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BIM-based automated design of drainage systems for panelized residential buildings

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ABSTRACT
The development of building information modelling has facilitated the improvement of cost and time management in panelized construction. This research proposes an automated method to design and draft drainage systems in the BIM environment. The 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 cutting optimization. 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.

KEYWORDS
Building information modelling (BIM); automated design; residential drainage system; panelized construction

Introduction and background

Prefabrication can increase construction project performance (Li et al. 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 (Tam and Hao 2014; Prefab Housing Canada 2018). As one classic type of prefabrication construction, panelized buildings 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 (Wang et al. 2020). However, in most cases, the residential drainage components (which is a sub-system of mechanical, electrical, and plumbing (MEP) system that is used to drain wastewater from a residential building to the municipal sewage network) including plumbing fixtures, pipe fittings, and pipes, are installed on-site in a conventional manner based on layout drawings and worker's experience, instead of being pre-installed off-site. Thus, there is a need for residential drainage components to be incorporated into the prefabricated panels in order to capitalize on the benefits of the prefabrication construction approach. To realize that, more efforts and time are needed since a higher level of design details is required for such a prefabrication process. In addition, potential clashes between the framed panels and MEP components need to be considered during the designing process, which makes the task more challenging. Therefore, improving the designing process for the panelized residential building drainage (PRBD) system is the major focus of the present research.

Building information modelling (BIM) can benefit almost all stages and processes involved in a construction project, especially the design and planning stage (Abdel-Hamid and Abdelhaleem 2021). It has been claimed that BIM techniques can improve design efficiency and accuracy, and eventually improve the performance of industrialization and prefabrication of the construction industry (Yin et al. 2019; Khanzadi et al. 2020; Bosch-Sijtsema and Gluch 2021). By leveraging the power of the BIM tool, this research thus proposes a rule-based framework for automatically designing and drafting a PRBD system to improve the assembling and installation efficiency at the prefabrication plant. The main contribution of this research is to propose and develop an automated designing and drafting method for the PRBD system. The PRBD system improves the accuracy and efficiency of the design process, in addition, layouts and shop drawings of the PRBD system with detailed information for installation are also generated automatically. In the shop drawings, the PRBD system is separated into smaller components adapted for panelized construction manufacturing. Cutting patterns for pipes are also generated in the proposed system based on the cutting stock algorithm to minimize material waste. To implement the proposed system, 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).

This paper consists of 5 sections. The first section introduces the research background, motivation, and provides an overview of the paper. *Methodology* section describes the proposed

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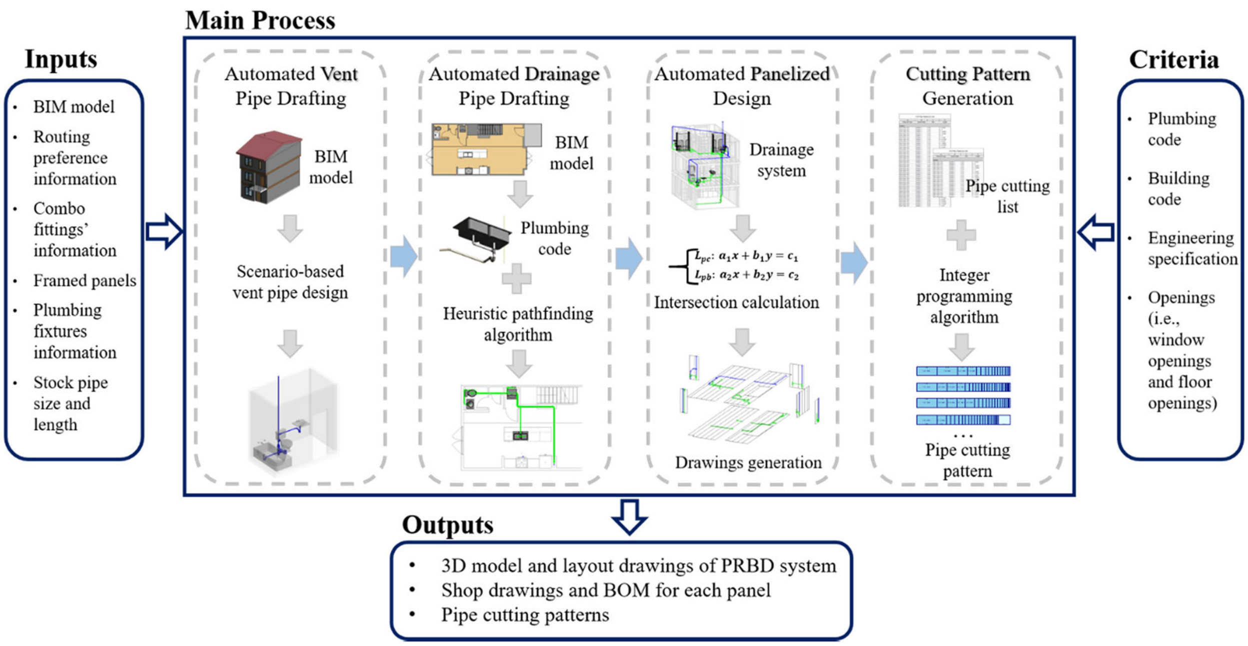


Figure 1. Overview of the proposed framework.

methodology framework, including methodology overview, a heuristic approach for the PRBD system, and pipe cutting optimization. The development of the prototyped system in the BIM environment is described in the section *Development of BIM-based automated design system*. A case study is presented to validate the methodology and verify the prototype system in *Case study* section. *Conclusion* section summarizes the results, highlights the contributions of this research, and presents the challenges of applying existing BIM extensions and recommendations for future research.

Related works

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, low-skilled workers (Li et al. 2017), and lack of cooperation among stakeholders in a project, such as the owners, the designers, the general contractor, the MEP sub-contractors, and the fabricator. (Lavikka et al. 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. A rational planning algorithm was designed to separate complex facilities of an MEP system into smaller fabricated components to improve the MEP construction performance in terms of safety, quality, productivity, reducing waste, etc. (Tserng et al. 2011). An efficient modularization algorithm was developed for reducing the cost of the assembly and handling of MEP modules (Samarasinghe et al. 2019). Another research proposed a BIM-based framework to eliminate the impacts of deviations between structures and MEP layout by integrating MEP layout from preliminary design to construction stage (Wang et al. 2016). However, there is no related research focusing on facilitating the automation of design and drafting for drainage systems in panelized residential buildings. Note that, this presented paper is extended research of one of our previous works (Zhang et al. 2020). In that paper, some initial attempts were made to address the issues related to rule-based fixture drainage design, knowledge-based vent pipe design, and drainage system prefab design algorithm, while in this research we not only further detailed those issues but also proposed a detailed framework to incorporate all the developed algorithms for automating the drainage system design process. In addition, we further validated the framework with a case study in a much more detailed manner.

Methodology

The presented method aims to automatically design and generate the drafting for a PRBD system in a BIM environment. The proposed framework is presented in Figure 1 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 information from the BIM model 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. These vent options will be illustrated in *Vent pipe design* section in detail. After that, the drainage pipe from plumbing fixtures to the soil-or-waste stack is designed automatically using a rule-based heuristic approach which will be shown in the following section. Next, the whole PRBD system is separated into smaller pieces at the panel boundaries, and the shop drawing and a bill of materials (BOM) for each plumbing panel, which is a floor or wall panel installed PRBD system, are produced. At last, the optimal cutting list is generated using the pipe schedule and stock pipe length.

In the proposed framework, the inputs of the automated design system include a BIM-based 3 D model, user-defined routing preference, pre-designed combo fittings, framed panels, plumbing fixtures, as well as stock pipe size and length. Level of details or level of development (LOD) is a commonly used indicator in the BIM model development process to describe the minimum requirements of different components in a model associated with a certain LOD (AIA 2013). The LOD includes levels from LOD 100 to LOD 500, interested readers are recommended to consult (Weygant 2011) for details of definitions of different LODs. In this research, To generate the proposed PRBD system, the LOD of the BIM model should be at least LOD 300, including the accurate sizes, shapes, locations, and orientations for wall panels, floor panels, windows, doors, and plumbing fixtures. 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 projects. Combo fitting is the combination of three or more elements (the smallest and most basic item in the PRBD system, i.e., pipes and pipe fittings) ending with a pipe fitting that will be connected to a pipe segment. All the combo fittings are designed before planning the PRBD system and can be selected as a type of pipe fitting. 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. The size and length of stock pipes are needed for optimizing cutting patterns.

