The location of the wall or shaft containing the main stacks is determined by engineers and is already located on the floor plan layout. The various methods used to connect plumbing fixtures to the vent stack and soil-or-waste stack, which determined based on the given scenario and architectural design layout, are shown in Table 3-3. These design options must all be compliant with the plumbing code. For instance, the plumbing code specifies that the diameter of the soil-or-waste stack must be at least 3 in. However, the exterior wall insulation is just 5 ½ in thick in most residential buildings, and routing a large pipe such as the soil-or-waste stack through the exterior wall thus reduces the insulating property by reducing the effective R-value of the exterior wall, and increases the risk of wastewater freezing in winter. As such, it is not advisable to locate the stack on an exterior wall even if the plumbing fixtures are located there except that the soil-or-waste stack acts as a vent stack with a small size pipe for the fixtures on top floor. Taking all these constraints into consideration, the design options are applied to the automated design system according to the project layout and user preferences.

Table 3-3: Scenario-based design options

One fixture to one vent	Only one vent	Share sink vent
		
For each plumbing fixture, a separate branch vent pipe is connected. The vent height is defined by the user.	All the plumbing fixtures share a common vent pipe. The soil-or-waste stack is in a plumbing wall which is at the back of the water closet.	All plumbing fixtures except the lavatory sink share a common vent pipe.

For the first design option, also named one fixture to one vent (1 to 1), each fixture is protected by an individual vent, which is joined to one branch vent before connecting to the soil-or-waste stack or main vent stack. Figure 3-13 shows a 3D view of this design style. In this research, a fixture vent pipe is the vent pipe connecting branch vent and the trap arm of a plumbing fixture. There are three types of user-defined parameters, including branch vent height (h_{bv}), fixture vent height (h_{fv}), and trap arm height (h_{ta_i}) of plumbing fixture i. In this research, the height of a pipe is defined as the height from the top surface of a floor to the centerline of a pipe. The parameter, h_{ta_i}, will be a negative number if the trap arm is below the top surface of the floor. The soil-or-waste stack is placed at the centerline of a plumbing wall and the location point is xyz_{sw}. By using programming within the BIM environment, fixture vent and branch vent can be generated automatically based on the user-defined pipe height, xyz_{sw} and h_{ta_i}. The drainage pipe connects to the soil-or-waste stack according to the plumbing code and the design of the drainage pipe will be introduced in the next section.

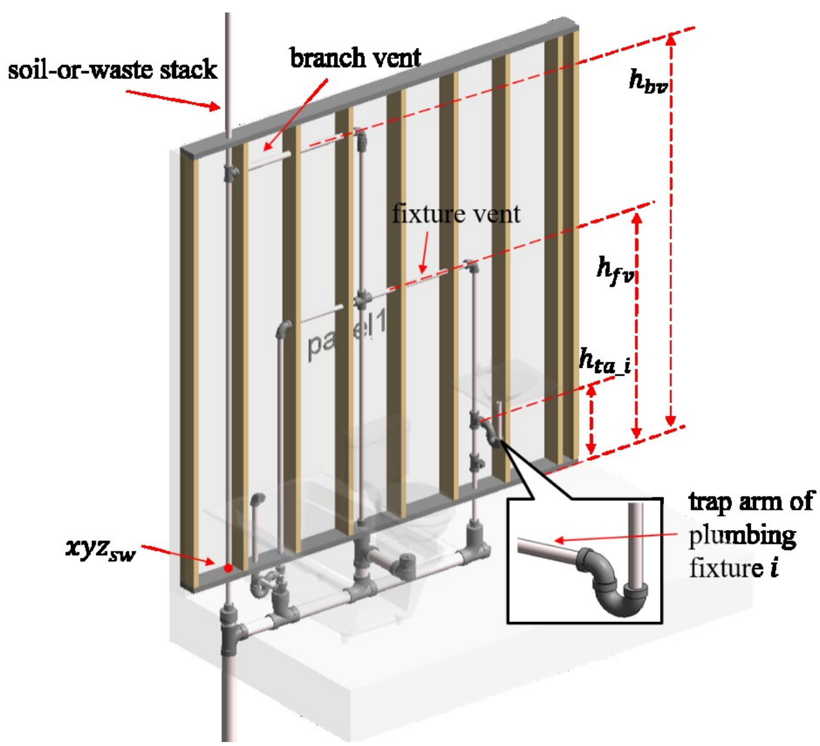


Figure 3-13: One fixture to one vent design option

For the second vent design option, which is shown in Figure 3-14, all fixtures in a bathroom share one vent that is located at the back of the water closet. This vent is a standpipe that is the soil-or-waste stack at the same time. The height (h_{ta_i}) of the trap arm is defined by the user. The plumbing fixtures connect to the vent respectively. In this scenario, there is no fixture from an upper floor discharging wastewater to the soil-or-waste stack, which allows for fresh air to enter the soil-or-waste stack that is playing the role of a vent pipe for the plumbing fixtures in this bathroom. This means that this design method, all fixtures to one vent (all to one), is only applicable for the fixtures on the top floor in a house.

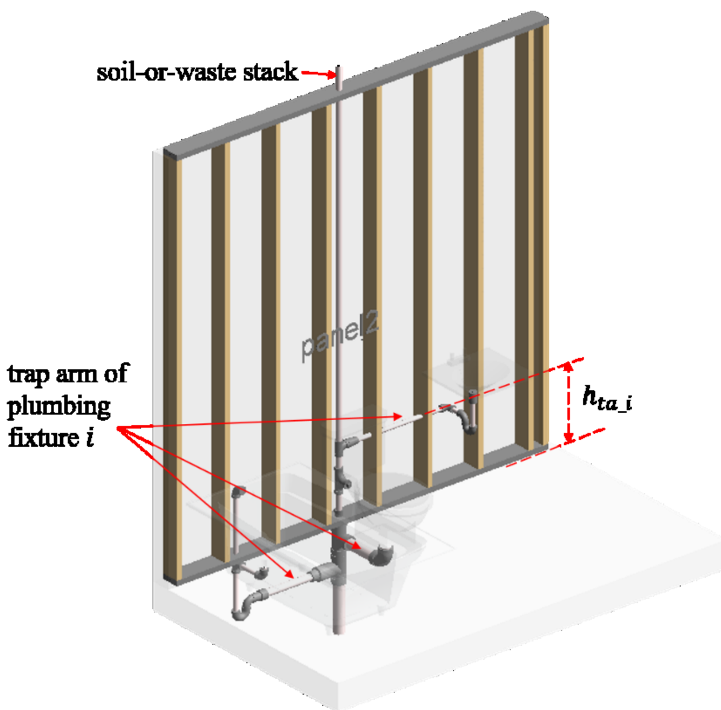


Figure 3-14: All fixtures to one vent design option

The last design option for vent pipes is similar to the second one, but the soil-or-waste stack is located in a plumbing wall that is not at the back of the plumbing fixtures. There is more freedom for the soil-or-waste stack. Figure 3-15 shows a 3D view of an example of this design style. The sink has an individual vent that is a branch vent connecting to the soil-or-waste stack. The other fixtures in the room are protected by the sink vent, which means the drainage pipe from the sink also acts as a wet vent, which was introduced in Section 3.1.2. There are two types of parameters that are user-defined, i.e., sink branch vent height (h_{bv}), and trap arm height (h_{ta_i}) of plumbing fixture i. In this design option, the branch vent can be connected to the main vent stack instead of the soil-or-waste stack. Thus, this design option is also applicable to fixtures on the main floor or basement.

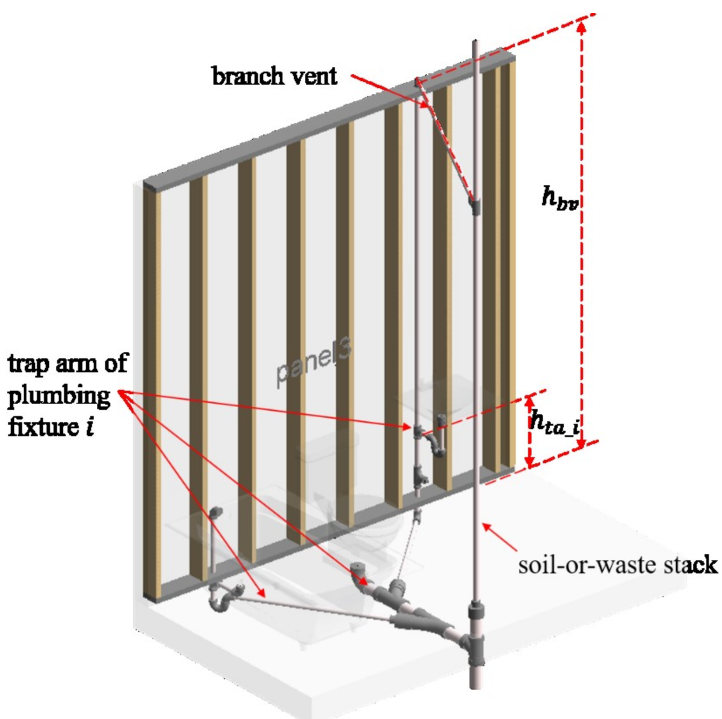


Figure 3-15: Share sink vent design option

Furthermore, pipe location is affected by window openings. According to earlier statement in this section that drainage pipe of large size (3 in and more than 3 in) is not advisable to be placed in an exterior wall, and windows are typically located on exterior walls. So only a vent pipe or a soil-or-waste stack acting as a vent pipe in an exterior wall can be affected by window openings. The pipe will turn along the edge of the king studs if there is a window located in the wall. In order to reduce the number of turns, the vent standpipe will be relocated at the edge of window king studs, as shown in Figure 3-16. The shortest path is chosen by comparing the horizontal distances (d_1 and d_2) from the central point (xyz_{t_arm}) of the sink trap arm to the locations (xyz_{ks_l} and xyz_{ks_r}) of two king studs, as shown in Eq. 3-6. Figure 3-17 illustrates the section view and top view of the plumbing panel with a window opening, a kitchen sink, and drainage pipes.

$$d = \begin{cases} d_1 \ (d_1 \leq d_2) \\ d_2 \ (d_1 > d_2) \end{cases} \tag{3-6}$$

where:

d_1 is the horizontal distance from the center line of the trap arm to the edge of the left king stud in the framed window panel when looking at the sink from inside the house;

d_2 is the horizontal distance from the center line of the trap arm to the edge of the right king stud in the framed window panel when looking at the sink from inside the house.

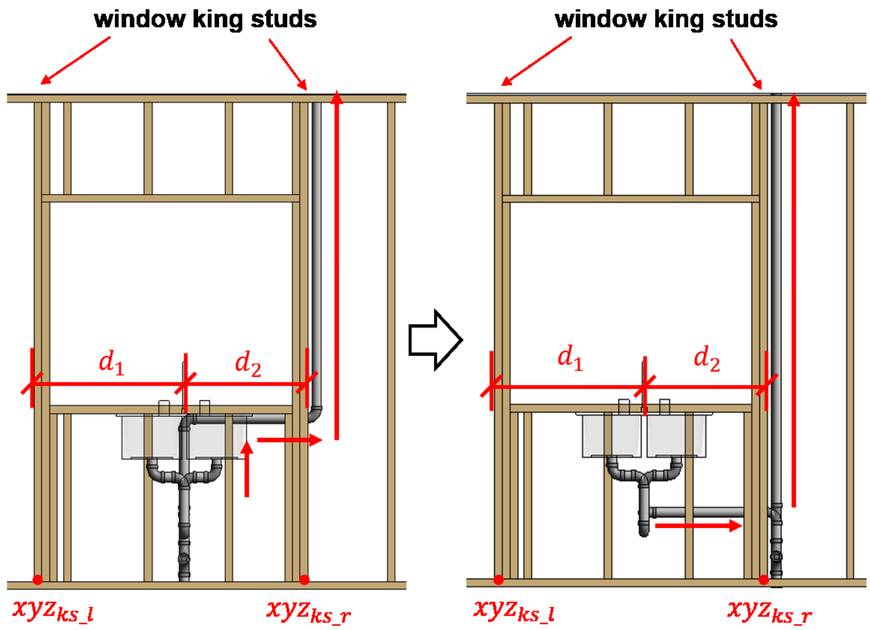
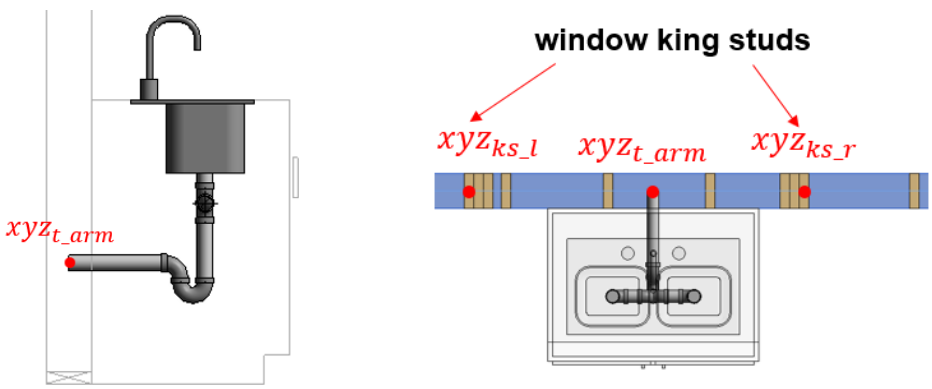


Figure 3-16: Vent pipe design for window opening in the wall



(a) Section view of kitchen sink drainage pipe design

(b) Top view of kitchen sink drainage pipe design for window opening in a wall panel

Figure 3-17: Section view and top view of a wall panel with a window opening

3.3 Rule-based plumbing fixture drainage pipe design

This section introduces two kinds of checking rules based on the plumbing code and the building code, respectively. The former defines how to design the drainage pipe network from a fixture to a vent stack, such as the minimum pipe slope, the maximum trap arm length, the maximum fixture outlet pipe length, and the maximal total degree change in direction of trap arm. The latter regulates the drilling location for passing pipe through a framing member.

3.3.1 Pipe slope and length design

In this research, the parameter definitions for drainage pipe design are described in Table 3-4, which also lists the parameters used in the equations for rule checking. The parameters consist of four sets, including constant parameters, parameters extracted from the BIM model, parameters defined by the user, and parameters for pipe length and height calculation.

