Apply Digital-Twin Model to Optimize the Planning of Equipment Pipeline System in the Laboratory Campus

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Abstract. Building Information Modeling plays an important role in laboratory design. The reasonable layout of the outdoor equipment pipeline is the key to supporting the efficient operation of the laboratory, increasing the flexibility of the laboratory space module, and planning a holistic smart campus space. However, the traditional BIM model lacks convenient visualization and interoperability in the early stage of the program and may lead to inconsistency. This paper aims to propose an integrated visual optimization model toolkit of the equipment and piping using the Rhino + Grasshopper platform. Based on this digital-twin model, the horizontal and vertical space required for the outdoor equipment piping system can be quickly calculated in the site planning stage. The workflow improves the efficiency and accuracy of equipment pipeline system design and reduces multiple design changes. After verifying the validity of the model through two virtual scenarios, it was demonstrated in a real laboratory campus. In the construction drawing stage, the toolkit was used to check whether the interspace of different professional pipeline meets the requirements. This paper expands the design concept, emphasizes the coupling relationship between pipelines and building space, and integrates the experimental and building space concepts throughout the design process.

Keywords: Smart park · Equipment pipeline system · Digital-twin model · Building information modeling

1 Introduction

With the gradual development of laboratories, research buildings gradually begin to show strong characteristics of technological integration. The integration of building space and the integration of mechanical and equipment pipeline system of various disciplines, and the use of integrated design patterns to create constructive synergy of equipment pipeline, can lead to the continuous improvement of the intrinsic value of laboratory buildings (Bachman 2003). The unpredictable virus mutations, the worldwide vaccine development competition, and the growing demand for scientific research in biology and medicine have made the need for biosafety laboratory construction stronger than ever.

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Nowadays, equipment pipeline system is a necessary part of the laboratory building. The reasonable way of equipment pipeline layout is the key to support the efficient operation of the laboratory, increase the flexibility of the laboratory space module and shape the image of the research building. The outdoor pipeline demand of biological laboratory is large, and the spatial relationship of pipeline system should be properly handled to avoid cross and other problems (Bachman 2003). The comprehensive equipment pipeline system is a structure and appurtenant facilities built underground in the city to collect various professional pipelines.

Existing equipment pipeline layout for laboratory buildings often involves a large number of interdisciplinary knowledge and complicated special content, resulting in a mismatch between drawings and process requirements. In addition, design changes are frequent. The existing research lacks the integration of equipment pipeline system as a design element into the preliminary spatial expression.

Using the developed toolkit, the integrated design concept was used to optimize the equipment pipeline system, aligning the different impact factors synergistically and enabling close collaboration between the various professionals throughout the project.

The contributions of this work are:

- Creation of a modeling toolkit for building and equipment interaction that can be flexibly adapted to the parameters.
- Optimization of the equipment pipeline system for research buildings using digital-twin simulation.
- Reference for campus planning and design at the early stage of the program.

The rest of this paper is organized as follows. Section 2 provides a brief overview of the equipment pipeline system and focuses on rules for the arrangement of integrated systems. Section 3 introduces an integrated a visual model toolkit and explains how the digital twin workflow in order to improve computational efficiency and accuracy. Section 4 experimentally evaluates the optimization performance of the toolkit in both virtual and real cases. Section 5 concludes this study as well as some discussions.

2 Background

2.1 Laboratory Equipment Pipeline System Arrangement

Outdoor pipe header system generally has two practices, railway engineering and equipment pipeline engineering. Common pipeline types mainly include water supply, gas, heating, rainwater, sewage, waste, cable, communication, etc. As can be seen from Table 1, although railway engineering and equipment pipeline engineering are both linear projects, they are constructed in different ways, with different economic costs, construction cycles, and expansion and maintenance methods. In addition, different construction methods have different constraints in the planning and landscape design stages.

Table 1. Characteristics of railway engineering and equipment pipeline engineering

Engineering characteristics	Railway engineering	Equipment pipeline engineering
Route characteristics	Linear engineering	Linear engineering
Economic cost	Lower	Higher
Construction period	Stage construction	One-time construction
Maintenance & expansion	Interference with road traffic	Maintenance through the manhole
Landscape greenery scale	More ground layer manhole cover	Freedom of landscape design
Planning management scale	Independent management	Combined management
Cover depth	3–4 m	2–3 m

2.2 Principle of Equipment Pipeline System Planning

The demand for outdoor piping in biological laboratories is large. The spatial relationship of the system should be properly handled to avoid crossover problems. When laying out the equipment pipeline system should

1. Firstly, determine the type, diameter (generally 200–300 mm) and material of the pipeline (plastic pipe, steel pipe, etc.).
2. Secondly, determine the laying sequence of the pipeline system. Generally based on the order of the city code for the layout, and give priority to water supply lines, sewage and rainwater pipelines, recycled water pipeline layout location.
3. Thirdly, ensure that the minimum burial depth of the pipeline (1000–1500 mm), while meeting the minimum horizontal and vertical clear distance.
4. Fourthly, consider laying the pipeline under the sidewalk or non-motorized road. If the green belt is wide, the engineering pipeline can be laid under the green belt, and pay attention to the depth of burial to coordinate with the greenery.