To set up the constraints of the PRBD 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 3 D models of the PRBD system, drainage piping layout, shop drawings, optimal cutting patterns of pipes, and a BOM of the panelized package, which includes the combo fittings, pipes, and pipe fittings for each framed plumbing panel.

A heuristic approach for pipe route optimization

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 et al. 2004), ship pipe system design (Park and Storch 2002), and aero-engine pipe route design (Yin et al. 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.

Three popular pathfinding algorithms, i.e., Dijkstra's algorithm (DA), A-star algorithm (AA), and genetic algorithm (GA), have been previously investigated and implemented for optimal path planning in a construction site (Soltani et al. 2002). DA (Dijkstra 1959) is an algorithm that 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. As one of the most famous pathfinding methods, DA always determines the best solution, but it takes a long calculation time, occupies more memory space, and only considers the shortest solution (Nguyen et al. 2016). AA is based on a maze algorithm and uses cell decomposition and connectivity graphs to find an optimal solution (Hart et al. 1968). It is widely used in pathfinding and graph traversal to find a path between multiple points. A genetic algorithm 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. This path is the optimal path, which may be the shortest path or the path with the minimum number of turns. 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. 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 (Soltani et al. 2002).

The proposed pipe route optimization algorithm is a new heuristic optimization algorithm incorporating a greedy search strategy into the AA and DA algorithms. The algorithm uses design rules as constraints to efficiently search optimal drainage pipe paths 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. 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. To obtain a default unit value and number of turns from plumbing fixture to soil-or-waste stack, the fitness function for each path node is expressed as per Equation (1).

$$f(n) = g(n) + h(n) + t(n) \tag{1}$$

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 Equation (2):

$$h(n) = |X_t - X_n| + |Y_t - Y_n| \tag{2}$$

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 (see Equations 3 and 4):

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

$$D(n) \ge l_{min} \tag{4}$$

where H_{Joist} is the floor joist height, d_{top} is the minimum safety drilling distance from the top edge of the floor joist, d_{bottom} is the minimum safety drilling distance from the top edge of the 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: 1) mark fixture drainage location on the floor as the start point, S; 2) calculate the fitness value, $f(n)$, for all possible neighbor path nodes; 3) check $g(n)$ and $D(n)$ for each node and store the node value if it passes the checking; 4) compare node values and set the node with minimum $f(n)$ as a new start point, S; and 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).

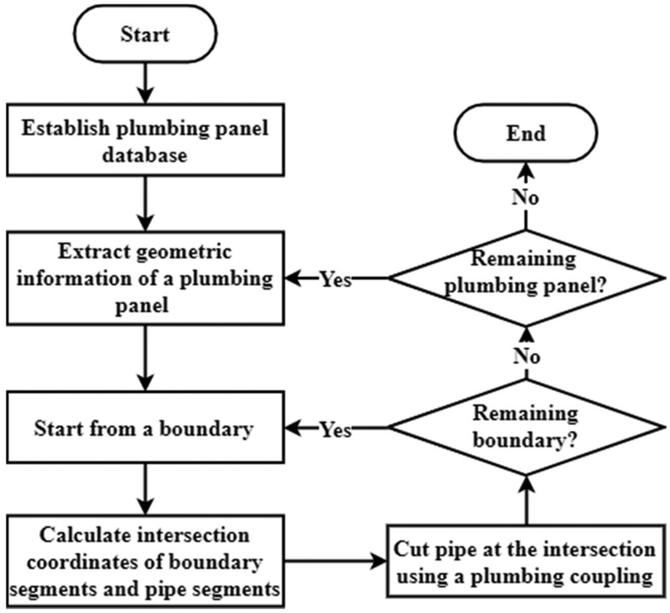


Figure 2. Flowchart of PRBD system panelization planning algorithm.

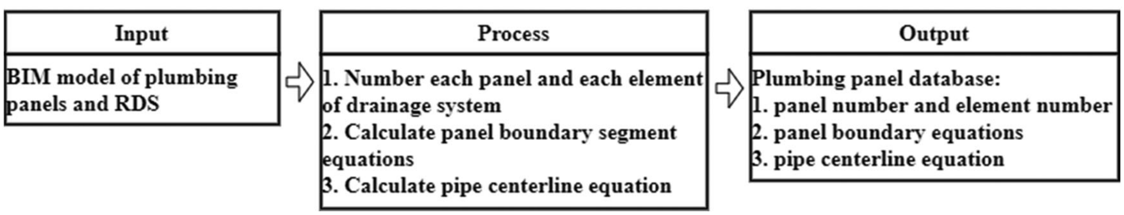


Figure 3. Flowchart of establishing a database of plumbing panels.

Residential drainage system panelization

To facilitate the shipping of an integrated package to the construction site, the PRBD system needs to be separated into smaller components. The decomposition process aims at cutting the PRBD system into panel sizes in order to load and ship with panels. The main process of a planning method for PRBD system panelization is illustrated in the flowchart shown in Figure 2. 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 PRBD system which passes through the panels, and the establishment process is illustrated in Figure 3. 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 PRBD 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.

This planning algorithm is developed to automatically panelize PRBD system 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 labeled with the panel name in order to be filtered and to generate the BOM for each panel.

An integer programming approach for pipe cutting optimization

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 CSP is to minimize the total waste, minimize the costs of the used objects, and maximize the profit. According to the dimensionality of the cutting, CSP is classified as one-dimensional (1 D), two-dimensional (2 D), and three-dimensional (3 D) problems. In the present research, cutting pipes belongs to a 1 D problem. The 1 D problem addresses the issue of cutting the standard-length stock to fit the required length in a project to minimize the total cutting waste. Linear programming (LP) has been commonly adopted for solving the CSP, for instance, (Gilmore and Gomory 1961; Dyckhoff 1981; Salem et al. 2007; Zheng et al. 2019). The 1 D-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

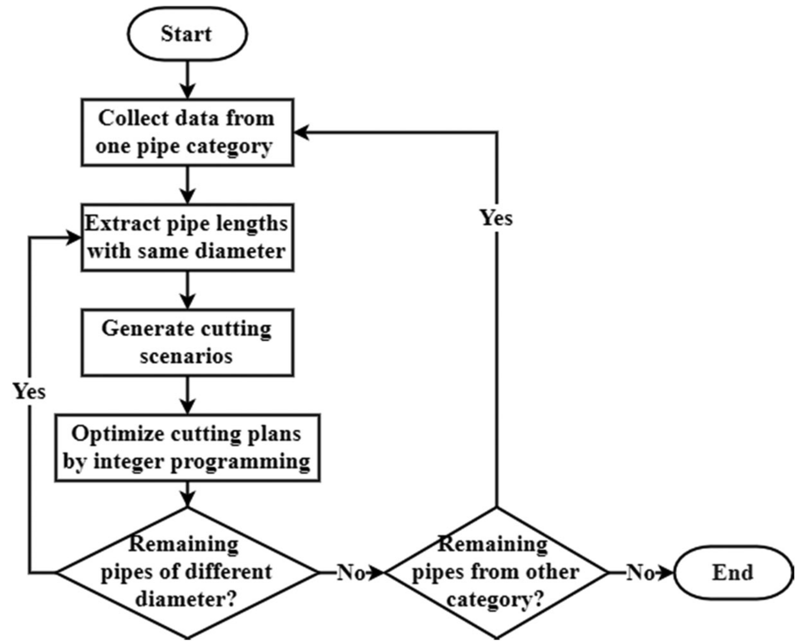


Figure 4. Cutting optimization process.

most cases, framed and produced in two respective manufacturing facilities. The pipe cutting optimization algorithm is applied to both 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 (IP) algorithm (Mogollon 2009) can be used to solve the 1 D-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 4.

The generation of cutting scenarios is an exhaustive search using a tree structure, as shown in Figure 5. 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 Equation (5).

$$L_n = L_s - \sum_{i=1}^{n} n_i l_i \tag{5}$$

where n_i represents the number of instances of length l_i.

Thus, the corresponding waste, w_h, in the 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 Equation (6).

$$w_h = L_k = L_s - \sum_{i=1}^{k} n_i l_i \tag{6}$$

Once all possible cutting scenarios (or patterns) has been generated along with corresponding wastes (w_i), an objective function is created in Equation (7) to minimize the total waste of cutting one size of pipe stocks. The optimal result is obtained by searching for a global minimum point.

$$\min \sum_{i=1}^{N} N_i w_i = \sum_{i=1}^{N} \left[N_i \times \left(L_s - \sum_{i=1}^{k} n_i l_i \right) \right] \tag{7}$$

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 the stock pipe by satisfying Equation (8).

$$\sum_{i=1}^{k} n_i l_i \leq L_s \tag{8}$$

Development of BIM-based automated design system

To prove the feasibility of the proposed methodology, a prototype system for automatically designing the PRBD system is developed and implemented in Autodesk Revit using Revit API in C# programming language.