Table 3-4: Definitions of drainage pipe parameters

Type	Notation	Description
Constant parameter	L_b	Width of a 90-degree bend (between two connector center points)
	L_u	Distance between two connector center points of a U-shape bend
	L_p	Length of a trap component (between two connector center points)
	H_p	Height of a trap component (between two connector center points)
Parameter from BIM model	H_{fd}	#k plumbing fixture drainage connector height from floor
	D_{fd}	#k plumbing fixture drainage connector size (outside diameter)
	H_L	Height of floor plan level L
User-defined parameter	H_{op}	Height of fixture outlet pipe
	H_{ta}	Height of fixture trap arm from floor plan level L
	S_{sp}	Drainage pipe slope
Calculated parameter	l_{1i}	Fixture outlet pipe i length
	S_i	Fixture outlet pipe i slope

Type	Notation	Description
	h_i	Fixture outlet pipe i fall length
	l_{2j}	Trap arm j length
	S_j	Trap arm j slope
	h_j	Trap arm j fall length
	m_j	Trap arm j clear span
	θ_{j-1}	Change degree in the direction from trap arm (j-1) to trap arm j
	r_1	Outside diameter (or pipe size) of the trap arm
	r_2	Inside diameter of the trap arm pipe
	a	Maximal length of total fixture outlet pipes
	b	Minimal length of total fixture outlet pipes
	c	The maximum length of total fixture trap arms
	d	A minimum slope of trap arms
	e	Maximum slope of trap arms
	f	Maximum cumulative change in direction of trap arms

The trap arm size is inherited from fixture outlet and fixture drain, which means the pipe size always equals D_{fd} from fixture to vent pipe or soil-or-waste pipe. According to the liquid flow direction, the connector of trap arm connecting to plumbing fixture is named as start connector (SC) and the other end of trap arm is end connector (EC). Trap arm height is the height of the SC which is slightly higher than the EC because the trap arm should have a slope to discharge sewage. The user can define one of two parameters, outlet pipe height (H_{ta}) or trap arm height (H_{op}) (shown in Figure 3-18), since the other one can be calculated according to the relationship defined by Eq. 3-7 or Eq. 3-8.

$$H_{ta} = H_{fd} - H_{op} + H_p \qquad (3\text{-}7)$$

$$H_{op} = H_{fd} - H_{ta} + H_p \quad (3\text{-}8)$$

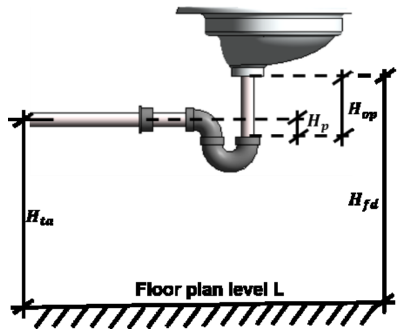


Figure 3-18: Fixture outlet and trap arm height relationship

The total drainage pipe length from the fixture drain connector to a vent stack or soil-or-waste stack is defined in Eq. 3-9.

$$\sum L = \sum l_{1i} + \sum l_{2j} + L_p \quad (3\text{-}9)$$

After the user inputs the parameters for the fixture drainage pipe design, the automated design system checks the pipe length based on the plumbing code. The drainage pipe design should be subjected to the constraints (Eq. 4-14) of total fixture outlet pipe length ($\sum l_{1i}$), total trap arm length ($\sum l_{2i}$), trap arm j slope (S_j), trap arm total fall length ($\sum h_j$), and the cumulative change in direction ($\sum_1^{j-1} \theta_n$) of trap arms. Moreover, the maximum length of total fixture trap arms (c) depends on the trap arm size (r_1) in Eq. 3-15. The threshold values of the fixture outlet and trap arm lengths vary for different types of fixtures. Table 3-5 defines the threshold values from Eq. 3-10 to Eq. 3-14 for each type of fixture according to the NPC (2015). The parameter value will be equal to *null* if there is no limit or the checking rule does not apply to one type of fixture. For instance, the checking rule of outlet length is out of scope for the water closet, since there is no outlet in a water closet.

$$\sum l_{1i} = l_{11} + l_{12} + \cdots, \sum l_{1i} \in [a, b] \quad (3\text{-}10)$$

$$\sum l_{2i} = l_{21} + l_{22} + \cdots, \sum l_{2i} \in [2r_1, c] \quad (3\text{-}11)$$

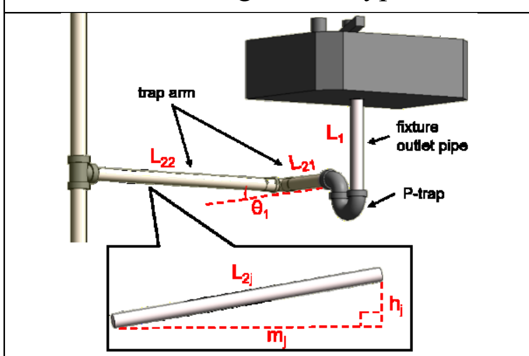
$$S_j = \frac{h_j}{m_j}, S_j \in [d, e] \quad (3\text{-}12)$$

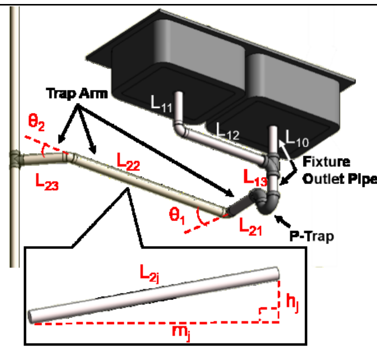
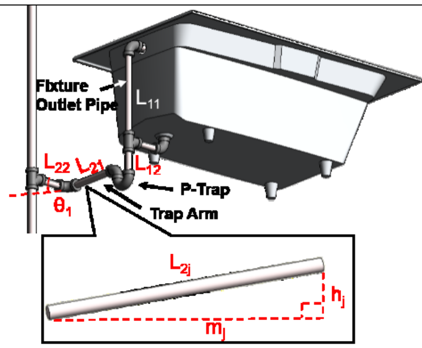
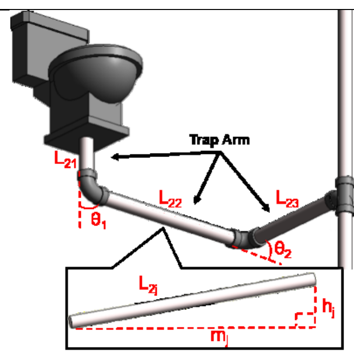
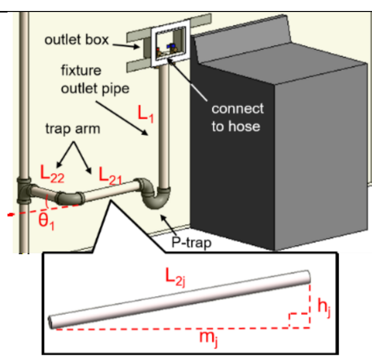
$$\sum h_j = h_1 + h_2 + \cdots\ ,\ \sum h_j \in (0, r_2] \quad (3\text{-}13)$$

$$\sum_1^{j-1} \theta_n = \theta_1 + \theta_2 + \cdots, \sum_1^{j-1} \theta_n \in (0, f]\ (\theta_n \in \{45°, 90°\}) \quad (3\text{-}14)$$

$$c = \begin{cases} 1500mm\ (r_1 = 32mm\ or\ 1\frac{1}{4}\ in) \\ 1800mm\ (r_1 = 40mm\ or\ 1\frac{1}{2}\ in) \\ 2400mm\ (r_1 = 50mm\ or\ 2\ in) \\ 3600mm\ (r_1 = 80mm\ or\ 3\ in) \\ 9800mm\ (r_1 = 100mm\ or\ 4\ in) \end{cases} \quad (3\text{-}15)$$

Table 3-5: Threshold values definition in checking rules for plumbing fixtures

Plumbing fixture type	Threshold values definition
	$a = null, b = 1200mm\ (47in)$ in Eq. 3-10 $c = Eq. 15$ in Eq. 3-11 $d = 1/50, e = 1/24$ in Eq. 3-12 $f = 135°$ in Eq. 3-14

<table>
<tr><th>Plumbing fixture type</th><th>Threshold values definition</th></tr>
<tr><td>
</td><td>$a = null, b = 1200mm\ (47in)$ in Eq. 3-10
$c = Eq. 15$ in Eq. 3-11
$d = 1/50, e = 1/24$ in Eq. 3-12
$f = 135°$ in Eq. 3-14</td></tr>
<tr><td>
</td><td>$a = null, b = 1200mm\ (47in)$ in Eq. 3-10
$c = Eq. 15$ in Eq. 3-11
$d = 1/50, e = 1/24$ in Eq. 3-12
$f = 135°$ in Eq. 3-14</td></tr>
<tr><td>
</td><td>$a = null, b = null$ in Eq. 3-10
$c = 3000mm\ (118in), l_{21} \leq 1000mm$ in Eq. 3-11
$d = 1/50, e = 1/24$ in Eq. 3-12
$f = 225°$ in Eq. 3-14</td></tr>
<tr><td>
</td><td>$a = 600mm\ (24in), b = null$ in Eq. 3-10
$c = Eq. 15$ in Eq. 3-11
$d = 1/50, e = 1/24$ in Eq. 3-12
$f = 135°$ in Eq. 3-14</td></tr>
</table>

There are two types of plumbing fixtures (shown in Figure 3-19) that have the same design rules as the sink and bathtub, respectively. The checking rule for a combo of bathtub and shower is the same as a bathtub, and the shower stall is the same as sink with one basin.

(a) bathtub combo with shower (b) shower stall

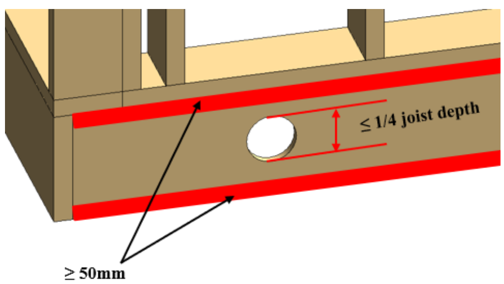
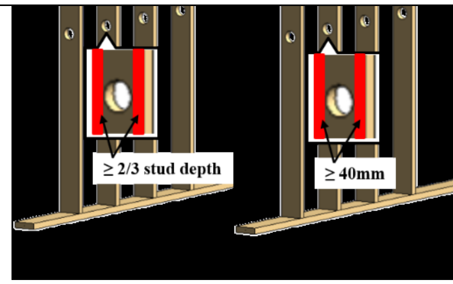
Figure 3-19: Drainage pipe design for bathtub combo and shower stall

The automated design system checks the user inputs against variables mentioned in the above equations in order to make sure that the user inputs meet the plumbing code. Then, a pipe layout is generated and is tested to see whether it passes the variable checks or not. If the checking fails, the automated design system will require the user to re-input variables. All the location of connection points are calculated based on user inputs and plumbing code, such as pipe slope and offset, and the scenario-based connection method for vent pipes selected by the user.

3.3.2 Pipe location design in framed panel

Another instance of rule checking is when the designed pipe passes through a wall stud or floor joist, which must be checked for building code compliance (Table 3-6). The automated system calculates the distance between the pipe center point and the closest edge of the framing member, and then subtracts the pipe exterior radius when there is a clash between pipe and framing element. The difference is then compared with the threshold values specified in the building code, with a warning prompting the user to modify the pipe route if the difference exceeds the threshold value.

Table 3-6: Building code requirements when designing drainage systems

Pipe routing constraint in floor joists	Pipe routing constraint in wall studs
	
Holes drilled in floor or ceiling framing members should not exceed 1/4 of the member depth and should be located not less than 50 mm from the nearest edge (NBC 9.23.5.1.(1)).	The undamaged portion should not be less than 2/3 the depth of the stud for a loadbearing stud, and should not be less than 40 mm for a non-loadbearing stud; otherwise the weakened studs should be suitably reinforced (NBC 9.23.5.3.(1)).

3.3.3 A heuristic approach for pipe route optimization

Three popular pathfinding algorithms, i.e., Dijkstra algorithm (DA), A-star algorithm (AA), and genetic algorithm (GA), were tested and evaluated for optimal path planning in a construction site (Soltani, Tawfik, Goulermas, & Fernando, 2002). In their research, DA can find the optimum solutions by testing all path nodes against a goal node, but it is inefficient for large-scale problems. AA is made more efficient by searching paths directly towards the goal through a heuristic approach. DA and AA use a greedy search method, which makes a set of choices that find the best at each step. These two algorithms perform outstandingly well for small and medium problems, while GA is better for large-scale problems. In the research of Soltani et al. (2002), GA testing generates a sequence of feasible, optimal, and near-optimal solutions for pathfinding problems; however, GA's performance is limited by the lack of accuracy on solutions and by the time-consuming fine-tuning process due to the probabilistic optimization approach. Therefore, in this research, a heuristic optimization algorithm is designed by adopting a greedy search strategy based on the A-star algorithm and Dijkstra algorithm that use design rules as constraints in order to search optimal drainage pipe paths efficiently in the context of residential construction.

For the process of generating the drainage pipes, the pathfinding problem is to investigate an optimal path from a plumbing fixture to the soil-or-waste stack with the shortest pipe length and the least number of turns. Figure 3-20 illustrates the start point (S) located a plumbing fixture, the terminal point (T) located at the soil-or-waste stack, and four vertices points (FO_a, FO_b, FO_c and FO_d) of an opening on the floor.

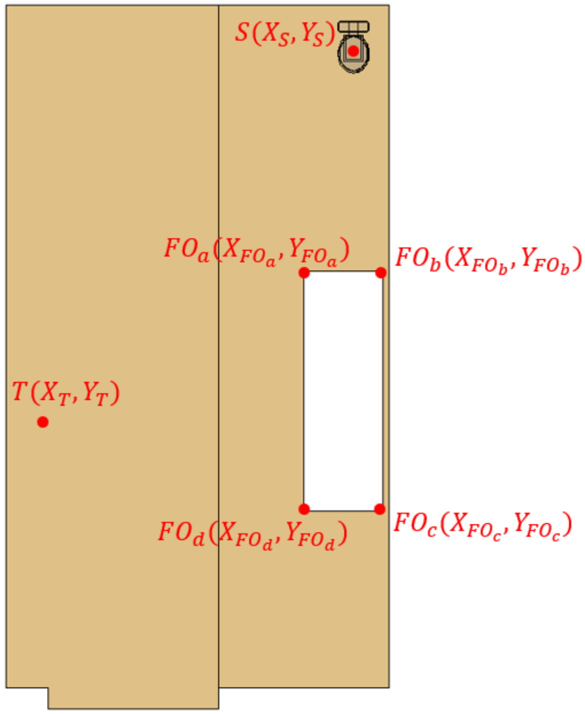


Figure 3-20: Start and terminal points and vertices points of a floor opening

The objective is to minimize the total drainage pipe length and number of turns from plumbing fixture to soil-or-waste stack. The pipe layout can be separated into small cells, which is the minimum pipe length defined as a default unit value. The pipe route is extended by a unit length ending with a point named path node. The fitness function for each path node is represented as follows:

$$f(n) = g(n) + h(n) + t(n) \tag{3-16}$$

where:

$f(n)$ is the fitness value for path node n,

$g(n)$ is the pipe length from start point to path node n,

$h(n)$ is the Manhattan distance from path node n to a terminal point,

$t(n)$ is the number of piping turns from a start point to path node n.

The Manhattan distance $h(n)$ is calculated by the following equation:

$$h(n) = |X_t - X_n| + |Y_t - Y_n| \tag{3-17}$$

where:

X_t is the x-coordinate of the terminal point,

X_n is the x-coordinate of the path node n,

Y_t is the y-coordinate of the terminal point,

Y_n is the y-coordinate of the path node n.

At each node, the following constraints are also checked:

$$g(n) \leq \frac{H_{Joist} - d_{top} - d_{bottom}}{S_{slope}} \tag{3-18}$$

$$D(n) \geq l_{min} \tag{3-19}$$

where:

H_{Joist} is the floor joist height,

d_{top} is the minimum safety drilling distance from the top edge of floor joist,

d_{bottom} is the minimum safety drilling distance from the top edge of floor joist,

S_{slope} is the pipe slope defined by the user,

$D(n)$ is the distance from node n to the edge of the opening,

l_{min} is the minimum pipe length or unit length.

The detailed process of the pipe route planning heuristic algorithm is described as follows:

Step 1: Mark fixture drainage location on the floor as the start point, S.

Step 2: Calculate the fitness value, $f(n)$, for all possible neighbor path nodes.

Step 3: Check $g(n)$ and $D(n)$ for each node and store the node value if it passes the checking.

Step 4: Compare node values and set the node with minimum $f(n)$ as a new start point, S.

Step 5: Repeat steps 2 to 4 until the pipe route reaches the terminal point (location point of the soil-or-waste stack on floor plan).

3.4 Drainage system panelization

The objective of this section is to separate the drainage system into smaller components to facilitate the shipping of an integrated package to the construction site. In panelized construction, the integrated package is a panel package, so drainage system decomposition is aimed at cutting the drainage system into panel sizes in order to load and ship with panels. The main process of a planning method for drainage system panelization is illustrated in the flowchart shown in Figure 3-21. The process begins with establishing a database of plumbing panels whose geometric information will be used for identifying the pipe break-point. This database also involves the information of the drainage system which passes through the panels, and the establishment process is illustrated in Figure 3-22. Then, the geometric information pertaining to a plumbing panel is extracted from the database before calculating the intersection coordinates of a boundary segment and pipe segments. Next, a separation in the drainage system is created at the intersection. The connection element of two panelized pipe networks is a coupling which is a type of pipe fitting used for connecting two pipes without changing directions. After calculating all intersections and finishing all corresponding separations on the boundary of a plumbing panel, the information of one remaining panel is extracted from the database and analyzed by repeating the above steps until no leftover panel.