The main purpose of space reservation for outdoor equipment pipeline system can contribute to maximize the use of underground space in the pre-design stage and increase the utilization rate of integrated pipe trench. This contributes to the reasonable landscape planning, in harmony with the underground equipment system (Fig. 1).

2.3 Related Work on Visualization of Equipment Pipeline System

Current laboratory designs tend to ignore variability and interdisciplinarity. Most of the existing studies focus on late design and apply BIM models to simulate. The demand for biomedical research experiments is rapidly iterating, and the smooth conduct of experiments depends on the support of equipment. Laboratories for biomedical disciplines are a unique class of laboratory buildings that need to be easily changed, modified and expanded. Architects need to consider the functional needs of the building for future use (Table 2).

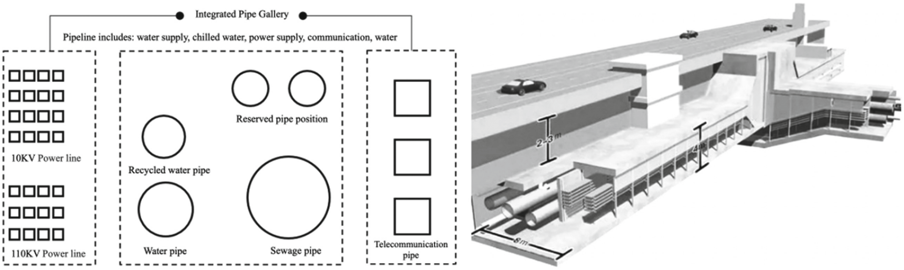

Fig. 1. Underground pipeline arrangement

Table 2. Summary of relevant equipment pipeline system planning proposed in the literature

Work	Building type	Model	Objective
Liu and Issa (2012)	Unlimited	BIM GIS	Visualize and analyze the subsurface pipelines
Zhao et al. (2020)	Unlimited	BIM	Improve the design quality
Zhang et al. (2020)	Residence	BIM	Auto-design method for residential drainage systems
Guo et al. (2021)	Residence	BIM	Collision check and pipeline integration, find problems in advance
Luis Suarez et al. (2023)	Residence	Fuzzy logic models	Minimize system installation cost

3 Methodology

Laboratory equipment pipeline system usually consist of more than 6 types of pipelines. Therefore, the calculation process of the system assembly and the reserved space is quite complicated. The toolkit is written using the GhPython platform to create a optimization model of the equipment pipeline system, which is intuitive and convenient.

3.1 Overview of the Digital-Twin Workflow

Define the logical framework of the digital-twin model. There are three types of input condition factors: (1) Pipeline variable parameters: building exterior contour line, pipeline type, and pipeline diameter. (2) Motorway variable parameters: motorway distance from the outer contour line of the building, motorway road width, and the minimum horizontal distance of the road edge line from the pipeline. Realization of the motorway automatic avoidance module. (3) Urban engineering pipeline planning requirements. And then apply GhPython Script to reproduce the distance between pipelines required in the specification, and realize the minimum horizontal and vertical clear distance filtered out according to the input pipeline type. Finally, the required horizontal and vertical spatial distances of the pipeline system are calculated by the merit-seeking algorithm module (Fig. 2).

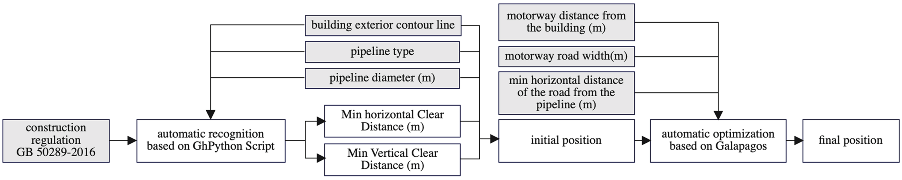

Fig. 2. Diagram of the overall methodology of optimization design (Input: gray block)

3.2 Equipment Integration Model Optimization Process

First, select the horizontal and vertical clearances in the specification. In *Section A*, use GhPython Script to write the horizontal and vertical clearance cells separately to reproduce the specification. This enables the process of inputting the type of pipeline that can be automatically filtered to derive the horizontal vertical clearance of the pipeline. If there are multiple pipes of the same type, for example, if the result shows 1000 "TO" 1500, then it is proved that the List contains sequences. Decomposing it by Domain leads directly to a value containing two spacing values.

