Development of Auto Route System for MEP (Mechanical, Electrical and Plumbing) Pipe Design in Construction

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Abstract – This study introduces a novel framework for optimizing material costs and construction efficiency in MEP (Mechanical, Electrical, and Plumbing) automatic routing design. Through a detailed literature review, the study identified key limitations in existing MEP auto routing systems, including insufficient consideration of material cost reduction, inefficiencies in handling complex installation steps, and the inability to manage additional costs related to the number and angles of bends and diverse material selections. The proposed framework addresses these challenges through five main stages: integration of physical and spatial data for accurate initial design, application of optimization algorithms such as A* and Genetic Algorithm (GA) to minimize total path length and bends, material cost evaluation to refine routes in cases of excessive material usage, construction feasibility analysis to ensure practical viability, and VR/AR-based simulations to identify and resolve potential construction issues. This comprehensive framework systematically reduces material waste, improves construction workflows, and enhances overall efficiency in MEP design. Future research aims to integrate machine learning and real-time adaptive technologies to further advance the adaptability and sustainability of MEP auto routing systems, meeting the demands of increasingly dynamic construction environments.

Keywords – MEP design; Optimized design; Auto Routing;

1 Introduction

MEP systems are essential for transporting fluids, electricity, and other utilities from storage to required locations in various structures, such as buildings and plants [1]. These systems provide fundamental functions, including heating, ventilation, air conditioning, lighting, water supply, and fire protection, ensuring the usability and safety of buildings [2]. Efficient MEP design goes beyond mere system installation, playing a crucial role in reducing energy consumption, optimizing operational costs, and enhancing the sustainability of buildings [3]. In particular, the complex interactions of various components in modern construction environments necessitate high levels of accuracy and efficiency in MEP design [4]. However, traditional design methods have shown limitations in managing this complexity [5].

Although automated MEP design has been introduced to address these challenges, existing solutions still face significant limitations, such as suboptimal routing, high computational demands, and difficulties in integrating real-world constraints. Among the various components of MEP systems, this study focuses specifically on MEP piping design, which plays a critical role in fluid transportation, including water supply, drainage, Heating, Ventilating, Air Conditioning (HVAC) piping. The intricate layout and routing of pipes demand high precision to avoid clashes with other building elements, optimize material usage, and ensure efficient installation. Thus, understanding the current state of automated piping design and its limitations is essential for further advancements in this field.

Traditional approaches to MEP design often require significant time and cost while being prone to errors during the design stage, which can lead to critical issues during construction [6]. To overcome these challenges, the automation of MEP design has garnered considerable attention as it addresses key design problems and meets the demands for high quality and productivity in modern construction [7]. Automated design systems can effectively process complex data, minimize design errors, and significantly improve overall project efficiency [8]. Automated piping design has gained attention due to its potential to optimize routing, detect clashes, and improve constructability by integrating computational design and artificial intelligence-based solutions. However, despite these advancements, automated piping design still faces challenges in adapting to real-world constraints, such as spatial limitations, material considerations, and construction feasibility. Addressing these issues is crucial for enhancing the effectiveness and practicality of automated MEP piping design systems. Therefore, this study aims to analyze the current technologies in automated MEP piping design and propose methods to address their limitations.

2 Literature Review on Optimized Auto Routing Systems for MEP Design

2.1 Space and Route Modeling

Space modeling serves as the foundation for representing design objectives and constraints in a structured, executable format. While a continuous representation method is ideal for capturing all potential MEP routing options, many automated MEP studies have opted for discretization techniques [9]. Discretization involves converting continuous variables into discrete elements or defining specific points through which MEP pipes can pass, effectively shaping the design space [10]. A widely used approach to achieve this is through graph-based methods, with grid graphs being a prominent example [11]. These graphs segment the space into uniform cells, each represented as a node, thereby transforming the design environment into a structured graph [12]. By constraining pipe bending angles to 90 degrees, grid graphs facilitate easier objective modeling, such as determining the shortest path between two points or avoiding obstacles. This approach simplifies intricate space modeling challenges and is frequently applied in practical design processes.