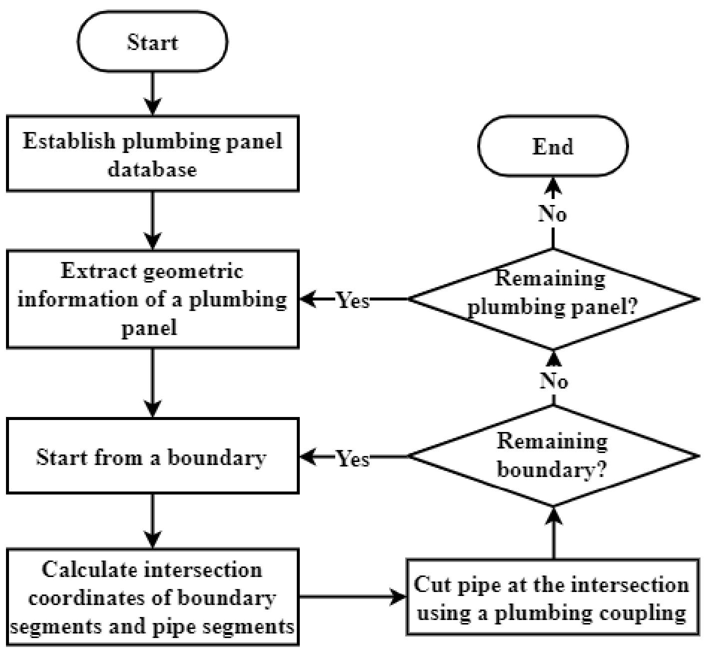


Figure 3-21: Flowchart of drainage system panelization planning algorithm

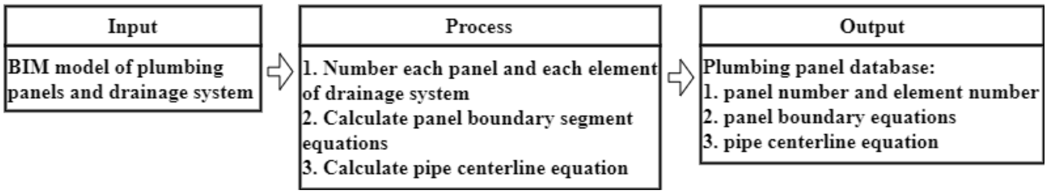


Figure 3-22: Flowchart of establishing database of plumbing panels

This planning algorithm is developed to automatically panelize drainage systems in a residential building. The algorithm is encoded and implemented in a BIM environment. The design rules explained in the previous sections are also translated into computer-processable codes. All the pipes and pipe fittings in a panelized package are labelled with the panel name in order to be filtered and to generate the bill of materials (BOM) for each panel.

3.5 An integer programming approach for pipe cutting optimization

The one-dimensional cutting stock problem (1D-CSP), in this research, is the optimization problem that cuts standard-length pipe stock into pieces to satisfy the required length in a project to minimize the total cutting waste. It commonly assumes the pipe stock as an unlimited supply with one standard length for all sizes of drainage pipes in residential projects.

The pipe segments are classified into two categories, wall panel pipe and floor panel pipe, as the wall and floor panels are, in most cases, framed and produced in two respective manufacturing facilities. The pipe cutting optimization algorithm is applied to both of the two pipe categories. Thus, the dataset of one size pipe in one category is a small dataset because of the relatively few pipe stock lengths and a small number of pipes with different lengths. Based on the small dataset, an integer programming algorithm (Mogollon, 2009) can be used to solve the 1D-CSP. An enumeration method is used to generate all possible cutting scenarios with corresponding waste (w_i). Then, an objective function with constraints is formulated and optimized to minimize waste. The constraints are for generating the required number of pipes for the project. The main process is illustrated in Figure 3-23.

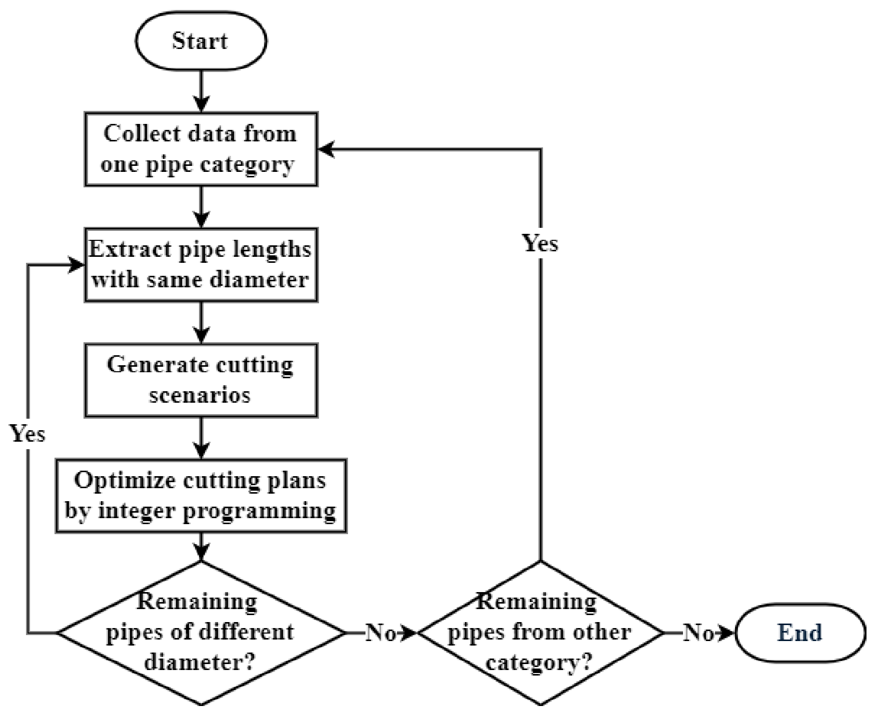


Figure 3-23: Cutting optimization process

The generation of cutting scenarios is an exhaustive search using a tree structure, as shown in Figure 3-24. L_s is the stock length with size s, and l_i is the required pipe length in the project. The total number of different desired pipe lengths is k. Thus, the largest number of pipe n that can be cut from one standard-length pipe is

$\left\lfloor {L_s}/{l_n} \right\rfloor$. The remaining length, L_n, after cutting pipe n in the tree structure is calculated by satisfying Eq. 3-19.

$$L_n = L_s - \sum_{i=1}^{n} n_i l_i \qquad (3\text{-}19)$$

where n_i represents the number of instances of length l_i.

Thus, the corresponding waste, w_h, in cutting scenario h is the same as the remaining length, L_k, after cutting the last type of pipe of size s, which is formulated in Eq. 3-20.

$$w_h = L_k = L_s - \sum_{i=1}^{k} n_i l_i \qquad (3\text{-}20)$$

Once all possible cutting scenarios (or patterns) has been generated along with corresponding wastes (w_i), an objective function is created in Eq. 3-21 to minimize the total waste of cutting one size of pipe stocks. The optimal result is obtained by searching for a global minimum.

$$\min \sum_{i=1}^{N} N_i w_i = \sum_{i=1}^{N} [N_i \times \left(L_s - \sum_{i=1}^{k} n_i l_i\right)] \qquad (3\text{-}21)$$

where N_i represents the required number of each cutting scenario.

The cutting is subjected to the constraint that the sum of all instances generated at each scenario should not exceed the length of stock pipe by satisfying Eq. 3-22.

$$\sum_{i=1}^{k} n_i l_i \le L_s \qquad (3\text{-}22)$$

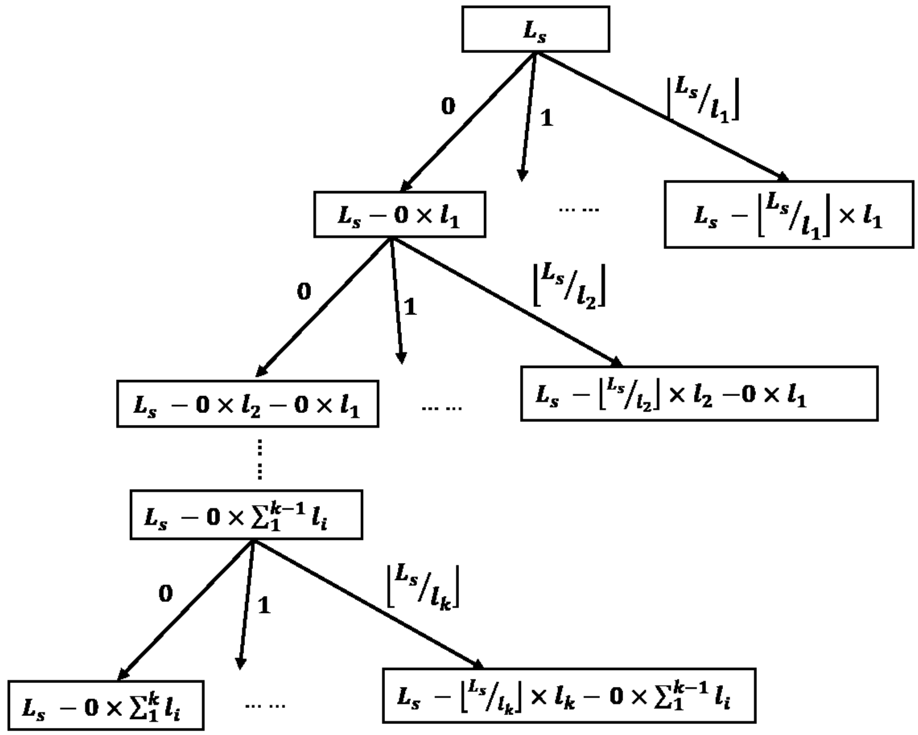


Figure 3-24: Tree structure for generating possible cutting scenarios

CHAPTER 4. IMPLEMENTATION AND CASE STUDY

This chapter introduces a prototype system aiming to test the feasibility of the proposed methodology. Autodesk Revit is chosen as the main platform for this implementation. One BIM model of a townhouse with five units is developed as a case study. First, the model is prepared for extracting framed panel and plumbing fixture information. Other inputs of the prototype system, such as combo fitting model, pipe fittings and accessory information, and stock pipe information, are also involved in the preparatory work. Then, the vent design and drainage pipe design are created based on design rules and the pipe route optimization method. After that, the drainage design layout and plumbing panel drawings are generated. Lastly, the optimal cutting pattern for pipes is produced by an integer programming approach.

4.1 BIM model preparation

To verify the proposed methodology, a case study is presented to demonstrate how the drainage pipe network design is generated and optimized, how the pipe network is panelized, and how the drawings and optimal cutting patterns are developed. The 3D BIM model that has been created to verify the proposed methodology is based on the traditional 2D design drawings from a panelized construction manufacturing facility. Figure 4-1 shows the 3D view of the BIM model, which is a two-story townhouse with five identical units. As the floor plans in Figure 4-2 show, each unit includes one garage and one flex room on the ground floor, one kitchen, one bathroom, one laundry room and a living room on the first floor, as well as three bedrooms and two bathrooms on the second floor. The unit is framed in the 3D model in Figure 4-3. The wall panels are framed using wood studs and plates, and floor panels are framed using wood joists and plates. All the studs, plates and joists have an attribute or property, such as host information, referring to the panel they belong to. Moreover, the plumbing fixtures, windows, and doors are placed according to the architectural drawings.

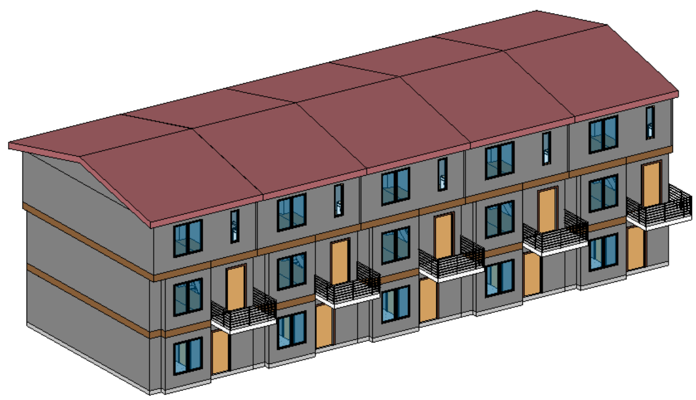
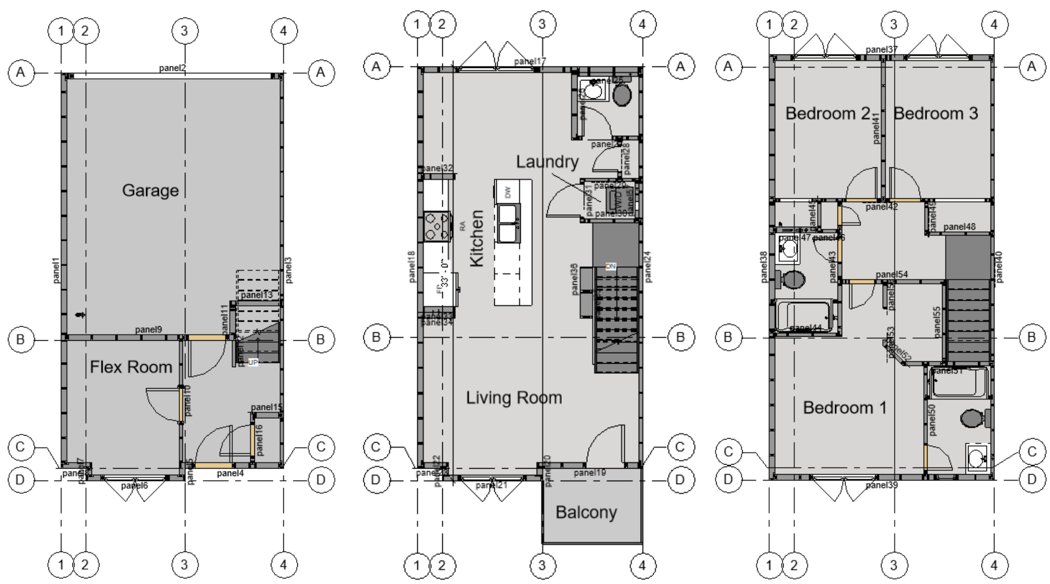


Figure 4-1: 3D view of the case study model



(a) Ground-floor layout (b) First-floor layout (c) Second-floor layout

Figure 4-2: Sample model of floor layouts in one unit building

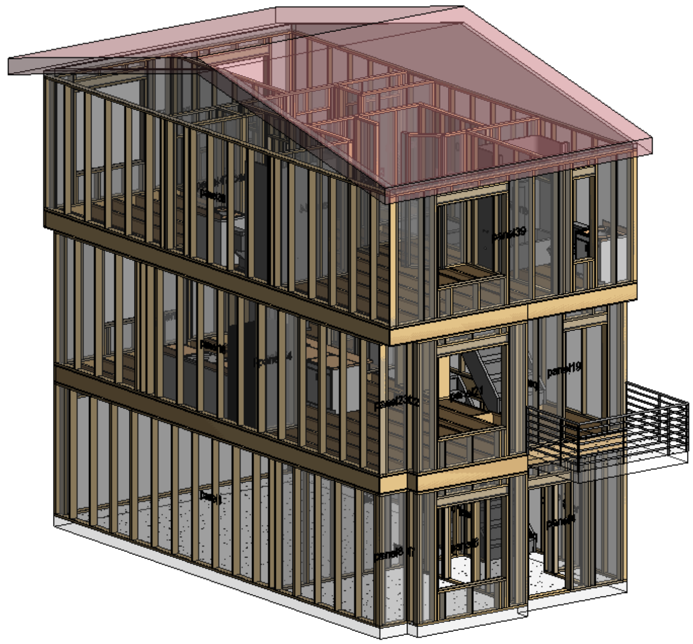


Figure 4-3: Sample model of one unit building

In addition to the 3D architecture and structure model, information regarding pipe fittings is also loaded in the model. In Revit, this kind of information is saved in a specified file, RVT. file, and named as a family. A family stores one type of pipe fittings with a set of properties, called parameters, and a respective graphical representation. The family can be loaded and reused in a project. Revit has a library comprising all the families that may be applied in a normal construction project. In this research, the plumbing-system related families are loaded to the case study model from the Revit library. Apart from the normal pipe fittings, the designed plumbing combo fittings are also loaded in the project. The models of combo fittings are saved in an independent RVT. file that can be linked to the BIM model in order to provide combo fitting options for users when running the automated design system. Next, there is a preference setting to control the priority of fittings used in a project. In the case study, with respect to the priority list of elbows for example, the first selection is standard PVC bend, the second is standard PVC elbow. This means if the pipe changes direction, it will try to join a standard PVC bend to the pipe segment first. It will try standard PVC elbow if the first choice cannot meet demand. The design rules follow the Canadian National Plumbing Code (NPC, 2015). The setting information includes the pipe fitting types, minimal size, and maximal size.