Figure 6 illustrates the data flow between the user and the prototype system. The name of the PRBD system and the locations of the 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 6. 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 PRBD system is finished because there are no fixtures remaining.

To realize the panelization for drainage and vent pipe networks, two-generation processes (i.e., the generation of drainage pipe to soil-or-waste stack and the generation of the vent pipe to the main vent stack) are included. In the case of both these two generation processes, the pipe is cut at the framed panel edge.

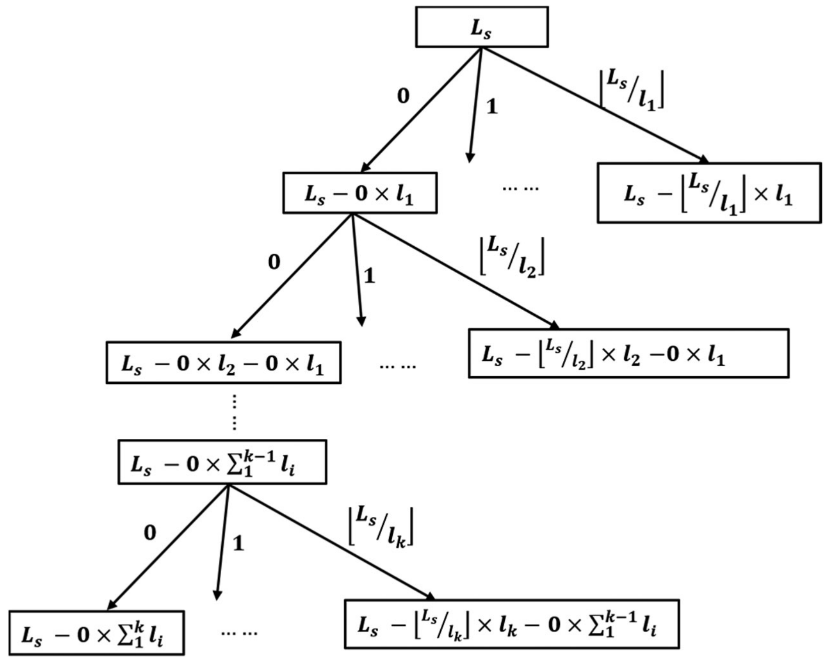


Figure 5. Tree structure for generating possible cutting scenarios.

Thus, checking for the cutting location is a key step included in the prototype system.

To build the prototype for the drainage automated design system, the algorithms are encoded according to the functions shown in Figure 7. The design rules 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 7. 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 (the smallest and most basic item in the PRBD system, such as elbows, pipes, and valves) 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 7, 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.

Vent pipe design

Any PRBD 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 are determined based on the given scenario and architectural design layout, are shown in Table 1 (Zhang et al. 2020). These design options must all be compliant with the plumbing code (NPC 2015).

The design style of the vent pipe is defined by the user and floor plan layout. The three options mentioned above are listed in a Windows Form of the prototype system, which is the interface shown in Figure 8. Before selecting the vent design scenario, a new PRBD 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 PRBD 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 8, including one vent for one fixture, only one vent for all fixtures, and a sink vent for all fixtures. 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.

Optimal drainage pipe route design

To validate the algorithms presented in *A Heuristic approach for pipe route optimization* section for rule-based drainage pipe design, the prototype system involves the Windows Form shown in Figure 9 to collect and save the inputs. The trap location is used as the start point for the pipe route design, and the locations of the vent stack and soil-or-waste stack are the endpoint. Also, the pipe from plumbing fixture to vent stack and soil-or-waste stack should be subjected to the slope of the pipe according to plumbing code (NPC 2015). Another design rule which is

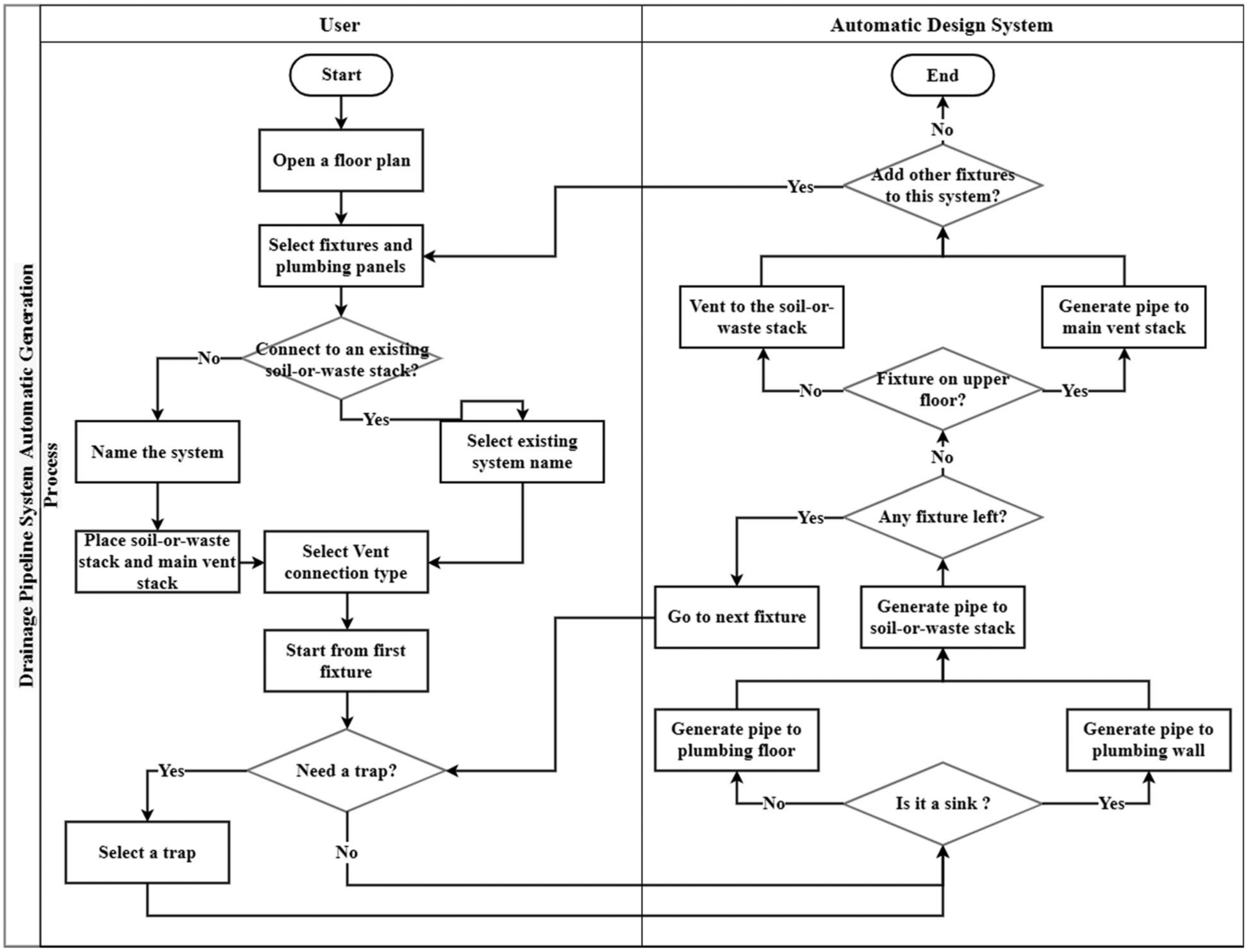


Figure 6. Cross-functional flowchart of the automated design system.

considered when generating pipe routes through wall stud and floor joist is about the location of cut-out hole for passing the pipe. The distance between the hole and the closest edge of the framing member should meet the threshold values specified in the building code (NBC 2015). These design rules based on NPC and NBC are checked when generating drainage pipe routes using the heuristic pathfinding algorithm.

In the dialog box of Figure 9, four user-defined parameters are entered for each fixture that is selected by its fixture name, and the corresponding 3 D 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. Furthermore, the parameters extracted from wall panels and floor panels are also shown in the tables of Windows Form shown in Figure 9. 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 pseudocode of the heuristic pathfinding algorithm for optimizing the drainage pipe route is shown in Figure 10.