MEP space and path modeling focuses on finding a balance between the complexity of the problem to be solved and the quality of the design. One way to simplify complex mathematical problems is by using the Manhattan distance metric [13]. The Manhattan distance method restricts paths to orthogonal forms, preventing pressure losses caused by sharp bends and facilitating parallel path modeling, making installation tasks more efficient [14]. This approach is commonly used in actual plant design. However, some studies adopt a continuous approach that utilizes all points within space. Both the discrete and continuous approaches have their respective advantages and disadvantages, and the appropriate method is chosen depending on the design environment.

2.1.1 Discretization Method

Graph-based methods abstract free space into graph forms to define paths, representing them using vertices and edges. These methods are implemented in various ways depending on how space is represented and can be broadly categorized into two main approaches: cell decomposition and skeletonization. The cell decomposition method divides free space into multiple non-overlapping cells. This approach associated vertices with regions rather than specific points, thereby opening multiple path finding possibilities instead of providing precise paths. Consequently, it is particularly useful in scenarios where path flexibility is essential. In contrast, the skeletonization method associated the vertices of a graph with specific points in space, while edges represent continuous lines connecting these points. This method can define more precise paths but offers relatively limited path finding possibilities. The cell decomposition and skeletonization approaches are closely related, as all edges of a cell decomposition graph can be converted into paths to generate a skeletonization graph. In this sense, the cell decomposition approach is considered a generalization of the skeletonization approach.

Major cell decomposition methods include uniform grids [11], quadtree and octree [15], non-uniform grids [16], trapezoidal decomposition, Delaunay triangulation, and minimal orthogonal decomposition. Uniform grids use fixed cell widths and enforce orthogonal routing, often associated with the diameter of the smallest pipe to be routed. Quadtree and octree refine cells further as obstacle detail increases. Non-uniform grids generate graphs by drawing orthogonal lines from obstacle points to the boundaries of the routing space. Trapezoidal decomposition constructs graphs by drawing horizontal or vertical lines from obstacle edges. Delaunay triangulation divides free space into triangles, while minimal orthogonal decomposition aims to minimize the number of cells or edge lengths.

Key implementations of the skeletonization method include Hanan grids, escape graphs [17], visibility graphs, and generalized Voronoi diagrams [18]. Hanan grids are generated based on obstacle points in non-uniform grids. Escape graphs, instead of drawing lines to the boundaries, connect obstacle points to the first obstacle encountered. Visibility graphs represent the shortest paths in spaces with polygonal obstacles, while Voronoi diagrams connect the midpoints between obstacles, defining regions of free space closest to each obstacle.

2.1.2 Continuous Method

In addition to graph-based discrete approaches, finding an unrestricted pipe path requires continuous specifications for both the space and the path. In continuous MEP path searching, it suffices to model only obstacles and boundaries for collision detection [19]. Such continuous paths consist of straight MEP segments and bends, where each bend is represented by an angle, and each segment is represented by a length. The degree to which these two attributes can be selected continuously determines the concepts of length continuity and bend continuity [20]. In other words, a length-continuous MEP path search allows the length of each straight pipe segment to be chosen freely, while a bend-continuous MEP path search allows the bend angle to be set without restriction [21].

Because graph-based methods adhere to length-discrete and bend-discrete approaches, both the usable segment lengths and bend angles are confined to a predetermined, discrete set of possibilities. However, the MEP path searching literature discusses a wider range of continuous properties, and in practice, restricting the shape of bends (among other factors) can further constrain the path's feasibility. Studies that integrate both continuous length and bend angle typically generate a path by placing bend points continuously, then connecting each pair of bend points with a straight pipe. In such methods, the primary variables to optimize are the number and location of bends, while collision detection and other constraints are handled through models of the pipe's diameter or centerline.

2.2 Objective and Constraint Modeling

An objective is a scalar goal defined explicitly for optimization, assessed as a function of the decision variables. A constraint represents a condition that limits the range of possible values for these decision variables. Decision variables consist of a set of configuration parameters that accurately define all MEP paths. The aim in an MEP path finding problem is to identify a set of decision variables that meets all constraints while optimizing the objectives to an acceptable level. Given that MEP multi path finding problems are generally integer-based and highly nonlinear, even small adjustments to the decision variables can substantially affect the quality or feasibility of a particular design. Therefore, whenever objectives or constraints change, it is necessary to carefully analyze the problem's characteristics and requirements and reorganize the relevant information accordingly. Chapter 2.2 describes how various algorithms leverage the information structures of these objectives and constraints to achieve optimization.