4.2 Implementation

4.2.1 Overview

The prototype system for automatically design the residential drainage system is developed using Revit API in C# programming language. It can achieve the following functions: 1) automated vent pipe and drainage pipe generation, 2) drainage system panelization, 3) plumbing panel drawings generation, and 4) pipe cutting pattern generation.

As the main function of the prototype system, automated design implements the method of vent pipe and drainage pipe design described in section 3.2 and 3.3 by an application in a BIM environment using the information provided by the user. Figure 4-4 illustrates the data flow between the user and the prototype system. The name of the drainage system and the locations of main soil-or-waste stack and main vent stack are defined at the beginning. Then, the connection style of a vent pipe and the type of fixture trap are selected by the user. After that, the fixture drainage and vent pipe generations follow the process shown in Figure 4-4. The fixture drainage pipe is created according to the fixture drain location and trap component type. As a commonly used sink trap, the P-trap can change the drainage pipe direction from vertical to horizontal. Thus, the drainage pipe from a sink is designed to be installed in a wall panel after a trap and then goes to the floor panel connecting to the main drainage pipe. However, for the water closet, which already has a trap, the drainage pipe goes directly to the floor. The next step is to generate a vent pipe from the fixture to the main vent stack. If there is any fixture on the upper floor connecting to the soil-or-waste stack, the vent pipe will joint to the main vent stack. If the current fixture is already on the top floor, the vent pipe can connect to the soil-or-waste stack directly. Finally, the automated design system stops when the drainage system is finished because there are no fixtures remaining.

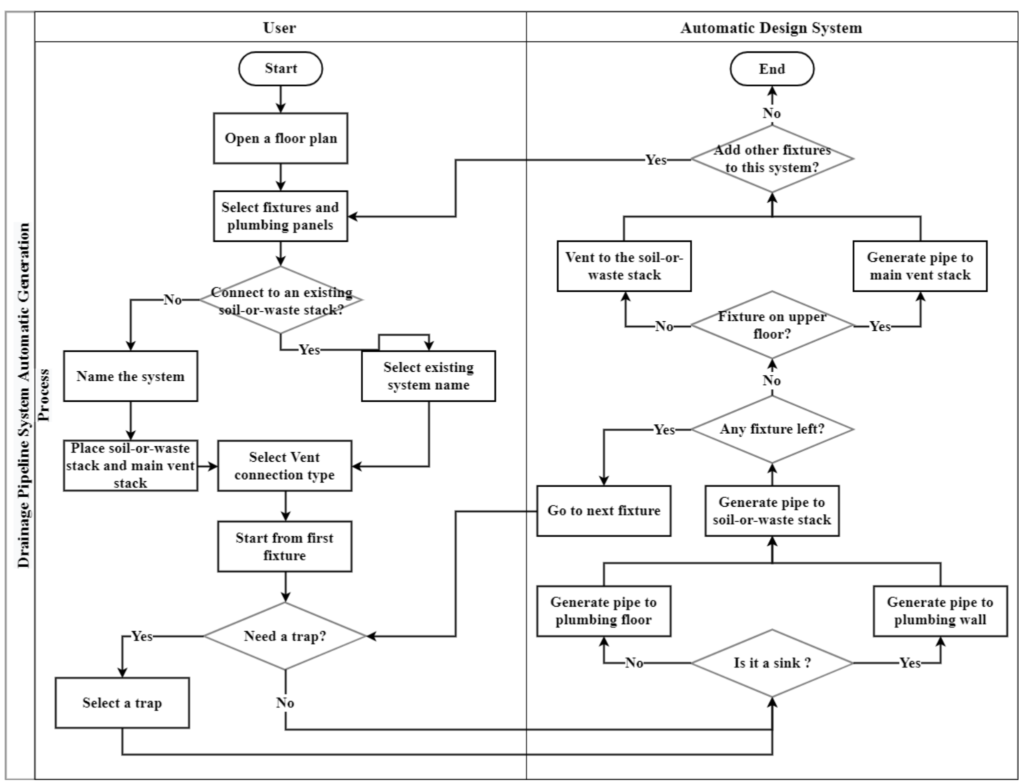


Figure 4-4: Cross-functional flowchart of automated design system

In this prototype system, panelization for drainage and vent pipe networks is also realized. As was shown in Figure 4-4, there are two processes, including the generation of drainage pipe to soil-or-waste stack and the generation of vent pipe to the main vent stack. In the case of both these two generation processes, the pipe is cut at the framed panel edge. Thus, checking for the cutting location is a step included in the prototype system and is introduced in Section 4.2.4.

To build the prototype for the drainage automated design system, the algorithms are encoded according to the functions shown in Figure 4-5. The design rules explained in Sections 3.3 and 3.4 are translated into computer-processable codes and implemented as an add-on to Autodesk Revit. The parameters and parameter types are used for programming and are shown in Figure 4-5. The Revit API provides functions to detect the framed wall and floor panels, as well as to create and connect pipes, such as *Pipe.Create (document, systemTypeId, pipeTypeId, levelId, startPoint, endPoint)*, and *Connector.ConnectTo (Connector)*. The former function is for pipe generation using six related parameters, and the latter is for connecting two elements that have connectors. Furthermore, there are two types of parameters, the extracted parameter from the existing BIM model, and the calculated parameter created for generating pipes and pipe fittings in the prototype system. The extracted parameter indicates the geometric boundary of a plumbing panel and the location of a plumbing fixture. The calculated parameter defines the start-point and end-point of a pipe and fitting, as well as the location of a trap component. Moreover, as shown in Figure 4-5, the classes, such as *PlumbingWall*, *PlumbingFloor*, *Pipe,* and *PlumbingFitting*, are defined within Visual Studio, which is a powerful software that is used to program applications. The classes are designed for modelling elements in Autodesk Revit using extracted parameters and calculated parameters.

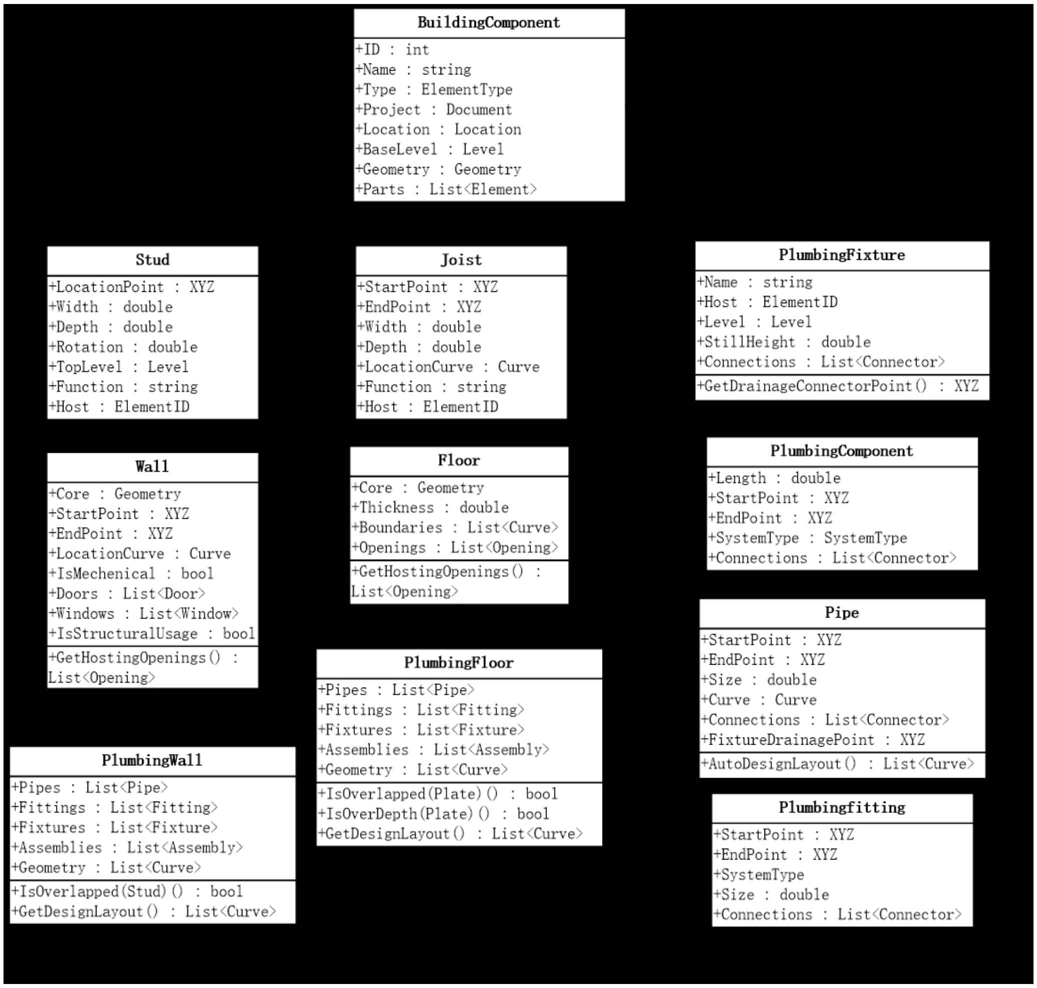


Figure 4-5: Excerpt of BIM information for drainage system design using UML

4.2.2 Vent pipe design

The design style of the vent pipe is defined by the user and floor plan layout. The three options that are proposed in Section 3.3 are listed in a Windows Form of the prototype system, which is the interface shown in Figure 4-6. Before selecting the vent design scenario, a new drainage system is created with the user-defined name and locations of the main vent pipe stacks after clicking plumbing fixtures and plumbing panels in the BIM model. The vents can also join a previous drainage system by selecting that system's name. The function, *Pipe.Create*, in Revit API is applied to create the main vent stack Then, three options for vent design are provided, as shown in Figure 4-6, including one vent for one fixture, only one vent for all fixtures, and sink vent for all fixtures. The reason why these three options are provided is based on real plumbing design cases and is explained in Section 3.3. For each vent design, the various parameters are used for mapping the model in Autodesk Revit. The pipe offset parameter is the height of the pipe centerline based on the level of the current floor plan. The fixture connecting order is also defined by the user, which typically begins at the plumbing fixture with the largest drainage connector, and the connector information can be extracted from the BIM model. If there are two fixtures with the same drainage size, the fixture that is farther from the main drainage stack has a higher priority.

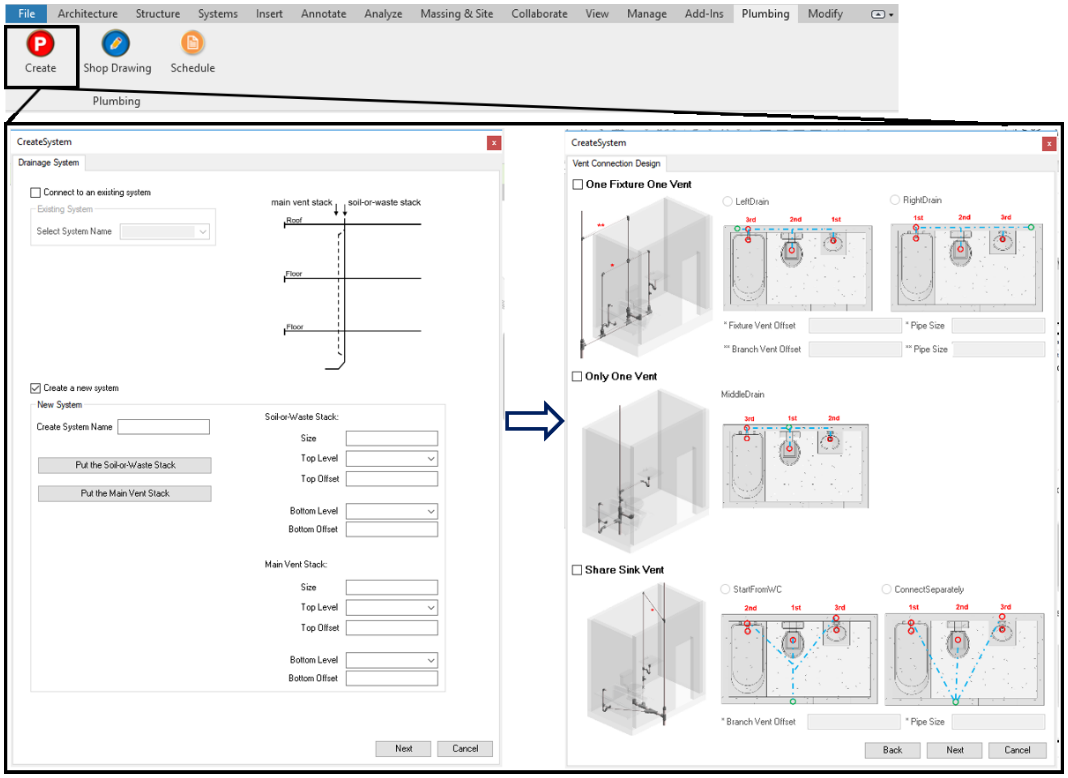


Figure 4-6: Graphic user interface of vent pipe design

4.2.3 Optimal drainage pipe route design

To validate the algorithms presented in Section 3.4 for rule-based drainage pipe design, the prototype system involves the Windows Form shown in Figure 4-7 to collect and save the inputs. In the dialog box, four user-defined parameters are entered for each fixture that is selected by its fixture name, and the corresponding 3D view is shown in the picture box. The parameters are saved and shown in the corresponding table. The trap arm height is based on the floor plan level, and the trap arm pipe size is inherited from the trap size and fixture drain's connector size.

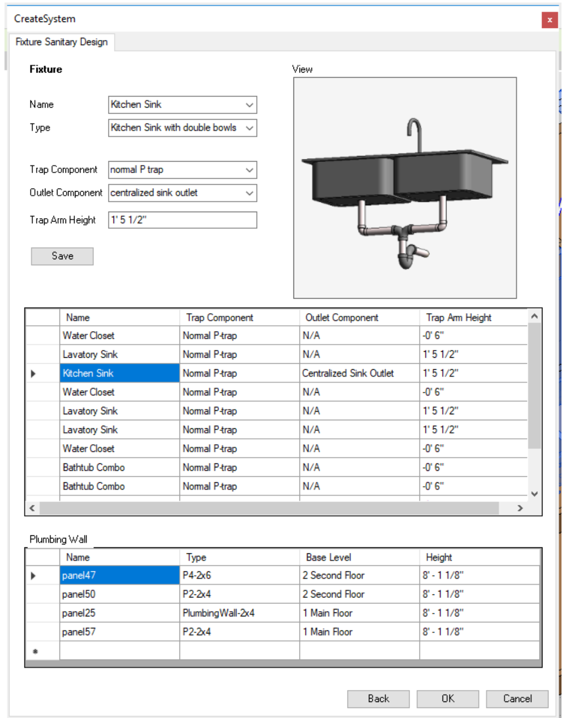


Figure 4-7: Windows Form for fixture drainage pipe design

Furthermore, the parameters extracted from wall panels and floor panels are also shown in the tables of Windows Form shown in Figure 4-7. For a wall panel, it includes panel name, panel family type, base level, and wall height. For the floor panel, it shows the panel name, panel family type, level, and floor core thickness. The heuristic pathfinding algorithm for optimizing the drainage pipe route is provided in Appendix A.

4.2.4 Drainage system panelization with shop drawings

This section introduces the implementation of the method that automatically separates the drainage system into panels and generates the corresponding shop drawings. For the panelization process, the boundary of the panel is defined as the centerline of the bordering stud and plate in the framed panels. The pipe ends at the centerline with a coupling, which is a type of plumbing fitting connecting two pipes without changing direction. In order to generate panel drawings, there is a shared parameter attached to each element in the drainage system. This parameter is a specific character presenting the name of the plumbing panel and is changed accordingly after coupling at the separation boundary.