Residential drainage system panelization with shop drawings

This section introduces the implementation of the method that automatically separates the PRBD 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 PRBD 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 BOM is shown in the shop drawings for a framed panel. Figure 11 shows three types of PRBD system shop drawings, which are plumbing layout drawing, plumbing floor panel shop drawing, and plumbing wall panel shop drawing, generated in Revit.

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 PRBD system model will be automatically reflected in the 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 the VB language in Microsoft Excel.

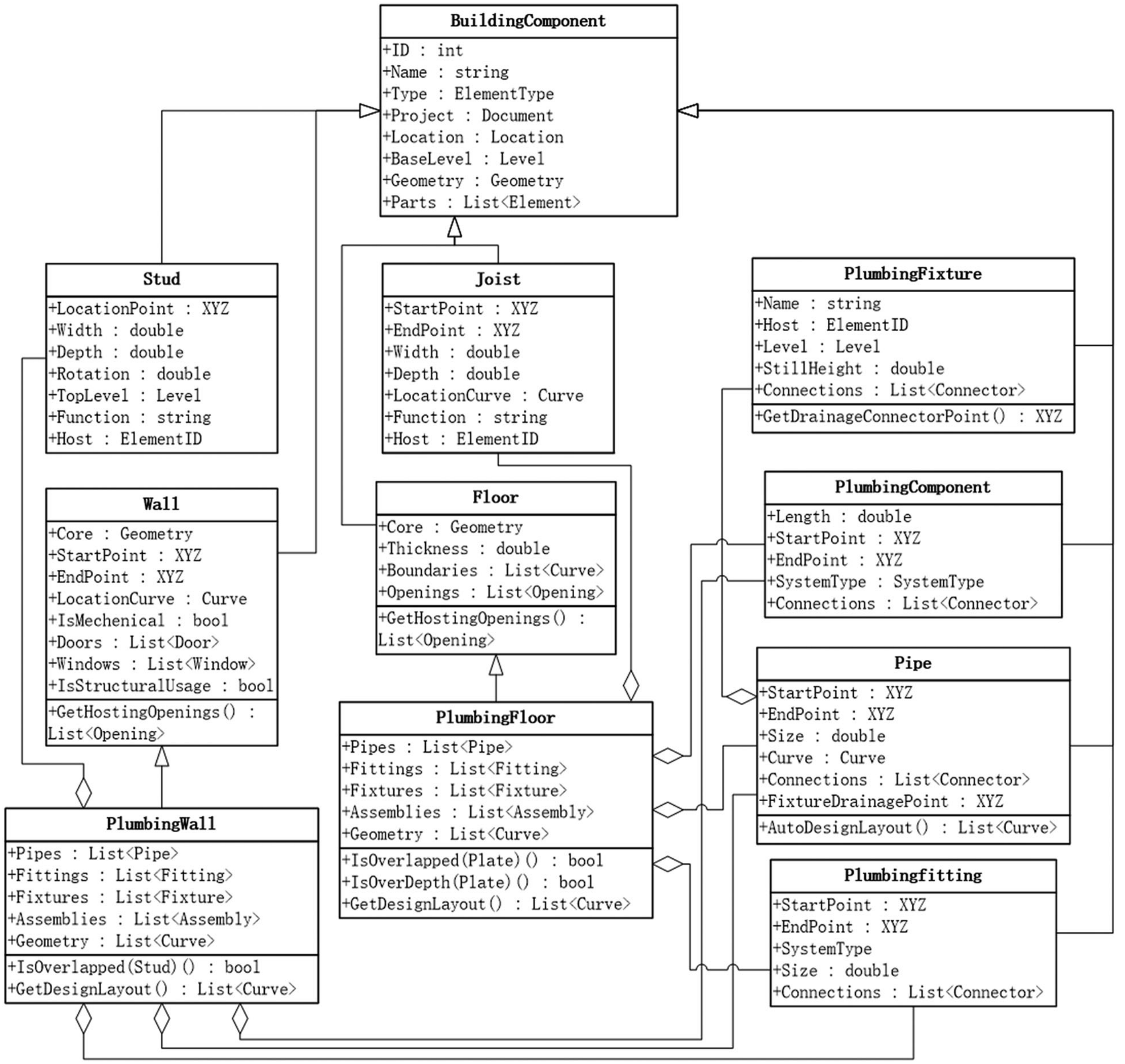
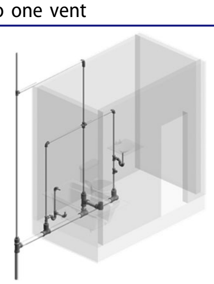
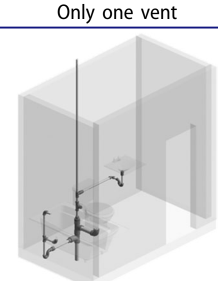
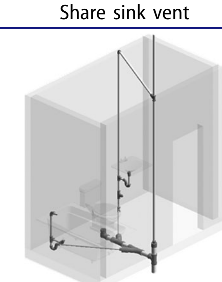


Figure 7. Excerpt of BIM information for PRBD system design using UML.

Table 1. 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.

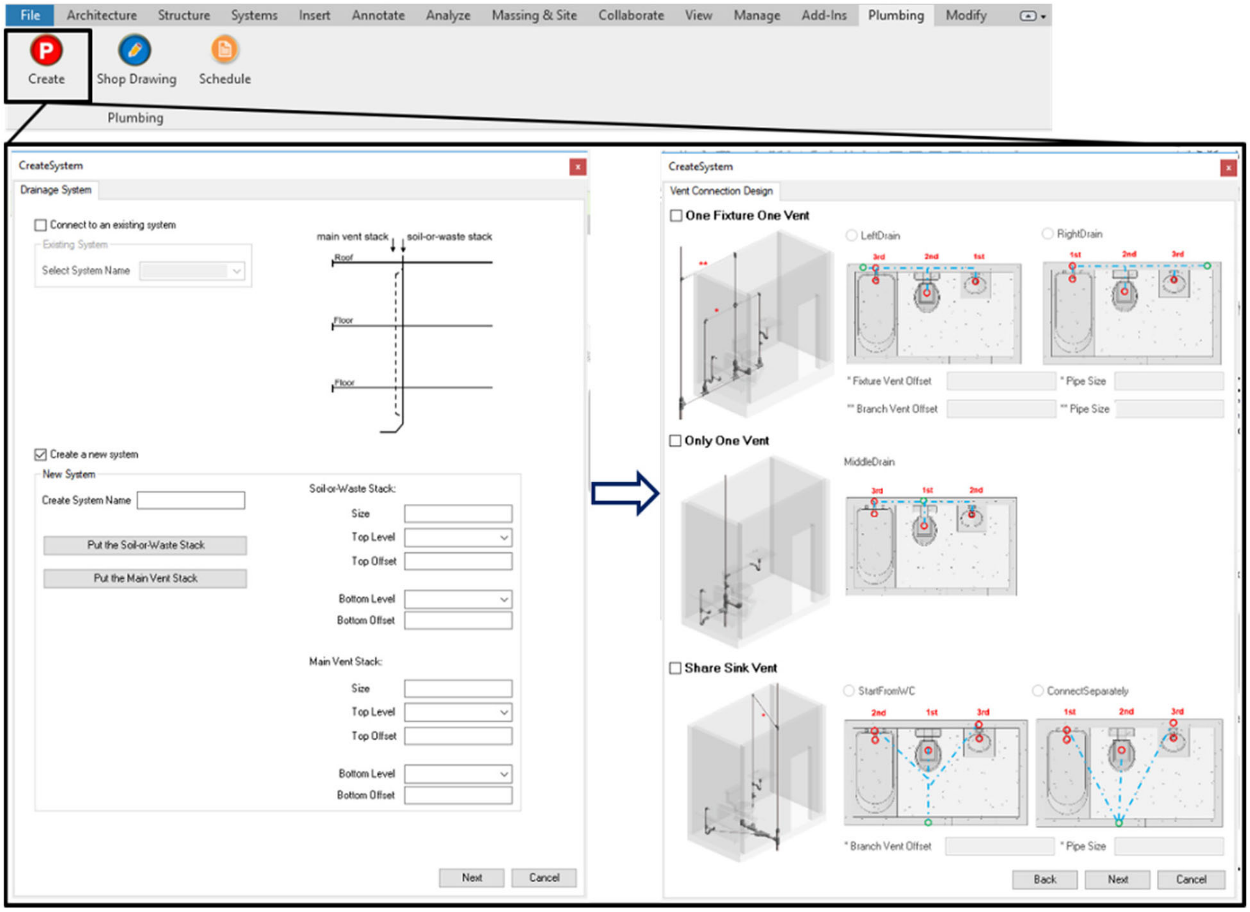


Figure 8. The graphic user interface of vent pipe design.