2.2.1 Physical Constraints

In research on automated MEP pipe design, physical constraints are implemented to ensure that decision variables do not lead to physically infeasible piping layouts. These constraints are typically categorized into collision avoidance and MEP pipe specification constraints. In terms of collision avoidance, a common approach involves expanding obstacles based on the diameter of MEP pipes. For instance, additional flange specifications may be incorporated into the pipe diameter to prevent collisions with other objects, or temporary obstacle grid cells can be introduced to dynamically accommodate varying pipe diameters during routing processes. While collision avoidance is fundamentally essential, some optimization approaches temporarily allow collisions to prevent the solution from becoming trapped in local optima. Additionally, MEP systems can be routed sequentially, treating already installed components as obstacles. However, this sequential approach increases the complexity of optimization and necessitates additional resource considerations.

Meanwhile, typical MEP pipe specification constraints include routing pipes orthogonally and sometimes imposing a minimum length on the straight pipe segments between bends. Because these minimum length restrictions often reflect real-world regulations, they must be carefully considered during implementation. Moreover, to account for the orientation of MEP pipe nozzles, some cases involve extending nozzles that originate from obstacles of a certain length, thus proposing a piping approach suitable for real design situations.

2.2.2 Maintenance Constraints

Maintenance constraints are conditions established to exclude any design states that could negatively impact maintenance procedures. They can be broadly divided into stability and reliability, and accessibility and necessity. To ensure stability and reliability, supports are often utilized, or MEP pipes are attached at right angles to floors or walls to reduce continuous stress. Meanwhile, accessibility and necessity constraints focus on streamlining maintenance by designating frequently serviced areas or equipment vicinities as virtual obstacles preventing pipes from passing through these zones or routing frequently serviced MEP pipes along easily accessible exteriors.

2.2.3 Material Cost Objective

Material objectives focus on minimizing the direct cost of MEP pipes. In the simplest case, the total length of MEP pipes may be used as a basis for estimating material costs, but in practice, additional variables such as pipe diameter can be highly significant. Although diameters can be modeled as continuous variables, suppliers typically maintain only a finite set of diameters, leading many to treat diameter as a discrete variable. However, using such a discrete set can increase the complexity of optimization. Meanwhile, although the number and angles of MEP pipe bends could also be factored into material costs at the time of purchase, the MEP automation design literature often assumes that pipe bends are fabricated rather than supplied, and thus primarily classifies them as construction costs.

2.2.4 Construction Objective

Construction objectives focus on making pipe construction and installation as cost-effective and seamless as possible. Since bending MEP pipes require personnel to operate bending machines, labor costs depend on the number and angles of the bends. Consequently, minimizing bending costs is a common goal, and different approaches such as step-function cost models for small versus large MEP pipes, or various strategies that limit or optimize the number and angles of bends have been explored. Meanwhile, it is also common to route MEP pipes in parallel to utilize shared support and thereby reduce construction costs. This can involve applying a potential energy approach, giving higher priority to areas adjacent to already routed MEP pipes, or directly optimizing the distances and angles between pipes to arrange them in parallel. Lastly, to minimize support structures, a frequent strategy is to place pipes close to obstacles such as walls, floors, and ceilings, thereby reducing the need for separate external supports. During this process, potential energy can again be used to give higher priority to regions near obstacles, and various methods evaluate obstacle distances and bending locations to further lower costs.

Current MEP Auto Routing Approaches and Limitations in Construction This section provides a comprehensive overview of the status of automated MEP auto routing applications in the construction and plant industries. The results are summarized in Table 1, detailing the application status of optimization modeling. In Section 2, various categories were described to organize this information, leading to the creation of the following table. Space can be divided into cell decomposition methods, skeletonization methods, or a combination of both. Length and bending relate to the continuity of pipe lengths and bends, which can be categorized as discrete, continuous, or a combination. Objective and constraint modeling is divided into physical constraints, maintenance constraints, material cost objectives, and construction objectives, each evaluated using ○, △, ×. The evaluation criteria are based on the complexity of constraints and the difficulty of application. ○ indicates high, △ indicates medium, and × indicates none or low.