For drawings generation, the bill of materials (BOM) is shown in the shop drawings for a framed panel. Compared to traditional 2D MEP design, the automated design system improves design efficiency and reliability by checking rules, although the 2D design is developed based on framed panel drawings.

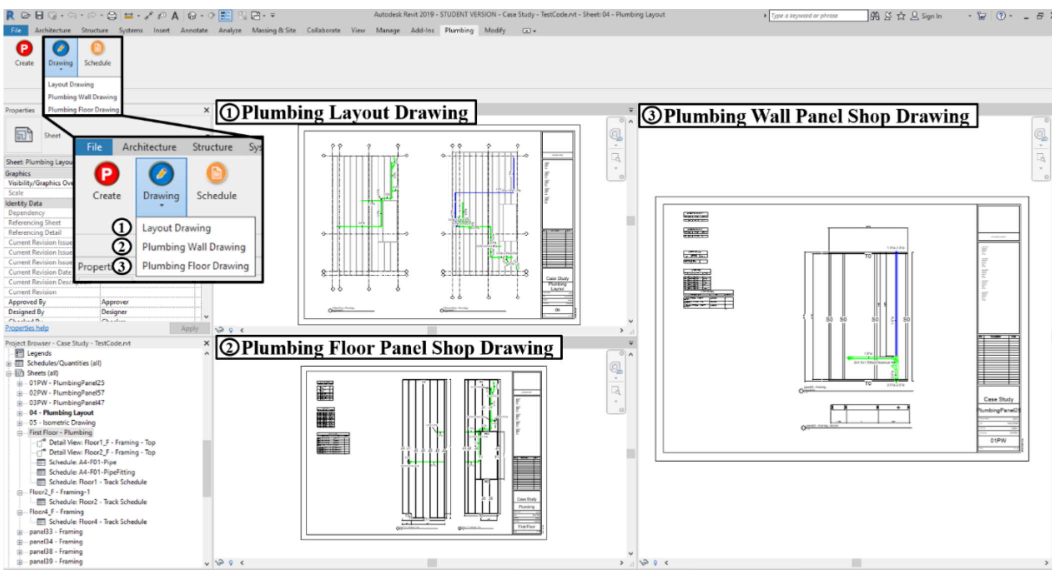


Figure 4-8: Shop drawing samples for drainage system in Revit

4.2.5 Optimal pipe cutting plan

A database is created with a list of pipes and pipe fittings for each plumbing panel. Any change in the BIM drainage system model will be automatically reflected in the bill of materials (BOM). In this research, the BOM for pipes in the panel is exported from Revit as a Microsoft Excel file, which is then used as the main input for pipe cutting plan optimization. The other input is stock pipe length. The optimized cutting pattern is generated using VB language in Microsoft Excel.

The BOM for generating cutting patterns is classified according to the type of plumbing panels, i.e., plumbing wall (PW) panel and plumbing floor (PF) panel, and the number of working stations. According to the panelized construction manufacturing facility, in most real cases, PW panels and PF panels are framed on two separate production lines. Thus, the BOM is classified as either PW or PF, since the drainage system are prepared for installation in wall panels and floor panels in two separate production processes. Moreover, there are usually two working stations for installing pipes in floors to increase the installation efficiency, because of the large number of pipes in floor panels and the complexity of the drainage pipe route. Compared to PF panels, PW panels have much smaller dimensions and are prepared for pipe installation at one working station. In summary, the BOM for cutting pattern generation and pipe installation is categorized for one PW panel and two PF working stations.

4.3 Case study

4.3.1 Vent pipe design

In this case study, the vent pipes for plumbing fixtures in one bathroom are shared by one sink vent, which is the "Share Sink Vent" option in the Revit add-on, as shown in Figure 4-9. The user-input parameters are branch vent offset, soil-or-waste stack top and bottom offset, main vent stack top and bottom offset, and pipe size for above pipes. In this case, the soil-or-waste stack top offset is lower than the branch vent offset, so the branch vent connect to the main vent stack automatically.

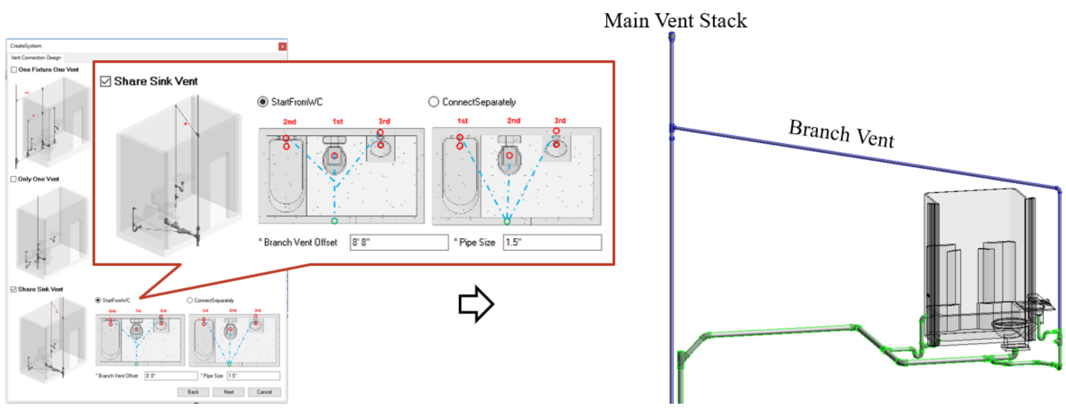


Figure 4-9: Vent pipe design example for a bathroom on the second floor

4.3.2 Drainage pipe design

The prototype system is tested by using the user-defined trap component, outlet component and trap arm height for each plumbing fixture in the case study. The location of ten plumbing fixtures, including four on the first floor and six on the second floor, and the soil-or-waste stack are already defined and measured in the

BIM model as input to the system. By running the system, the drainage pipe from plumbing fixture to soil-or-waste stack is generated as shown in Figure 4-10.

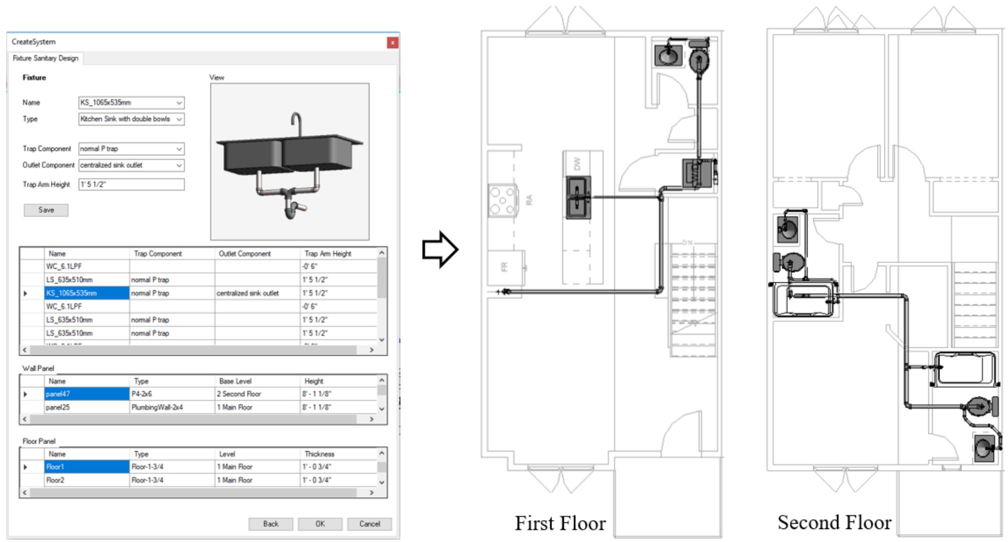


Figure 4-10: Drainage pipe generation

4.3.3 Panelized drainage system

The whole drainage system in one unit house is separated into seven panels as shown in Figure 4-11, including three plumbing wall (PW) panels and four plumbing floor (PF) panels.

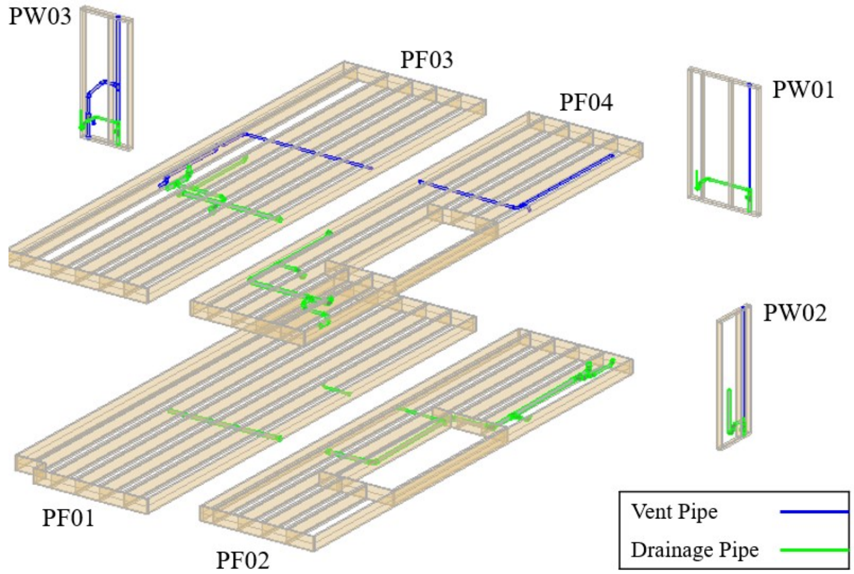


Figure 4-11: Panelized drainage system for one unit building

Once the shop drawings (presented in Appendix of this thesis) have been generated, the information contained in the corresponding bill of materials (BOM) for pipes (i.e., drainage pipes and vent pipes) is exported from Autodesk Revit to Microsoft Excel Spreadsheet.

The total time spent on designing and drafting a drainage system by implementing the prototype system in this case study is around 20 minutes which is much shorter than the time spent in real case. For this project, it spent engineer approximately one week to design the drainage system. Thus, the prototype system for designing and drafting drainage system improves the design efficiency.

4.3.4 Optimal cutting pattern generation

In this case study, the bill of materials (BOM) for pipes is classified according to the pipe size and corresponding panel type, since the pipe installation happens after the production of the framed panels in the wall and floor framing plants. All the plumbing walls of the five units in the townhouses are framed together and prepared for drainage system installation. For the floor framing process, all the floor panels at the same level of the five units are produced continuously and are prepared for pipe installation at one working station. Thus, the pipes are sorted into three groups for generating cutting patterns, including wall pipe list, first-floor pipe list, and second-floor pipe list. For each list, the pipe sizes and lengths are listed and sorted by three nominal sizes, i.e., 1.5 in, 2 in and 3 in. The stock pipe length is 12 ft (144 in) for all sizes. The classified BOM is shown in Table 4-1, 4-2 and 4-3.

Table 4-1: BOM for pipes in wall panels of one townhouse unit

Size (in)	Panel#	Length (in)	Length (mm)
1.5	PW01	2.00	50.80
1.5	PW01	31.63	803.28
1.5	PW01	78.00	1981.20
1.5	PW01	5.63	142.88
1.5	PW02	82.75	2101.85
1.5	PW02	5.63	142.88
1.5	PW03	7.00	177.80
1.5	PW03	15.00	381.00
1.5	PW03	13.25	336.55
1.5	PW03	1.75	44.45
2	PW01	1.88	47.63
2	PW01	8.50	215.90
2	PW01	2.88	73.03
2	PW02	31.88	809.63
2	PW02	8.00	203.20
2	PW02	2.00	50.80
2	PW02	6.00	152.40
2	PW02	3.00	76.20
2	PW03	2.88	73.03
2	PW03	5.88	149.23
2	PW03	7.50	190.50
2	PW03	8.13	206.38
2	PW03	24.38	619.13
2	PW03	14.75	374.65

Size (in)	Panel#	Length (in)	Length (mm)
2	PW03	49.25	1250.95
2	PW03	4.38	111.13
2	PW03	12.75	323.85
2	PW03	12.50	317.50

Table 4-2: BOM for pipes in first-floor panels of one townhouse unit

Size (in)	Panel#	Length (in)	Length (mm)
1.5	PF01	22.00	558.80
1.5	PF02	40.00	1016.00
2	PF02	5.00	127.00
2	PF02	1.63	41.28
2	PF02	20.88	530.23
3	PF01	94.13	2390.78
3	PF02	78.88	2003.43
3	PF02	3.00	76.20
3	PF02	26.75	679.45
3	PF02	2.63	66.68
3	PF02	7.63	193.68
3	PF02	18.63	473.08
3	PF02	71.25	1809.75
3	PF02	38.13	968.38

Table 4-3: BOM for pipes in second-floor panels of one townhouse unit

Size (in)	Panel#	Length (in)	Length (mm)
1.5	PF03	106.88	2714.63
1.5	PF03	23.13	587.38
1.5	PF04	3.00	76.20
1.5	PF04	2.88	73.03
1.5	PF04	105.88	2689.23
1.5	PF04	83.13	2111.38
2	PF03	4.13	104.78
2	PF03	1.75	44.45
2	PF03	5.13	130.18
2	PF03	13.50	342.90
2	PF03	8.25	209.55
2	PF03	59.00	1498.60
2	PF03	8.00	203.20
2	PF03	2.38	60.33
2	PF03	9.25	234.95
2	PF03	22.25	565.15
2	PF03	57.50	1460.50

Size (in)	Panel#	Length (in)	Length (mm)
2	PF03	3.50	88.90
2	PF04	5.13	130.18
2	PF04	13.50	342.90
2	PF04	8.00	203.20
2	PF04	9.25	234.95
2	PF04	6.00	152.40
2	PF04	6.50	165.10
2	PF04	13.88	352.43
2	PF04	1.63	41.28
2	PF04	12.63	320.68
3	PF03	4.63	117.48
3	PF03	8.13	206.38
3	PF03	10.50	266.70
3	PF03	80.38	2041.53
3	PF03	3.25	82.55
3	PF03	13.00	330.20
3	PF04	2.13	53.98
3	PF04	47.13	1196.98
3	PF04	10.38	263.53
3	PF04	59.13	1501.78
3	PF04	30.75	781.05
3	PF04	4.13	104.78

In each BOM, pipes with the same length are combined and summed up as shown in Figure 4-12(a). The cutting pattern is generated as a metric list. For instance, as shown in Figure 4-12(b), the configuration [2,0,1,5,0,4,0,0,3] illustrates the scenario in which a 12-ft pipe is cut into five types of lengths: 2 in (50.8 mm), 78 in (198.2 mm), 5.63 in (142.88 mm), 7 in (177.8 mm) and 1.75 in (44.45 mm) in the quantities of 2, 1, 5, 4 and 3, respectively.

Table a

Size (in)	Panel#	Length (in)	Length (mm)	Quantity
1.5	PW01	2.00	50.80	5
1.5	PW01	31.63	803.28	5
1.5	PW01	78.00	1981.20	5
1.5	PW01	5.63	142.88	5
1.5	PW02	82.75	2101.85	5
1.5	PW02	5.63	142.88	5
1.5	PW03	7.00	177.80	5
1.5	PW03	15.00	381.00	5
1.5	PW03	13.25	336.55	5
1.5	PW03	1.75	44.45	5

Table b

Size (in)	Quantity	Length (in)	Length (mm)
1.5	5	2.00	50.80
1.5	5	31.63	803.28
1.5	5	78.00	1981.20
1.5	10	5.63	142.88
1.5	5	82.75	2101.85
1.5	5	7.00	177.80
1.5	5	15.00	381.00
1.5	5	13.25	336.55
1.5	5	1.75	44.45

(a) Consolidation of pipes with the same length

Table b

Size (in)	Quantity	Length (in)	Length (mm)
1.5	5	2.00	50.80
1.5	5	31.63	803.28
1.5	5	78.00	1981.20
1.5	10	5.63	142.88
1.5	5	82.75	2101.85
1.5	5	7.00	177.80
1.5	5	15.00	381.00
1.5	5	13.25	336.55
1.5	5	1.75	44.45

Table c

Cutting Pattern	Quantity
[2,0,1,5,0,4,0,0,3]	1

(b) Relationship of bill of materials and cutting pattern

Figure 4-12: Example of generating a cutting pattern

After applying an integer programming (IP) approach, which was introduced in Section 3.6 for pipe cutting optimization, Table 4-4 shows the cutting patterns and respective quantities and waste The total waste is calculated for each size of pipe for each type of panel listed in Table 4-5.