The BOM for generating cutting patterns is classified according to the type of plumbing panels, i.e., plumbing wall panel and plumbing floor panel, and the number of working stations. Each classification can be filtered and saved as a small database including the list of lengths of required pipes with the same size and same type at one working station. Then, the pipe cutting plan is optimized by the integer programming algorithm shown in Figure 12. The outputs of this optimization are cutting patterns and minimum total material waste.

Case study

To validate the proposed methodology and verify the prototype system, a case study is presented to demonstrate how the drainage pipe network design is automatically generated and optimized, how the pipe network is panelized, and how the drawings and optimal cutting patterns are developed. The 3 D BIM model is generated based on the traditional 2 D design drawings from a panelized construction manufacturing facility, which is a two-story townhouse with five identical units. Figure 13 shows the 3 D view of the case study model and one framed unit sample. The LOD of this model used for the case study is LOD 300 as required. 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. As the floor plans in Figure 14 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.

In addition to the 3 D architecture and structure model, information regarding pipe fittings is also loaded in Revit and 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. The models of combo fittings are developed and saved in an independent RVT. file that can be linked to the BIM model. In the present research, the plumbing-system-related families including the normal pipe fittings and the combo fittings are loaded to the case study model. Next, there is a preference setting to control the priority of fittings used in a project. 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.

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

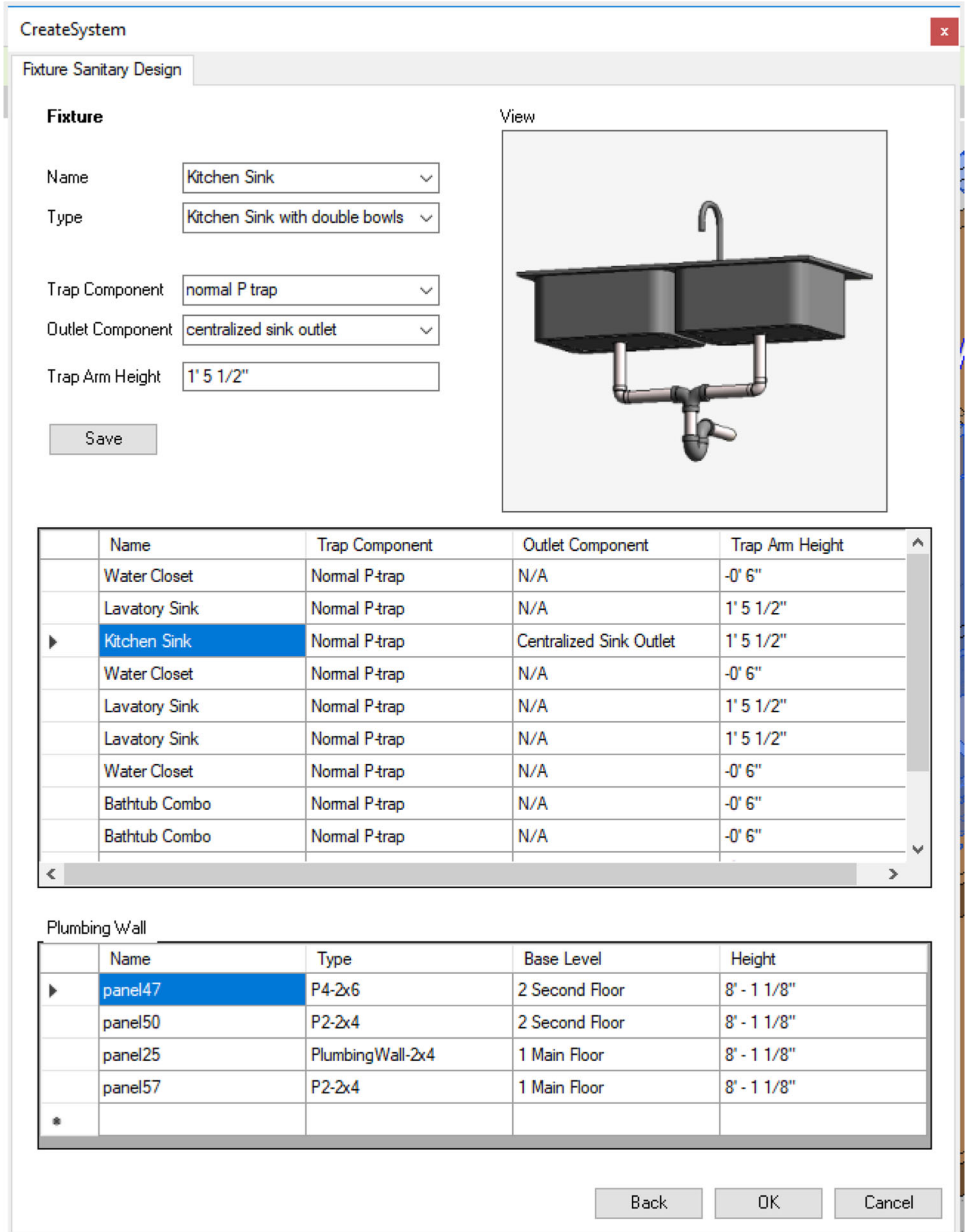


Figure 9. Windows Form for fixture drainage pipe design.

Vent" option in the Revit add-on, as shown in Figure 15. 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 connects to the main vent stack automatically.

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 16.

Panelized drainage system

The whole PRBD system in one unit building is decomposed into seven panels as shown in Figure 17, including three plumbing wall panels and four plumbing floor panels. Once the shop drawings have been generated, the information contained in the corresponding BOM for pipes (i.e., drainage pipes and vent pipes) is exported from Revit to Microsoft Excel Spreadsheet.

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

Optimal cutting pattern generation

In this case study, the BOM for pipes is classified according to the pipe size and corresponding panel type, since the pipe