Table 1. MEP Auto Routing System in Construction

	Space and Route			Objection and Constraint			
	Space	**Length**	**Bend**	**Physical**	**Maintenance**	**Material Cost**	**Construction**
[20]	Cell Decomposition	Discretization	Discretization	○	○	△	△
[22]	Cell Decomposition	Discretization	Discretization	○	○	△	△
[23]	Cell Decomposition	Discretization	Discretization	○	○	△	△
[24]	Cell Decomposition	Discretization	Discretization	○	○	△	△
[25]	Skeletonization	Discretization	Discretization	○	△	○	○
[26]	Cell Decomposition + Skeletonization	Discretization	Discretization	○	○	○	○
[27]	Cell Decomposition + Skeletonization	Discretization	Discretization	○	○	○	○

The Optimized MEP Auto Routing System still faces challenges in addressing material cost goals and construction efficiency. Existing Auto Routing Systems primarily focus on path optimization and meeting physical constraints, but they fall short of adequately considering material cost reduction and efficiency in the construction process. Specifically, while the optimization of pipe length and diameter has been achieved to some extent, additional costs associated with the number and angles of bends, as well as design considerations for diverse material selections, remain limited. Furthermore, in terms of construction goals, current systems lack support for managing complex installation steps or facilitating worker accessibility during the construction process.

To overcome these limitations, a new Auto Routing System is needed that more comprehensively reflects material costs and construction processes. This system should evaluate a wide range of cost factors during the material selection phase and include features such as orthogonal route design to enhance construction feasibility and compatibility analysis with construction tools. Additionally, it should implement prioritized routing features that account for worker accessibility and maintenance requirements during construction. Such a system will ultimately reduce material costs, simplify construction workflows, and significantly enhance the overall effectiveness of automated routing solutions.

4. The Proposed MEP Auto Route System

Figure 1 illustrates the proposed MEP automatic routing framework, an approach designed to optimize material costs and construction efficiency while addressing key challenges in the MEP design process. This framework consists of five main stages. Several previous studies have also attempted to develop new optimization frameworks for MEP automatic routing. However, these studies primarily focus on computational efficiency and heuristic-based search methods, lacking comprehensive integration of material cost evaluation and real-world construction feasibility. Therefore, it is necessary to introduce these previous efforts, discuss their limitations, and clearly differentiate the proposed framework from prior research. The proposed framework overcomes these limitations by incorporating a hybrid optimization approach that integrates A* for initial pathfinding and Genetic Algorithm (GA) for iterative refinement. Additionally, it enhances practical applicability by integrating material cost analysis, construction feasibility evaluation, and VR/AR-based verification.

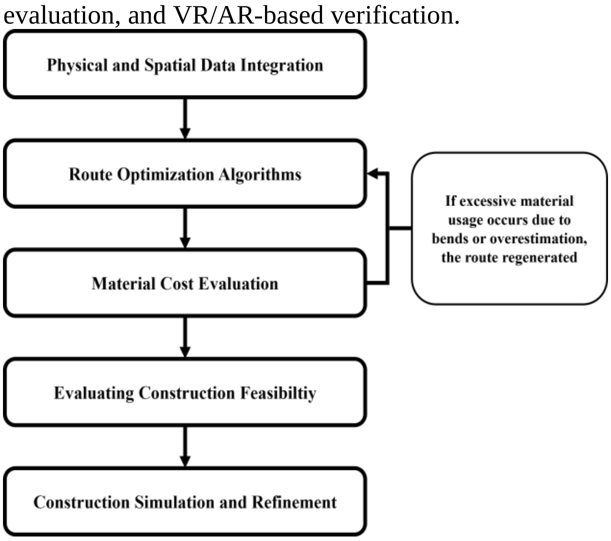

Figure 1. Proposed Framework of MEP Auto Routing

The first stage involves the integration of physical and spatial data required for design, such as pipes, ducts, and electrical wiring. This process identifies pipe diameter, length, material, as well as the location of obstacles and structural features, enabling the creation of a discretized spatial model for route exploration. In this stage, physical constraints (collision avoidance and maintaining minimum spacing) and maintenance constraints (ensuring accessibility) are also defined

The second stage involves applying route optimization algorithms. In this framework, the A* algorithm and Genetic Algorithm (GA) are employed in a hybrid manner, leveraging the strengths of both methods to enhance pathfinding efficiency and adaptability. A* is a graph-based search algorithm that finds the shortest path between nodes using a heuristic function, making it well-suited for initial path generation. It operates by evaluating possible paths based on the sum of the travel cost from the start node to the current node and an estimated heuristic cost to the goal. On the other hand, GA is an evolutionary optimization technique that iteratively refines the initially generated path by optimizing path length, reducing unnecessary bends, and improving overall feasibility.