Table 4-4: Optimized pipe cutting plan

Panel Type	Pipe Size (in)	Cutting Pattern	Quantity	Waste (in)
Wall Panel	1.5	[2,0,1,5,0,4,0,0,3]	1	0.625
		[0,1,0,0,1,0,1,1,0]	5	1.375
		[3,0,1,5,0,1,0,0,2]	1	21.375
		[0,0,1,0,0,0,0,0,0]	3	66
	2	[1,0,5,0,0,1,0,0,0,0,1,0,1,2,1,0,0]	2	0
		[1,0,0,0,0,0,5,0,0,0,0,1,0,1,0,3,0]	1	0.25
		[0,1,0,1,2,3,0,1,0,0,0,2,2,0,0,0,0]	1	0.375
		[0,1,0,0,0,0,4,1,2,4,0,0,1,0,3,0,5]	1	0.375
		[0,0,0,3,2,0,0,0,0,1,0,1,0,0,0,0,0]	1	0.5

Panel Type	Pipe Size (in)	Cutting Pattern	Quantity	Waste (in)
		[2,3,0,1,1,0,0,0,0,0,3,1,0,0,0,2,0]	1	0.625
		[0,0,0,0,0,0,0,3,3,0,0,0,0,0,0,0,0]	1	117.375
First Floor Panel	1.5	[2,2]	2	20
		[1,1]	1	82
	2	[5,5,5]	1	6.5
	3	[0,0,0,0,0,0,0,2,0]	2	1.5
		[1,0,1,1,0,0,1,0,0]	5	1.5
		[0,1,0,0,1,3,0,0,1]	1	1.5
		[0,1,0,0,0,0,0,0,1]	3	27
		[0,0,0,0,0,0,0,1,0]	1	72.75
ASecond Floor Panel	1.5	[1,0,5,5,0,0]	1	7.75
		[0,1,0,0,1,0]	5	15
		[1,0,0,0,0,0]	4	37.125
		[0,0,0,0,0,1]	5	60.875
	2	[0,2,0,5,0,1,0,0,0,0,0,0,0,0,1,0,0]	2	0.125
		[0,0,2,0,0,0,0,0,2,0,2,0,0,0,0,0,0]	2	0.25
		[1,0,0,0,10,0,1,0,0,1,0,0,0,0,0,1,1]	1	0.25
		[0,0,2,0,0,1,0,1,1,0,0,0,3,3,0,0,2]	1	0.375
		[0,0,4,0,0,0,0,0,3,4,0,0,1,0,0,0,0]	1	0.75
		[3,1,0,0,0,0,9,4,0,0,0,0,0,0,2,4,1]	1	1.5
		[1,0,0,0,0,2,0,0,0,0,0,0,1,0,1,0,0]	1	2
		[0,0,0,0,0,0,0,0,2,0,1,5,0,2,0,0,0]	1	37.5
	3	[1,0,2,0,0,0,0,0,0,2,0,0]	2	0.125
		[0,0,0,0,0,0,1,0,5,1,1,0]	1	0.125
		[0,0,0,1,1,1,0,1,0,0,0,0]	5	0.25
		[0,1,1,0,0,0,1,0,0,0,4,0]	1	0.25
		[3,4,0,0,0,0,3,0,0,0,0,5]	1	70.625

Table 4-5: Total waste for cutting patterns in each type of pipe

Panel Type	Pipe Size (in)	Total Waste (in)	Total Waste (%)
wall panel	1.5	222.88	15.48%
	2	119.50	10.37%
first floor panel	1.5	122.00	28.24%
	2	6.50	4.51%
	3	167.00	8.92%
second floor panel	1.5	521.25	24.31%
	2	43.13	3.00%
	3	72.50	5.03%
Total	N/A	1274.76	13.02%

Table 4-6 shows the comparison of material wastes between cutting pipes using IP algorithm ($W_{IP}\%$) and cutting pipes in production sequence ($W_{ps}\%$) which is normally used in real cases. The production sequence for pipe installation is from panel to panel, from bottom to top for wall panel and from one side to another for floor panel (e.g., from north to south in this case study). In Table 4-6, the total percentages of $W_{IP}\%$ and $W_{ps}\%$ for all panels are calculated by dividing total length of waste of all panels by total length of used stock pipes. Overall, the total waste calculated by IP algorithm is 13.02% which is smaller than the total waste of cutting pipes by production sequence in this case study.

Table 4-6: Total waste comparison of cutting by IP algorithm and production sequence

Panel Type	Pipe Size (in)	Total Waste ($W_{IP}\%$)	Total Waste ($W_{ps}\%$)	Decrease ($W_{ps}\% - W_{IP}\%$)
wall panel	1.5	15.48%	18.58%	3.10%
	2	10.37%	10.37%	0
first floor panel	1.5	28.24%	28.24%	0
	2	4.51%	4.51%	0
	3	8.92%	20.37%	11.45%
second floor panel	1.5	24.31%	24.80%	0.49%
	2	3.00%	14.23%	11.23%
	3	5.03%	20.86%	15.83%
Total	N/A	13.02%	19.43%	6.41%

CHAPTER 5. CONCLUSION

5.1 Summary

Panelization has been made one of the more popular and efficient approaches to constructing residential projects with the development of building information modelling (BIM). However, in most cases, some components, such as mechanical, electrical and plumbing components, are still installed on site in a traditional manner without being incorporated into prefab panels in order to capitalize on the benefits of the panelized construction approach. Due to the high level of design detail required for these types of components, the design stage will be made more difficult and time-consuming if the components are prefabricated and installed at the prefabrication plant. In order to improve the accuracy and efficiency of current drainage system design for panelized construction, this research explores a framework of a rule-based automated design system and incorporates a heuristic approach into BIM design to realize the automated planning of a panelized drainage system.

First, this research automates the design and modelling of a drainage system, including drainage pipes and vent pipes, in accordance with the plumbing code and typical design styles used by construction trades. For vent pipe design, a scenario-based method is developed to meet the requirements of the plumbing code and architectural layout planning in most cases. For drainage pipe design, a heuristic approach is implemented to integrate the consideration of framing members in a panel and the path of gravity-based pipes, in order to optimize for total pipe length.

The prototype design application provides more accurate details, i.e., gravity-based pipe height and length, and saves time in drainage system design. The automated approach can generate an optimized pipe route design that reduces material waste.

Also, this research proposes a planning algorithm to panelize the drainage system in a BIM environment to improve the pipe installation efficiency for panelized construction. In the proposed approach, the gravity-based pipes are separated into smaller pieces at the boundary of plumbing panels, which is meant to facilitate the shipping of an integrated package to the construction site. The geometric data extracted from the BIM model are used for defining the panelization constraints. This proposed method is applied when generating both vent pipes and drainage pipes. Meanwhile, a parameter is designed and attached to each pipe and pipe fitting to identify the corresponding plumbing panel. The identification of the corresponding plumbing panel is critically necessary in the pipe cutting and installation processes.

Furthermore, this research investigates one-dimensional cutting stock problems for cutting pipes from a standard-length stock pipe. An analytical approach is applied to minimize pipe cutting waste. First, the Bill of Materials (BOM) for pipes generated form the prototype system is classified as either pipes in plumbing walls or pipes in plumbing floors. Then, for each category, an enumeration method is used to generate all possible cutting scenarios with the corresponding amount of waste. The goal of this cutting stock problem is to minimize the waste of cutting patterns. An integer programming approach, in this case, is used to calculate the optimal cutting patterns.

In conclusion, the proposed methodology and prototype system in this research are capable of enhancing the design accuracy and design efficiency of the residential drainage system in panelized construction.

5.2 Research contributions

The proposed automated design system can contribute in many respects to both academic research and current industry practices in panelized construction. The primary contributions of this research are summarized as follows:

(1) Automation of the process of drainage system design improves its accuracy and efficiency by taking advantage of rich building information in the BIM model and by integrating the plumbing code in the context of gravity-based pipes. The framework incorporates an approach of scenario-based vent pipe design and rule-based drainage pipe design to accomplish drainage system design, in most cases. During the process of mapping a piping route, a heuristic approach is proposed to optimize path design to reduce the total length of pipes and create an obstacle-free route.

(2) Panelization of the drainage system improves the feasibility and efficiency of pipe installation for panelized construction. Drainage system separation based on plumbing panels facilitates the generation of the corresponding bill of materials (BOM) and management of the cutting and installation processes. The shop drawing with detailed annotations also increases the accuracy of drainage system installation in framed panels.

(3) Optimization of generating cutting patterns allows the pipes to be cut to the desired length from standard stock pipe with waste minimization. An integer programming algorithm is developed to solve the one-dimensional cutting stock problem.

(4) Development of prototype system under Autodesk Revit platform realizes three main functions, including automated design of drainage system (i.e., vent pipes and drainage pipes), panelization of pipes, and generation of optimal cutting patterns. The prototype system can produce the design in a reasonable amount of time and in accordance with the plumbing code, which not only assists the user to improve the efficiency of the design process but also increases the design accuracy for further pipe installation.

5.3 Limitations and future research

In order to improve the performance of the proposed methodology and prototype system, the following directions can be pursued in the future:

(1) The presented methodology and prototype system apply only to residential buildings. To extend the applicability of the system, future studies should investigate how to accommodate the plumbing code for commercial buildings.

(2) The scope of the prototype system is limited to panelized construction. Further investigation will need to be conducted for other types of prefabrication construction (e.g., modular construction).

(3) The current prototype system is based on the Canadian Plumbing Code and Canadian National Building Code and validated by a case study in Alberta, Canada. Other codes and standards from multiple regions and countries should be involved in the future.

(4) In this research, the locations of the soil-or-waste stack and main vent stack are defined by the user. According to architectural layout design and plumbing code, a suggestion of the pipe location can be provided to minimize the total length of pipes based on the calculation of a hydraulic load of plumbing fixtures in future research.

(5) In this research, the optimal pipe route design finds only the shortest path. In future work, cost estimation can be involved in the prototype system to search for a least-cost path based on the optimal cutting plan in consideration of minimizing cutting waste.

(6) In real cases, the cutting waste material can be recycled and reused by joining two pipes with a pipe fitting (i.e., coupling). This consideration will be involved for minimizing cutting waste in the future.

(7) This research focuses only on automated design for the drainage system. Other plumbing systems (e.g., hot water and cold water supply system) will be investigated in the future to enhance the integrity of the presented framework.

REFERENCES

Altaf, M. S., Bouferguene, A., Liu, H., Al-Hussein, M., & Yu, H. (2018). Integrated production planning and control system for a panelized home prefabrication facility using simulation and RFID. *Automation in construction, 85*, 369-383.

Burdorf, A., Kampczyk, B., Lederhose, M., & Schmidt-Traub, H. (2004). CAPD - computer-aided plant design. *28*(1-2), 73-81.

Cherri, A., Arenales, M., & Yanasse, H. (2009). The one-dimensional cutting stock problem with usable leftover–A heuristic approach. *European Journal of Operational Research, 196*(3), 897-908.

CIRIA. (1999). *Standardisation and Pre-assembly Adding Value to Construction Projects.* London.

Craven, D., Okraglik, H., & Eilenberg, I. (1994). Construction waste and a new design methodology. *In Proceedings of the First Conference of CIB TG*, *Vol. 16*, pp. 89-98.

Dijkstra, E. W. (1959). A note on two problems in connexion with graphs. *Numerische Mathematik, 1*(1), 269-271.

Dorigo, M., & Gambardella, L. (1997). Ant colonies for the travelling salesman problem. *biosystems, 43*(2), 73-81.

Dyckhoff, H. (1981). A new linear programming approach to the cutting stock problem. *Operations Research, 29*(6), 1092-1104.

Editors of Cool Springs Press. (2015). *Black & Decker: The complete guide to plumbing, 6th edition.* Minneapolis: Cool Springs Press.

Ferguson, J. (1995). *Managing and minimizing construction waste: a practical guide.* Thomas Telford.

Gibb, A. G. (1999). *Off-site fabrication: prefabrication, pre-assembly and modularisation.* Latheronwhee: John Wiley & Sons.

Gilmore, P. C., & Gomory., R. E. (1961). A linear programming approach to the cutting-stock problem. *Operations research, 9*(6), 849-859.

Gradišar, M., Kljajić, M., Resinovič, G., & Jesenko, J. (1999). A sequential heuristic procedure for one-dimensional cutting. *European Journal of Operational Research, 114*(3), 557-568.

Haas, C., O'Connor, J., Tucker, R., Eickmann, J., & Fagerlund, W. (2000). *Prefabrication and preassembly trends and effects on the construction workforce.* Austin, Texas: Center for Construction Industry Studies.

Haessler, R. (1975). Controlling cutting pattern changes in one-dimensional trim problems. *Operations Research, 23*(3), 483-493.

Hart, P. E., Nilsson, N. J., & Raphael, B. (1968). A formal basis for the heuristic determination of minimum cost paths. *IEEE transactions on Systems Science and Cybernetics, 4*(2), 100 - 107.

Hightower, D. W. (1969). A solution to line-routing problems on the continuous plane. *the 6th annual Design Automation Conference*, (pp. 1-24).

Institute, C. I. (2004). *Modularization and Offsite Assembly (Best Practice)*. (Construction Industry Institute: Austin, TX, USA, 2004.) Retrieved August 2, 2019, from https://www.construction-institute.org/resources/knowledgebase/knowledge-areas/modularization/topics/rt-171

IRC. (2006). *International Residential Code.* International Code Council.

Ito, T. (1999). A genetic algorithm approach to piping route path planning. *Journal of Intelligent Manufacturing, 10*(1), 103-114.

Jang, S., & Lee, G. (2018). Process, productivity, and economic analyses of BIM based multi-trade prefabrication-A case study. *Automation in Construction, 89*, 86-98.

Jiang, W., Lin, Y., Chen, M., & Yu, Y. (2015). A co-evolutionary improved multi-ant colony optimization for ship multiple and branch pipe route design. *Ocean Engineering, 102*, 63-70.

Kai-jian, S., & Hong-e, Z. (1987). Efficient routing algorithm. *Computer-Aided Design, 19*(7), 375-379.

Kai-jian, S., & Zhu, H.-e. (1987). Efficient routing algorithm. *Computer-Aided Design, 19*(7), 375-379.

Kennedy, J., & Eberhart, R. (1995). Particle swarm optimization. *IEEE International Conference on Neural Networks IV* (pp. 1942-1948). Perth, Australia: IEEE Press.

Knaack, U., Chung-Klatte, S., & Hasselbach, R. (2012). *Prefabricated systems: Principles of construction.* Walter de Gruyter.

Lavikka, R. H., Chauhan, K., Peltokorpi, A., & Seppanen, O. (2018). Fostering prefabrication in construction projects-case MEP in Finland. In J. Karlshoj, & R. Scherer (Ed.), *12th European Conference on Product and Process Modelling (ECPPM)*, (pp. 273-280). Copenhagen, DENMARK.

Lawson, M., Ogden, R., & Goodier, C. (2014). *Design in modular construction.* CRC Press.

Lee, C. (1961). An algorithm for path connections and its applications. *IRE transactions on electronic computers, EC-10*(3), 346 - 365.

Li, X., Li, Z., & Wu, G. (2017). Modular and Offsite Construction of Piping: Current Barriers and Route. *Applied Sciences, 7*(6), 547.

Li, Z., Shen, G. Q., & Xue, X. (2014, Jul 1). Critical review of the research on the management of prefabricated construction. *Habitat international*(43), 240-249.

Lindow, E. S., & Jasinski, L. F. (2003). Panelized wall construction: Design, testing, and construction procedures. *Symposium on Performance of Exterior Building Walls. 1422*, pp. 231-241. PHOENIX, AZ: ASTM International.