Algorithm: 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
```

Figure 10. Pseudocode of heuristic pathfinding algorithm.

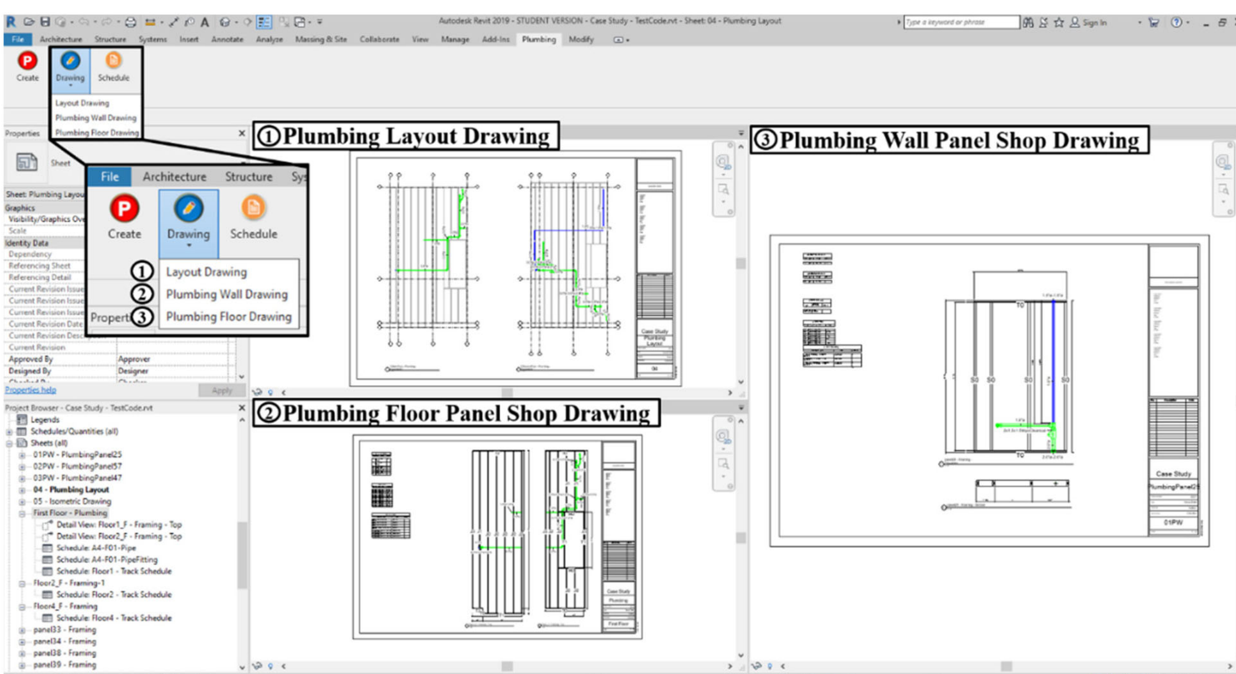


Figure 11. Shop drawings generation for PRBD system in Revit.

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 PRBD 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 2.

In each BOM list, pipes with the same length are combined and summed up as shown in Figure 18(a). The cutting pattern is generated as a matrix list. For instance, as shown in Figure 18(b), the configuration [2,0,1,5,0,4,0,0,3] illustrates the scenario

Algorithm: Integer Programming Algorithm

Input: $\mathbf{L_s}$– length of stock pipe, $\boldsymbol{R_l}\{\}$– a list of length $\boldsymbol{l_i}$ of desired pipes, $\boldsymbol{R_n}\{\}$– a list of number $\boldsymbol{n_{ri}}$ of desired pipes

Output: Cutting pattens $\boldsymbol{C_k}\{\}$, total material waste $\boldsymbol{W_k}$

Begin

Create a list $C_1\{\}$ as a cutting scenario

$R_l \times C_1 \leq L_s$

Set material waste $w_1 = L_s - R_l \times C_1$

Generate all possible cutting scenarios $C_1\{\}, C_2\{\} \ldots C_n\{\}$

Calculate material waste $w_1, w_2 \ldots w_n$

Set scenario matrix $M_c\{\} = \{C_1\{\}, C_2\{\} \ldots C_n\{\}\}$

Create a list $N_1\{\}$ showing the number of each scenario

$M_c \times N_1 = R_n$

Set total material waste $W_1 = N_1 \times \{w_1, w_2 \ldots w_n\}$

Calculate all possible scenario numbers $N_1\{\}, N_2\{\} \ldots N_m\{\}$

Calculate total material waste $W_1, W_2 \ldots W_m$

Select the scenario number $N_k\{\}$ with minimum total material waste W_k

Set cutting patterns $C_k = M_c$ with scenario number $N_k\{\}$

End

Figure 12. Pseudocode of integer programming algorithm.

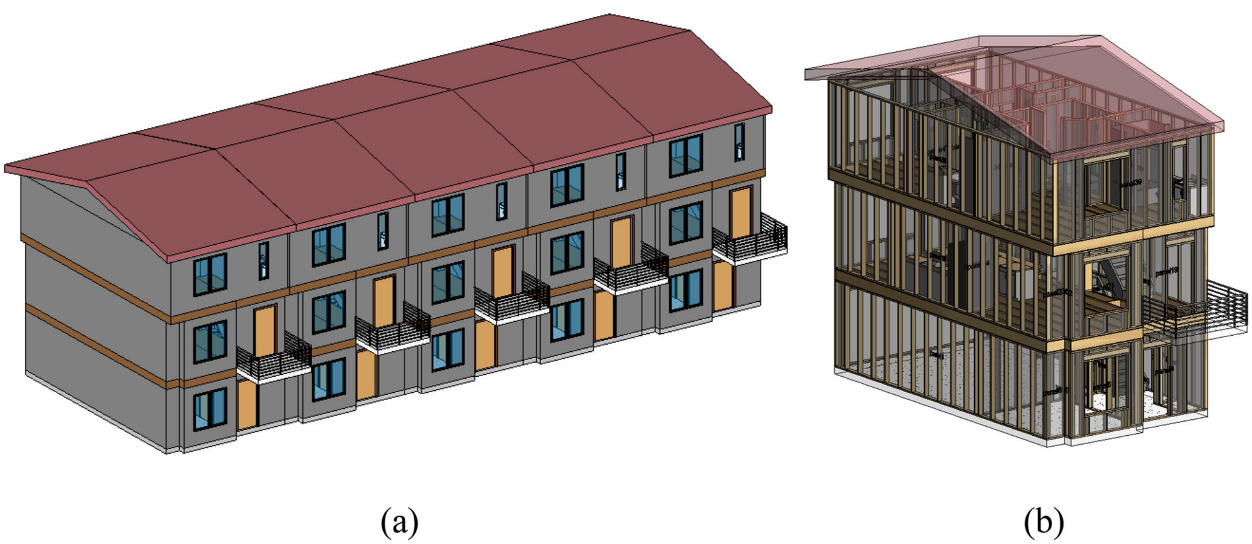


Figure 13. (a) 3 D view of the case study model, and (b) one framed unit sample.

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.

After applying the IP algorithm for pipe cutting optimization, the cutting patterns and respective quantities and waste can be generated. The total waste is calculated for each size of pipe for each type of panel listed in Table 3.

Table 4 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). The total percentages of $W_{IP}\%$ and $W_{ps}\%$ for all panels is calculated by dividing the total length of waste of all panels by the total length of used stock pipes. Overall, the total waste calculated by the IP algorithm is 13.02% which is smaller than the total waste of cutting pipes by production sequence in this case study.

Conclusion

This research has proposed a framework of an automated design system for the PRBD system with the integration of a rule-based pipe route planning approach and optimal cutting stock algorithm to improve the accuracy and efficiency of the design process. First, this research automates the design and modelling of a PRBD 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 the total

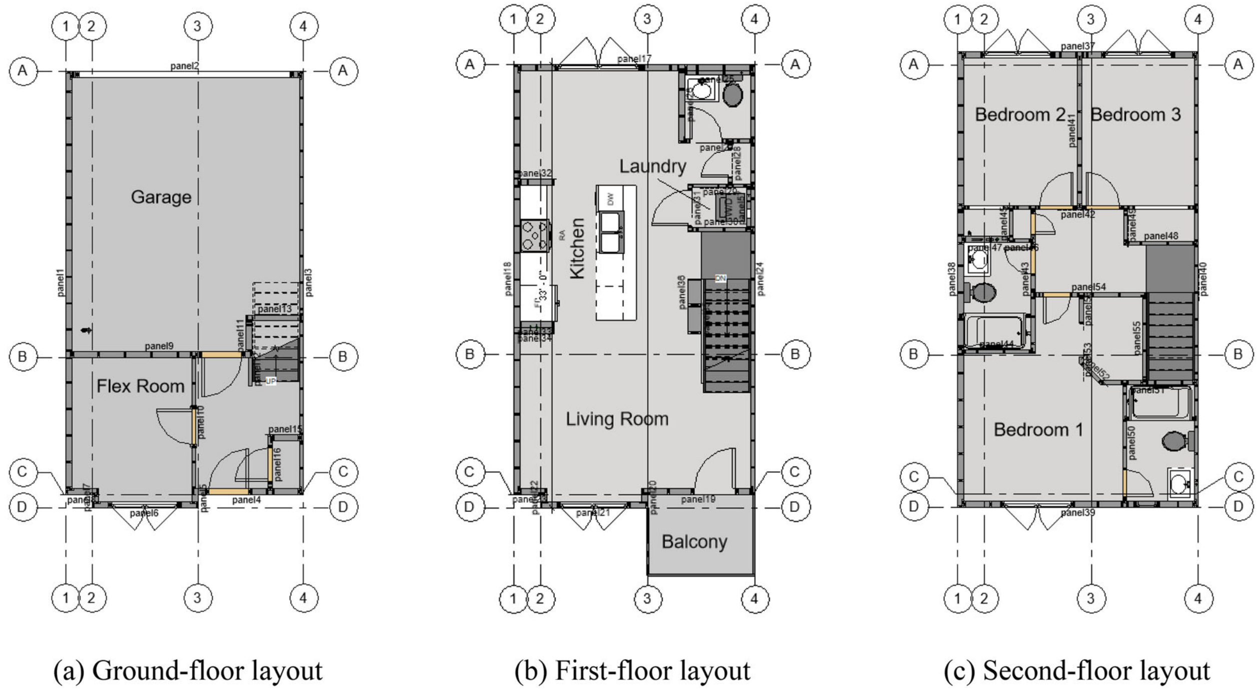


Figure 14. Sample model of floor layouts in one unit building.
(a) Ground-floor layout.
(b) First-floor layout.
(c) Second-floor layout.

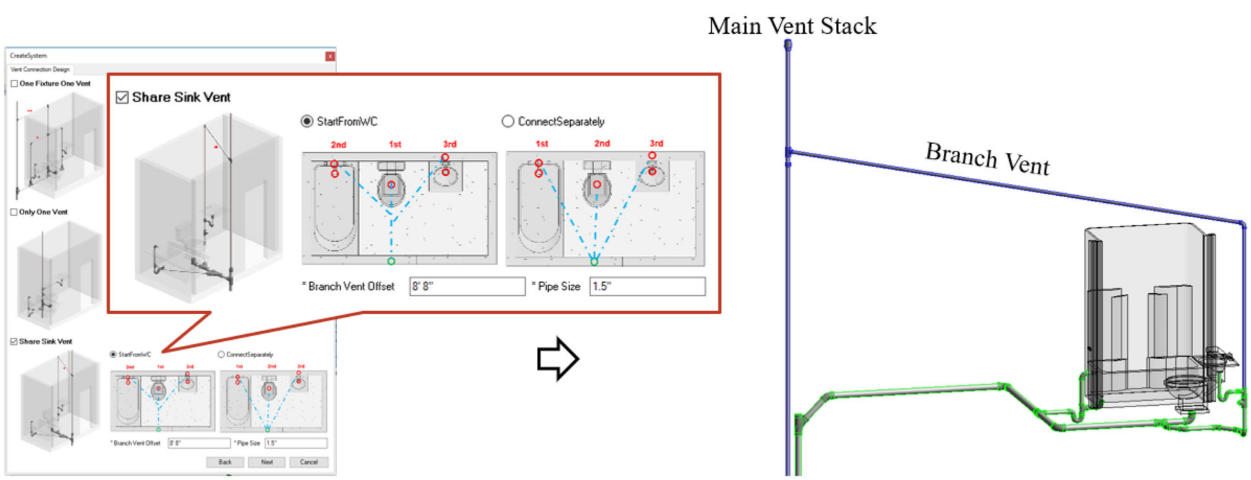


Figure 15. Vent pipe design example for a bathroom on the second floor.

pipe length. The developed prototype of the design application showcase the useability of the proposed method. The case study shows that the proposed method can generate an optimized pipe route design that reduces material waste.