The goal of route optimization is to minimize total length and bends while avoiding collisions with obstacles. In this approach, A is used to establish an initial collision-free path with reasonable efficiency, while GA fine-tunes the path by adjusting node positions and bend placements to achieve a more optimized routing solution. The algorithm calculates the weights between nodes to find the optimal path and dynamically adjusts the route in real-time according to changing constraints. By integrating A and GA, the system benefits from the deterministic nature of A for rapid pathfinding and the adaptive, global search capability of GA for further optimization.

The third stage is material cost evaluation. Based on the designed route, the total length of pipes and ducts, as well as the number of bends, is calculated. Using material specifications and supplier data, the total cost is estimated. Additionally, if excessive material usage occurs, the route is regenerated and optimized.

The fourth stage focuses on evaluating construction feasibility. The designed route is verified for actual constructability, analyzing aspects such as maintenance accessibility and ensuring adequate installation space. A collision detection system is employed to check for overlaps with obstacles, and the route is adjusted if issues are identified. For complex installations, step-by-step construction plans are developed, starting with the primary lines and subsequently installing auxiliary lines.

Finally, the fifth stage involves construction simulation and refinement. Although route generation and optimization processes are primarily automated in the previous stages, the designed route the designed route is tested in a virtual environment using VR or AR to identify potential installation issues in advance. Here, VR is primarily used to immerse project teams in a fully virtual space allowing them to thoroughly examine large scale or complex routes from multiple perspectives while AR overlays the digital design onto the real environment, which is especially useful for verifying maintenance accessibility and ensuring the route integrates well with existing facilities. Each technology offers distinct benefits and challenges, yet the document previously treated them somewhat interchangeably.

Importantly, this VR/AR-based validation serves as a separate, user-driven verification step, complementing the system's automated processes by accounting for real-world factors and on-site complexities that purely algorithmic methods might miss. In practice, the evaluation of aspects such as installation time, maintenance accessibility, and construction collision risks are conducted visually and manually by users navigating within the VR or AR environment. Users can "walk through" the design (in VR) or view it overlaid on the actual site (in AR), checking clearances, simulating worker paths, and spotting any conflicts. If issues are discovered, the design is iteratively refined. Ultimately, the final route balancing material costs, construction time, and maintenance accessibility is documented and ready for implementation.

This framework systematically addresses potential challenges in MEP routing design, reducing material waste and installation time while enhancing maintenance accessibility. It significantly improves the quality and efficiency of the MEP automatic routing process.

5. Conclusion

This study proposes a new framework to effectively achieve material cost objectives and construction efficiency goals in MEP automatic routing design. Through a comprehensive literature review, the limitations of existing MEP auto routing systems were identified. While these systems are effective in path optimization and addressing physical constraints, they fall short in adequately considering material cost reduction and construction efficiency. Specifically, challenges such as managing the number and angles of bends, additional costs associated with diverse material selections, and the lack of functionality to handle complex installation steps were highlighted.

To address these limitations, the proposed framework consists of five key stages. It integrates physical and spatial data to establish an accurate initial design and leverages optimization techniques such as the A* algorithm and Genetic Algorithm (GA) to minimize total path length and bends while avoiding collisions. Additionally, material cost evaluation analyzes material usage and costs based on the designed route, with the ability to regenerate and optimize routes in cases of excessive material usage. Furthermore, construction feasibility evaluation and VR/AR-based simulations ensure the design's practical viability by proactively identifying and resolving potential issues, enabling efficient design and construction processes.

This framework overcomes the limitations of existing systems and provides a practical solution to reduce material waste and enhance construction efficiency in MEP design. Future research should focus on integrating machine learning and real-time adaptive design technologies to develop systems that can effectively respond to dynamic construction environments. This approach will further improve the sustainability and efficiency of MEP automatic routing design.

Acknowledgements

This research was supported by Brain Pool program funded by the Ministry of Science and ICT through the National Research Foundation of Korea (RS-2023-00257444; RS-2023-00282283)

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