Liu, Q., & Wang, C. (2010). Pipe-assembly approach for aero-engines by modified particle swarm optimization. *Assembly Automation, 30*(4), 365-377.

Lopez, D., & Froese, T. M. (2016). Analysis of costs and benefits of panelized and modular prefabricated homes. *International Conference on Sustainable Design, Engineering and Construction (ICSDEC). 145*, pp. 1291-1297. Arizona State Univ, Coll Avenue Commons, Tempe, AZ: Procedia Engineering.

Lu, W., Chen, K., Xue, F., & Pan, W. (2018, Nov 10). Searching for an optimal level of prefabrication in construction: An analytical framework. *Journal of cleaner production*(201), 236-245.

Mogollon, J. D. (2009). *Automation of Design and Drafting for Wood Frame Structures and Construction Waste Minimization (Unpublished doctoral dissertation)*. Edmonton, AB, Canada: University of Alberta.

Morse-Fortier, L. J. (1995). Structural Implications of Increased Panel Use in Wood-Frame Buildings. *Journal of Structural Engineering, 121*(6), 995-1003.

Mousa, M. A.-M.-R. (2007). Optimization of Structural Panels for Cost Effective Panelized Construction.

(2015). *National Plumbing Code of Canada.* Canadian Commission on Building and Fire Codes;National Research Council of Canada.

NBC. (2015). *National Building Code of Canada.* Canadian Commission on Building and Fire Codes;National Research Council of Canada.

Neale, R., Price, A., & Sher, W. (1993). *Prefabricated modules in construction: a study of current practice in the United Kingdom.* Ascot: Chartered Institute of Building.

Nguyen, H., Kim, D., & Gao, J. (2016). 3D Piping Route Design Including Branch and Elbow Using Improvements for Dijkstra's Algorithm. *2016 International Conference on Artificial Intelligence: Technologies and Applications.* Atlantis Press.

Nguyen, H., Kim, D.-J., & Gao, J. (2016). 3D Piping Route Design Including Branch and Elbow Using Improvements for Dijkstra's Algorithm. *International Conference on Artificial Intelligence - Technologies and Applications (ICAITA)*, *127.*

NPC. (2015). *National Plumbing Code of Canada.* Canadian Commission on Building and Fire Codes;National Research Council of Canada.

Park, J., & Storch, R. (2002). Pipe-routing algorithm development: case study of a ship engine room design. *EXPERT SYSTEMS WITH APPLICATIONS, 23*(3), 299-309.

Prefab Housing Canada. (2018). *Prefab Housing Canada*. Retrieved from https://prefabhousing.ca/

Richard, R.-B. (2005). Industrialised building systems: reproduction before automation. *Automation in Construction, 14*(4), 442-451.

Rogoff, M. J., & Williams, J. F. (2012). *Approaches to implementing solid waste recycling facilities.* William Andrew.

Roodman, G. M. (1986). Near-optimal solutions to one-dimensional cutting stock problems. *Computers & operations research, 13*(6), 713-719.

Salem, O., Shahin, A., & Khalifa, Y. (2007). Minimizing cutting wastes of reinforcement steel bars using genetic algorithms and integer programming models. *Journal of construction engineering and management, 133*(12), 982-992.

Samarasinghea, T., Gunawardenaa, T., Mendisa, P., Sofia, M., & Aye, L. (2019). Dependency Structure Matrix and Hierarchical Clustering based algorithm for optimum module identification in MEP systems. *Automation in Construction, 104*(May 2018), 153-178.

Soltani, A., Tawfik, H., Goulermas, J., & Fernando, T. (2002). Path planning in construction sites: performance evaluation of the Dijkstra, A∗, and GA search algorithms. *Advanced engineering informatics, 16*(4), 291-303.

Steinhardt, D. A., & Manley, K. (2016). Adoption of prefabricated housing–the role of country context. *Sustainable cities and society*(22), 126-135.

Tam, V. W., Tam, C. M., Zeng, S. X., & Ng, W. C. (2007). Towards adoption of prefabrication in construction. *Building and environment*(42(10)), 3642-3654.

Testa, C. (1972). *The Industrialisation of Building.* New York: Van Nostrand Reinhold.

The Canadian Timber Company. (2007). *What is Panelized Construction?* Retrieved August 15, 2019, from The Canadian Timber Company: http://www.canadiantimber.ca/build_panelized.html

Tserng, H. P., Yin, Y. L., Jaselskis, E. J., Hung, W. C., & Lin, Y. C. (2011). Modularization and assembly algorithm for efficient MEP construction. *Automation in Construction*(20(7)), 837-863.

Wang, P., Mohamed, Y., Abourizk, S. M., & Rawa, A. R. (2009). Flow Production of Pipe Spool Fabrication: Simulation to Support Implementation of Lean Technique. *Journal of Construction Engineering and Management, 135*(10), 1027-1038.

Weiss, A. (2002, August 1). *U.S Patent No. 09/774,675.*

Weiss, A. (2005, February 15). *Washington, DC: U.S Patent No. 6,854,218.*

Yin, Y. H., Xu, L. D., Bi, Z., Chen, H., & Zhou, C. (2013). A Novel Human-Machine Collaborative Interface for Aero-Engine Pipe Routing. *IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS, 9*(4), 2187-2199.

Zheng, C., Yi, C., & Lu, M. (2019). Integrated optimization of rebar detailing design and installation planning for waste reduction and productivity improvement. *Automation in Construction, 101*, 32-47.

Zhu, D., & Latombe, J.-C. (1991). Pipe routing-path planning (with many constraints). *1991 IEEE International Conference on Robotics and Automation*, (pp. 1940-1947).

APPENDIX A: PSEUDOCODE

Algorithm 1: Heuristic Pathfinding Algorithm

Input: S – start point, T – terminal point, H_j– height of floor joist, d_t– minimum distance from top edge of joist to pipe top edge, d_b– minimum distance from bottom edge of joist to pipe bottom edge, S – pipe slope, l_{min} – pipe unit length, FO{} – floor opening

Output: Pipe path P{}

Begin

Set node N = S

Set prepend point P(i) = N, i ∈ $[1, 2, 3, 4]$

Create an empty curve list P{}

While N is not T **do**

  P(1) = N + (l_{min}, 0), P(2) = N − (l_{min}, 0),
  P(3) = N + (0, l_{min}), P(4) = N − (0, l_{min})

  for each P(i) **do**

    Calculate the minimum distance d(i) from N to FO{}

      If g(i) ≤ $(H_j - d_t - d_b)$/S and d(i) ≥ l_{min} and i ≤ 4 **then**

        Calculate the pipe length g(i) from S to P(i)

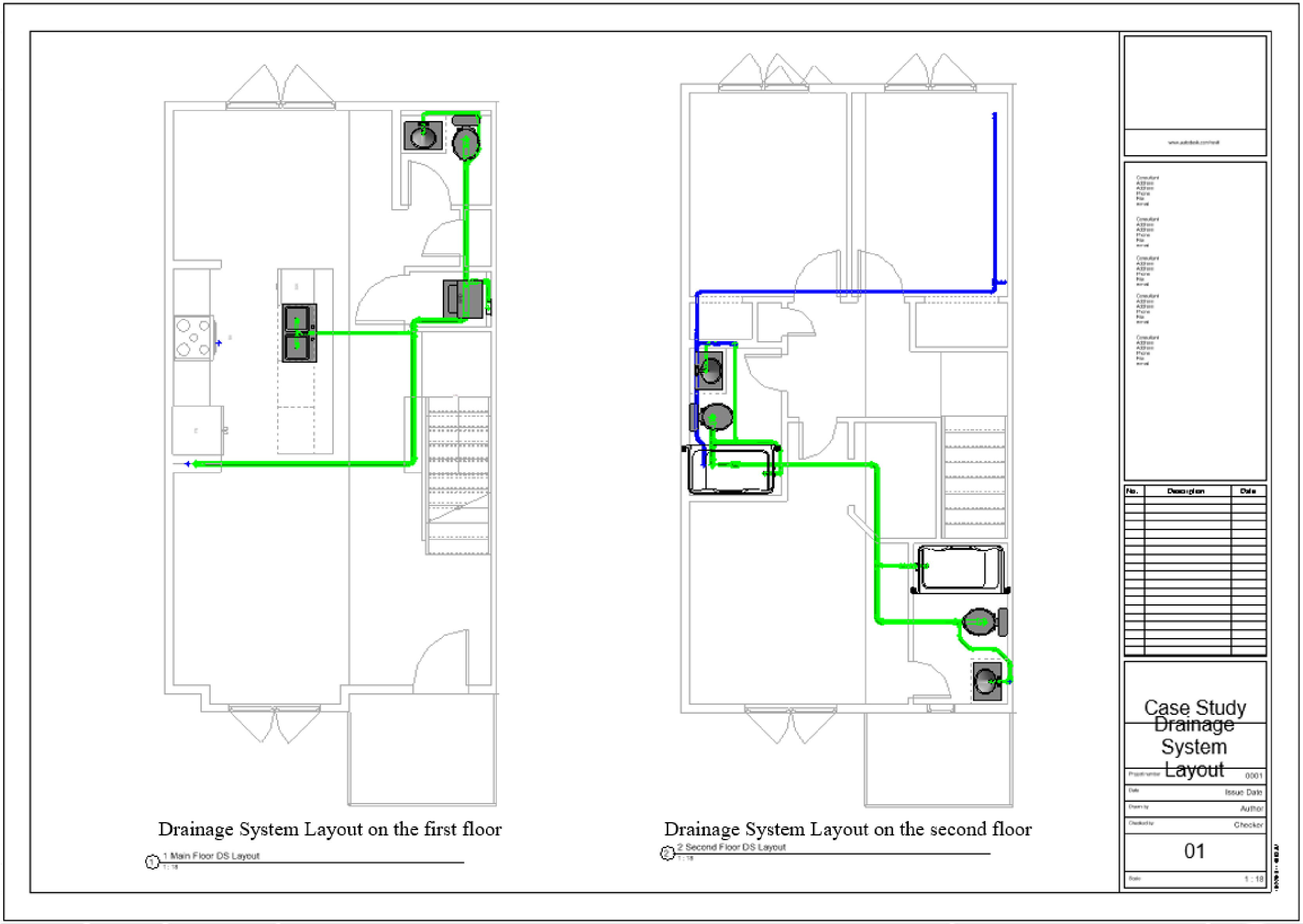
        Calculate the Manhattan distance h(i) from P(i) to T

        Calculate the number of turns t(i) from S to P(i)

        Fitness value of P(i) is f(i) = g(i) + h(i) + t(i)

```
        else
          i = i + 1
        end
    end for
    Select the P(i) with minimum f(i)
    Add NP(i) to P{}
    N = P(i)
  End While
End
```

APPENDIX B: DRAINAGE SYSTEM LAYOUT DRAWINGS



APPENDIX C: PLUMBING WALL SHOP DRAWINGS

A1-PW01-Assembly

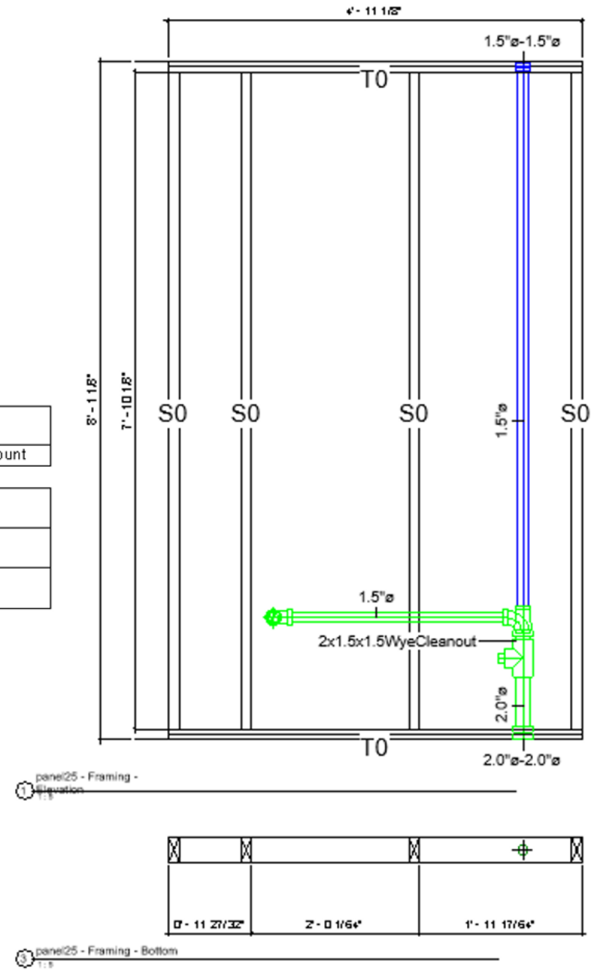
Type	Naming Category	Count
2x1.5x1.5WyeCleanout	Pipe Fittings	1
		1

A1-PW01-Pipe

Family and Type	Size	Length
Pipe Types: PVC	1.5"ø	2' - 6 5/32"
Pipe Types: PVC	1.5"ø	6' - 4 1/2"
Pipe Types: PVC	2.0"ø	0' - 7 1/16"

A1-PW01-PipeFitting

Family and Type	Size	Count
M_Bend - PVC - Sch 40 - DWV: Standard	1.5"ø-1.5"ø	1
M_Coupling - PVC - Sch 40 - DWV: Standard	1.5"ø-1.5"ø	1
M_Coupling - PVC - Sch 40 - DWV: Standard	2.0"ø-2.0"ø	1
		3



Case Study

PlumbingPanel25

Project number 0001

Date Issue Date

Drawn by Author

Checked by Checker

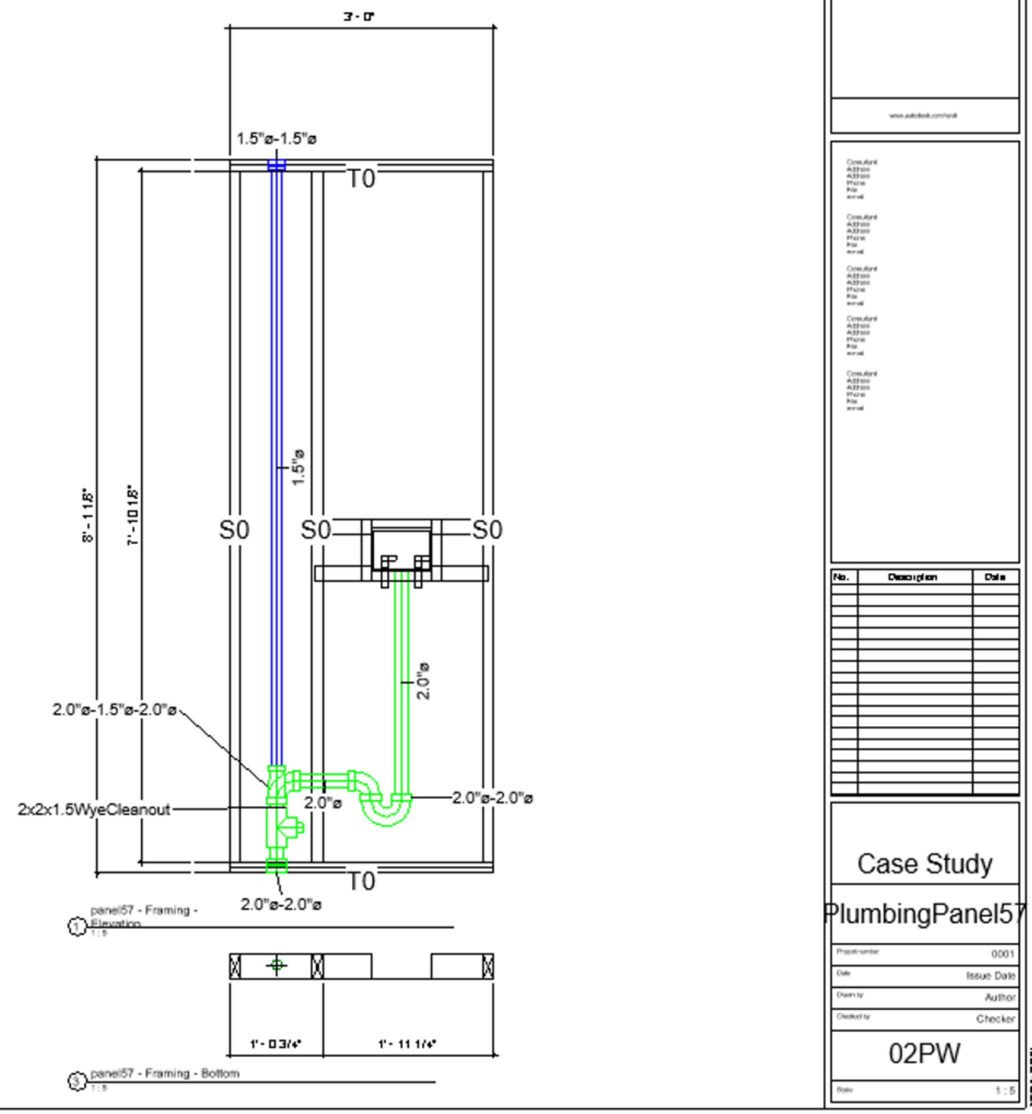
01PW

Scale 1 : 5

A2-PW02-Assembly		
Type	Naming Category	Count
2x2x1.5WyeCleanout	Pipe Fittings	1
		1