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 PRBD system design improves its accuracy and efficiency by taking advantage of rich building information in the BIM 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 PRBD system design. 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) Optimization of generating cutting patterns allows the pipes to be cut to the desired length from the standard stock pipe with waste minimization. An integer programming algorithm is developed to solve the one-dimensional cutting stock problem. (3) Development of prototype system under Autodesk Revit platform realizes three main functions, including automated design of PRBD 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.

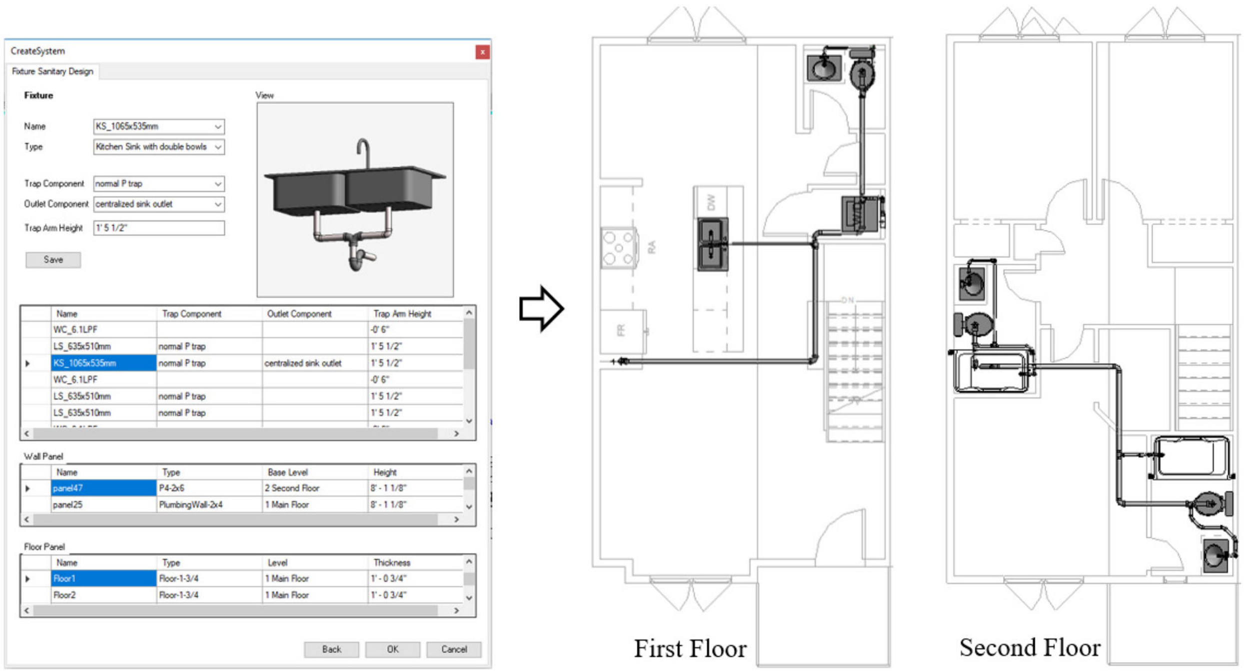


Figure 16. Drainage pipe generation.

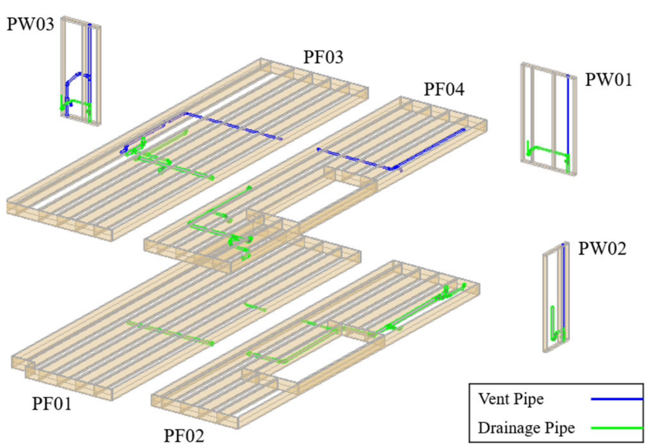


Figure 17. Panelized PRBD system for one unit building.

Table 2. BOM for pipes in one townhouse unit.

BOM for pipes in wall panels			
Size (in)	Panel#	Length (in)	Length (mm)
1.5	PW01	2.00	50.80
1.5	PW01	31.63	803.28
…	…	…	…
2	PW01	1.88	47.63
2	PW01	8.50	215.90
…	…	…	…
BOM for pipes in first-floor panels			
Size (in)	Panel#	Length (in)	Length (mm)
1.5	PF01	22.00	558.80
1.5	PF02	40.00	1016.00
…	…	…	…
2	PF02	1.63	41.28
2	PF02	20.88	530.23
…	…	…	…
3	PF01	94.13	2390.78
3	PF02	78.88	2003.43
…	…	…	…
BOM for pipes in second-floor panels			
Size (in)	Panel#	Length (in)	Length (mm)
1.5	PF03	106.88	2714.63
1.5	PF03	23.13	587.38
…	…	…	…
2	PF03	4.13	104.78
2	PF03	1.75	44.45
…	…	…	…
3	PF03	4.63	117.48
3	PF03	8.13	206.38
…	…	…	…

The proposed prototype is not ready for commercial use since more testing and improvements are still needed to better integrate the tool into the daily workflow of practitioners. In order to improve the performance of the proposed methodology and prototype system, the following directions can be pursued in the future: (1) 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 of drainage system design from multiple regions and countries should be involved in the future. (2) 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. (3) This research focuses only on automated design for the PRBD 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.

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Disclosure statement

No potential conflict of interest was reported by the authors.

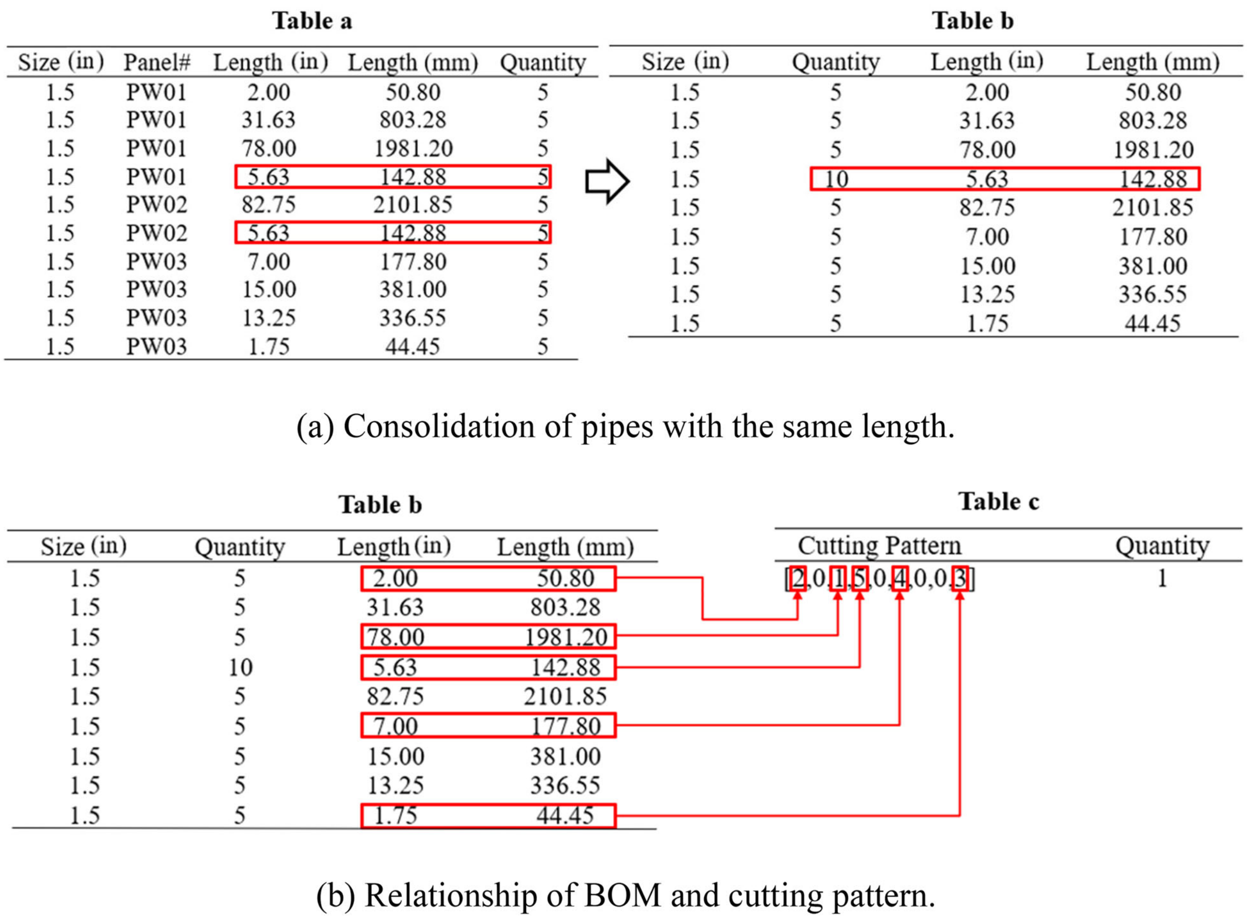

Table a

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 BOM and cutting pattern.

Figure 18. Example of generating a cutting pattern.
(a) Consolidation of pipes with the same length.
(b) Relationship of BOM and cutting pattern.

Table 3. 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. 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%

Data availability statement

All data generated or analyzed during the study are available from the corresponding author by request.

References

Abdel-Hamid M, Abdelhaleem HM. 2021. Project cost control using five dimensions building information modelling. Intern J Construct Manage. 1–10. 15623599.2021.1880313.

[AIA] American Institute of Architects. 2013. Guide, instructions and commentary to the 2013 AIA digital practice documents. American Institute of Architects (AIA). https://www.aiacontracts.org/resources/69541-guide-instructions-and-commentary-to-the-2013-aiadigital-practice-documents.

Bosch-Sijtsema P, Gluch P. 2021. Challenging construction project management institutions: the role and agency of BIM actors. Intern J Construct Manage. 21(11):1077–1087.

Burdorf A, Kampczyk B, Lederhose M, Schmidt-Traub H. 2004. CAPD—computer-aided plant design. Comp Chem Eng. 28(1–2):73–81.

Dijkstra EW. 1959. A note on two problems in connexion with graphs. Numer Math. 1(1):269–271.

Dyckhoff H. 1981. A new linear programming approach to the cutting stock problem. Oper Res. 29(6):1092–1104. 10.1287/opre.29.6.1092

Gilmore PC, Gomory RE. 1961. A linear programming approach to the cutting-stock problem. Oper Res. 9(6):849–859.