A2-PW02-Pipe		
Family and Type	Size	Length
Pipe Types: PVC	1.5"ø	6' - 9 15/64"
Pipe Types: PVC	2.0"ø	2' - 6 13/32"
Pipe Types: PVC	2.0"ø	0' - 6 15/32"
Pipe Types: PVC	2.0"ø	0' - 1 35/64"

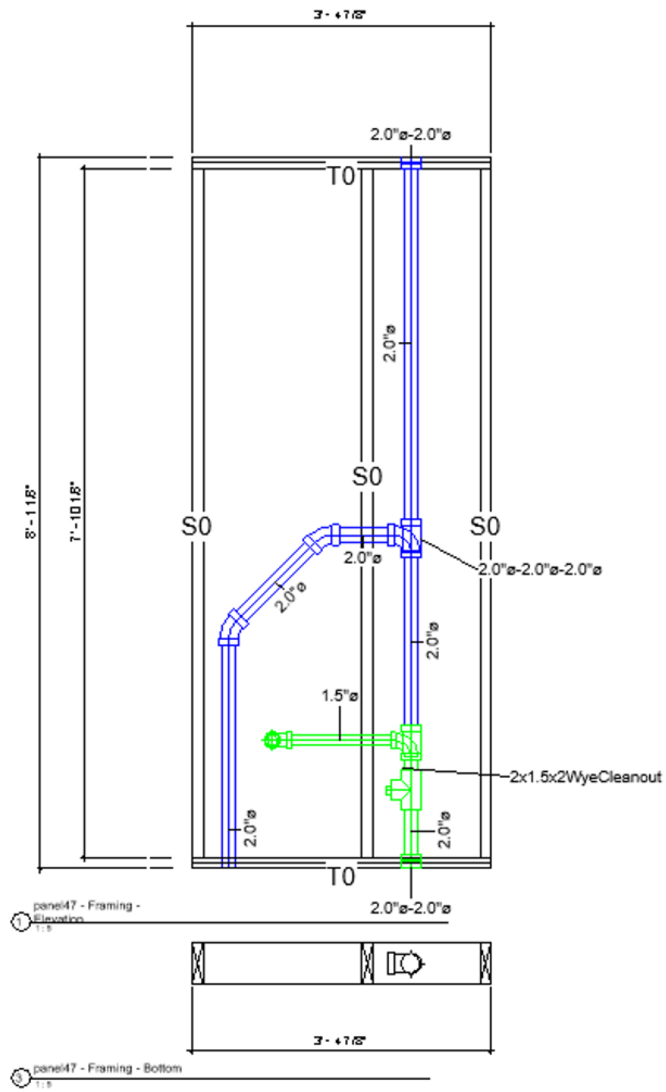
A2-PW02-PipeFitting		
Family and Type	Size	Count
M_Coupling - PVC - Sch 40 - DWV: Standard	1.5"ø-1.5"ø	1
M_Coupling - PVC - Sch 40 - DWV: Standard	2.0"ø-2.0"ø	1
Trap P - PVC - Sch 40 - DWV - E: Standard	2.0"ø-2.0"ø	1
		3



A3-PW03-Assembly		
Type	Naming Category	Count
2x1.5x2WyeCleanout	Pipe Fittings	1
		1

A3-PW03-Pipe		
Family and Type	Size	Length
Pipe Types: PVC	1.5"ø	1' - 1 31/64"
Pipe Types: PVC	2.0"ø	0' - 6 5/8"
Pipe Types: PVC	2.0"ø	1' - 10 55/64"
Pipe Types: PVC	2.0"ø	1' - 1 15/64"
Pipe Types: PVC	2.0"ø	2' - 9 9/64"
Pipe Types: PVC	2.0"ø	3' - 11 45/64"
Pipe Types: PVC	2.0"ø	0' - 6 1/32"

A3-PW03-PipeFitting		
Family and Type	Size	Count
M_Bend - PVC - Sch 40 - DWV: Standard	1.5"ø-1.5"ø	1
M_Bend - PVC - Sch 40 - DWV: Standard	2.0"ø-2.0"ø	2
M_Coupling - PVC - Sch 40 - DWV: Standard	2.0"ø-2.0"ø	2
M_Plug - PVC - Sch 40 - DWV: Standard	2.0"ø	1
M_Tee - PVC - Sch 40: Standard	2.0"ø-2.0"ø-2.0"ø	1
M_Tee Reducing Sanitary - PVC - Sch 40 - DWV: Standard	2.0"ø-2.0"ø-1.5"ø	1
M_Tee Reducing Sanitary - PVC - Sch 40 - DWV: Standard	2.0"ø-2.0"ø-2.0"ø	1
		9



Case Study
PlumbingPanel47
0001
Issue Date
Author
Checker
03PW
1 : 5

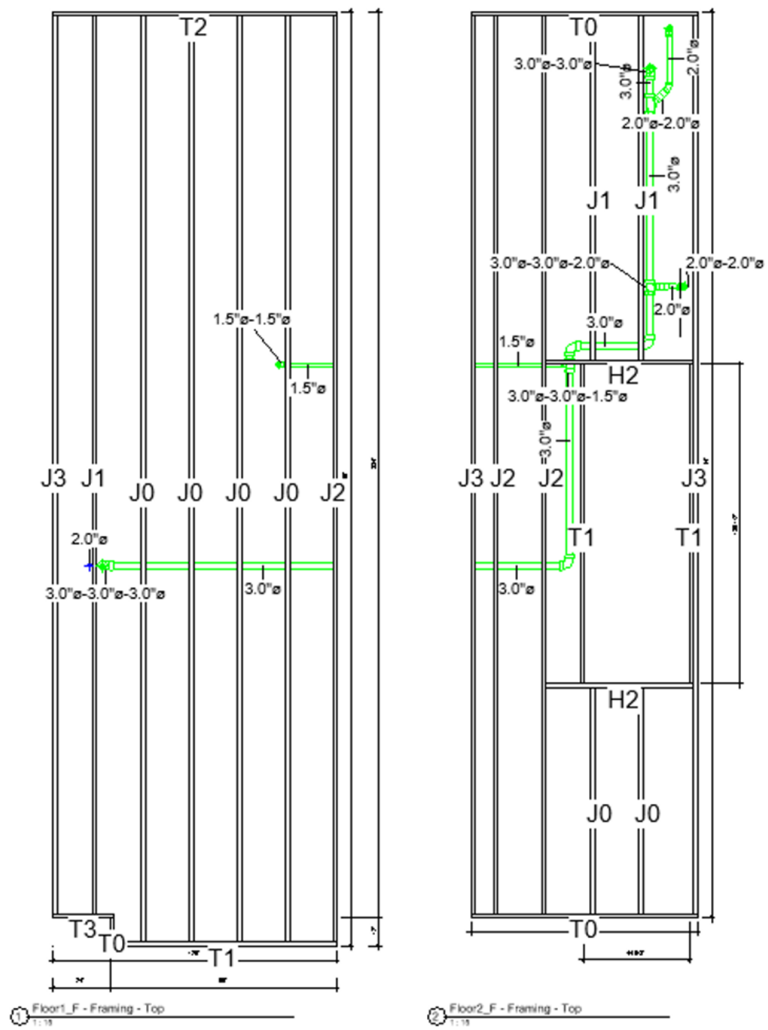
APPENDIX D: PLUMBING FLOOR SHOP DRAWINGS

A4-F01-Pipe

Family and Type	Size	Length
Pipe Types: PVC	1.5"ø	60 3/8"
Pipe Types: PVC	2.0"ø	3 1/2"
Pipe Types: PVC	2.0"ø	1/8"
Pipe Types: PVC	2.0"ø	19 3/8"
Pipe Types: PVC	3.0"ø	77 3/8"
Pipe Types: PVC	3.0"ø	132 1/4"
Pipe Types: PVC	3.0"ø	1 1/2"
Pipe Types: PVC	3.0"ø	25 1/4"
Pipe Types: PVC	3.0"ø	1 1/8"
Pipe Types: PVC	3.0"ø	6 1/8"
Pipe Types: PVC	3.0"ø	17 1/8"
Pipe Types: PVC	3.0"ø	69 3/4"

A4-F01-PipeFitting

Family and Type	Size	Count
M_Bend - PVC - Sch 40 - DWV: Standard	1.5"ø-1.5"ø	1
M_Bend - PVC - Sch 40 - DWV: Standard	2.0"ø-2.0"ø	3
M_Bend - PVC - Sch 40 - DWV: Standard	3.0"ø-3.0"ø	4
M_Coupling Reducing - PVC - Sch 40: Standard	2.0"ø-2.0"ø	2
M_Tee Reducing Sanitary - PVC - Sch 40 - DWV: Standard	3.0"ø-3.0"ø-1.5"ø	1
M_Tee Reducing Sanitary - PVC - Sch 40 - DWV: Standard	3.0"ø-3.0"ø-2.0"ø	2
M_Tee Reducing Sanitary - PVC - Sch 40 - DWV: Standard	3.0"ø-3.0"ø-3.0"ø	1
		14



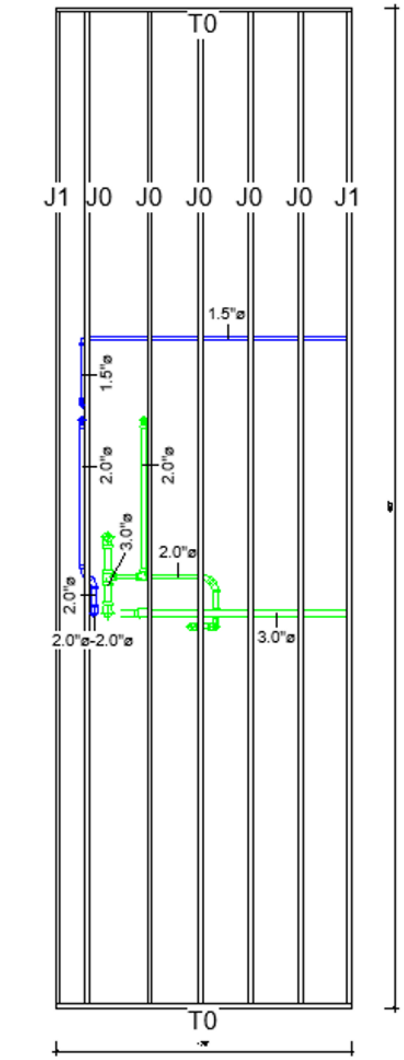
Case Study

Plumbing

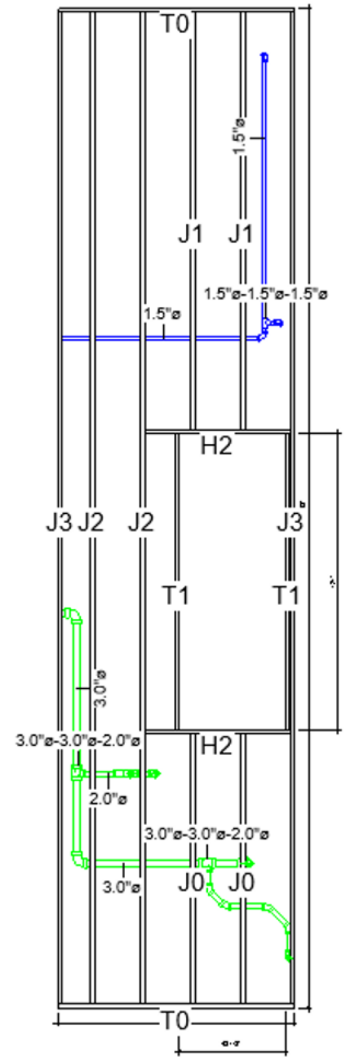
First Floor

A4-F02-Pipe		
Family and Type	Size	Length
Pipe Types: PVC	1.5"ø	1 1/2"
Pipe Types: PVC	1.5"ø	1 3/8"
Pipe Types: PVC	1.5"ø	188 1/4"
Pipe Types: PVC	1.5"ø	104 3/8"
Pipe Types: PVC	1.5"ø	21 5/8"
Pipe Types: PVC	2.0"ø	2 5/8"
Pipe Types: PVC	2.0"ø	1/4"
Pipe Types: PVC	2.0"ø	3 5/8"
Pipe Types: PVC	2.0"ø	6 3/4"
Pipe Types: PVC	2.0"ø	57 1/2"
Pipe Types: PVC	2.0"ø	6 1/2"
Pipe Types: PVC	2.0"ø	7/8"
Pipe Types: PVC	2.0"ø	7 3/4"
Pipe Types: PVC	2.0"ø	20 3/4"
Pipe Types: PVC	2.0"ø	3 5/8"
Pipe Types: PVC	2.0"ø	6 1/2"
Pipe Types: PVC	2.0"ø	7 3/4"
Pipe Types: PVC	2.0"ø	4 1/2"
Pipe Types: PVC	2.0"ø	5"
Pipe Types: PVC	2.0"ø	12 3/8"
Pipe Types: PVC	2.0"ø	1/4"
Pipe Types: PVC	2.0"ø	1/8"
Pipe Types: PVC	2.0"ø	11 1/8"
Pipe Types: PVC	2.0"ø	56"
Pipe Types: PVC	2.0"ø	2"
Pipe Types: PVC	3.0"ø	3 1/8"
Pipe Types: PVC	3.0"ø	6 5/8"
Pipe Types: PVC	3.0"ø	9"
Pipe Types: PVC	3.0"ø	5/8"
Pipe Types: PVC	3.0"ø	45 5/8"
Pipe Types: PVC	3.0"ø	8 7/8"
Pipe Types: PVC	3.0"ø	84 1/4"
Pipe Types: PVC	3.0"ø	57 5/8"
Pipe Types: PVC	3.0"ø	29 1/4"
Pipe Types: PVC	3.0"ø	1 3/4"
Pipe Types: PVC	3.0"ø	11 1/2"

A4-F02-PipeFitting		
Family and Type	Size	Count
M_Bend - PVC - Sch 40 - DWV: Standard	1.5"ø-1.5"ø	5
M_Bend - PVC - Sch 40 - DWV: Standard	2.0"ø-2.0"ø	14
M_Bend - PVC - Sch 40 - DWV: Standard	3.0"ø-3.0"ø	6
M_Coupling - PVC - Sch 40 - DWV: Standard	2.0"ø-2.0"ø	1
M_Tee - PVC - Sch 40: Standard	1.5"ø-1.5"ø-1.5"ø	1
M_Tee Reducing Sanitary - PVC - Sch 40 - DWV: Standard	2.0"ø-2.0"ø-2.0"ø	3
M_Tee Reducing Sanitary - PVC - Sch 40 - DWV: Standard	3.0"ø-3.0"ø-2.0"ø	3
Trap P - PVC - Sch 40 - DWV - E: Standard	2.0"ø-2.0"ø	2
		35



1 Floor3_F - Framing - Top



2 Floor4_F - Framing - Top

Case Study

Plumbing

Project number	0001
Date	Issue Date
Drawn by	Author
Checked by	Checker

Second Floor

Scale 1 : 16