Hart PE, Nilsson NJ, Raphael B. 1968. A formal basis for the heuristic determination of minimum cost paths. IEEE Trans Syst Sci Cyber. 4(2): 100–107.

Ito T. 1999. A genetic algorithm approach to piping route path planning. J Intelligent Manufacturing. 10(1):103–114.

Khanzadi M, Sheikhkhoshkar M, Banihashemi S. 2020. BIM applications toward key performance indicators of construction projects in Iran. Intern J Construct Manage. 20(4):305–320.

Lavikka RH, Chauhan K, Peltokorpi A, Seppanen O. 2018. Fostering prefabrication in construction projects-case MEP in Finland. In: J. Karlshoj, R. Scherer, editors. 12th European Conference on Product and Process Modelling (ECPPM). Copenhagen: Denmark; p. 273–280.

Li X, Li Z, Wu G. 2017. Modular and offsite construction of piping: Current barriers and route. Appl Sci. 7(6):547.

Li Z, Shen GQ, Xue X. 2014, Jul 1. Critical review of the research on the management of prefabricated construction. Habitat Intern. 43:240–249.
Mogollon JD. 2009. Automation of Design and Drafting for Wood Frame Structures and Construction Waste Minimization [Unpublished doctoral dissertation]. Edmonton (AB), Canada: University of Alberta.
NBC. 2015. National Building Code of Canada. Canadian commission on building and fire code. Ottawa: National Research Council of Canada.
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. ICAITA. 127
NPC. 2015. National Plumbing Code of Canada. Canadian commission on building and fire codes. Ottawa: National Research Council of Canada.
Park J, Storch R. 2002. Pipe-routing algorithm development: case study of a ship engine room design. Expert Syst Appl. 23(3):299–309.
Prefab Housing Canada. 2018. Prefab housing Canada. Retrieved from https://prefabhousing.ca/.
Salem O, Shahin A, Khalifa Y. 2007. Minimizing cutting wastes of reinforcement steel bars using genetic algorithms and integer programming models. J Constr Eng Manage. 133(12):982–992.
Samarasinghe T, Gunawardena T, Mendis P, Sofi M, Aye L. 2019. Dependency Structure Matrix and Hierarchical Clustering based algorithm for optimum module identification in MEP systems. Autom Constr. 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. Adv Eng Inf. 16(4):291–303.
Tam VW, Hao JJ. 2014. Prefabrication as a mean of minimizing construction waste on site. Intern J Construct Manage. 14(2):113–121.
Tserng HP, Yin YL, Jaselskis EJ, Hung WC, Lin YC. 2011. Modularization and assembly algorithm for efficient MEP construction. Autom Constr. (20(7):837–863.
Wang J, Wang X, Shou W, Chong H-Y, Guo J. 2016. Building information modeling-based integration of MEP layout designs and constructability. Autom Constr. 61:134–146.
Wang M, Altaf MS, Al-Hussein M, Ma Y. 2020. Framework for an IoT-based shop floor material management system for panelized homebuilding. Intern J Construct Manage. 20(2):130–145.
Weygant RS. 2011. BIM content development: Standards, strategies, and best practices. New York: John Wiley & Sons.
Yin X, Liu H, Chen Y, Al-Hussein M. 2019. Building information modelling for off-site construction: Review and future directions. Autom Constr. 101(2019):72–91.
Yin YH, Xu LD, Bi Z, Chen H, Zhou C. 2013. A novel human-machine collaborative interface for aero-engine pipe routing. IEEE Trans Ind Inf. 9(4): 2187–2199.
Zhang N, Tian Y, Wang J, Al-Hussein M. 2020. BIM-based automated drainage system design in prefabrication construction. Construction Research Congress 2020: Computer Applications. Reston, VA: American Society of Civil Engineers; p. 1146–1155.
Zheng C, Yi C, Lu M. 2019. Integrated optimization of rebar detailing design and installation planning for waste reduction and productivity improvement. Autom Constr. 101:32–47.