Then determine the variable values of the disturbance factor motorway in the following *Section B*. Based on the motor vehicle distance from the outer contour of the building, motor vehicle road width, road edge line from the minimum horizontal distance of the pipeline three values. Calculated to obtain the "road edge line from the outer contour of the building distance a" and "road edge line from the outer contour of the building distance value b".

In *Section C*, automatic motorway avoidance module. Ideally, the pipe header system should be laid avoiding the road. This will reduce the impact of the maintenance manhole cover on the traffic and will not affect the normal traffic during the maintenance. The values a and b from the construction are used to filter the resulting equipment lines in the XY direction. The magnitude of the "distance of the equipment pipeline from the outer contour of the building" and the "value a" are determined. If the value is less than a, it is considered that the category of pipeline meets the requirement in horizontal direction, otherwise the pipeline needs to be offset in XY direction (Fig. 3).

And then, calculate of the offset value in *Section D*. In order to reduce the horizontal space distance required for the equipment pipeline system as a whole, the first pipe to be offset coincides with the outer contour of the road by default. Therefore, the offset value of the first pipeline to be adjusted is the difference between the "value b" and the "distance of the first pipeline to be adjusted from the outer contour of the building". After determining the first pipeline to be adjusted by the offset, the remaining pipelines to be adjusted are OFFSET according to the previously determined minimum horizontal offset, and the final position of the pipeline system in the XY direction is obtained.

Finally in *Section E*, calculate the required vertical spatial distances for the system. The location of the pipeline in the XY direction is selected, and the initial location in the

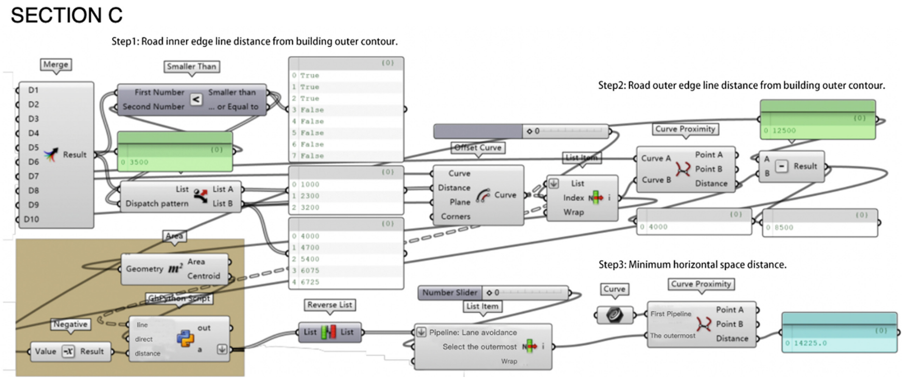

Fig. 3. *Section C*: auto Lane avoidance program and analysis

XZ direction is obtained by sequentially moving the pipeline system according to the minimum vertical clear distance requirement value constructed by GhPython Script. In the vertical direction, we also need to consider that the sewage is discharged with a slope and the pipeline is buried deeper, so it is easy to affect the foundation of the building without a basement if it is too close to the building. Since there is a basement in this project, the depth of the sewage pipe does not have a significant impact. Since there are many solutions to meet the minimum vertical clear distance between pipes, Galapagos is introduced for the optimization analysis to calculate the minimum value of the vertical direction of the system. Based on the initial position in XZ direction, the solid model after the pipe is established. The height of the box is the vertical spatial distance (Fig. 4).

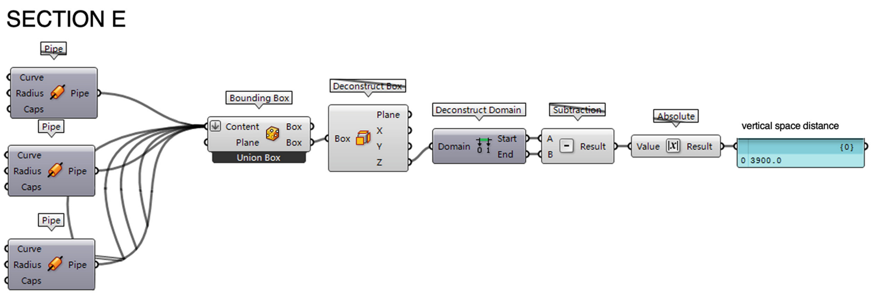

Fig. 4. *Section E*: calculation of vertical space required for integrated system

3.3 Optimal Genetic Algorithm Evaluation

There are several ways of arranging the system, and the toolkit is designed to select the optimal one. Take the relative position between 'water supply pipe-rainwater pipe-sewage pipe' as an example, after determining the position of the water supply pipe, there are 4 idealized layout patterns of rainwater pipe and 8 patterns for sewage pipe. After determining the burial depth of the first pipe line, the offset distance of the next pipeline can be derived based on the minimum vertical clear distance between pipes and the diameter. Positive and negative directions exist for each type of pipe line. The minimum spatial distance in the vertical direction of the pipeline system should be ensured with the burial depth. The optimal genetic algorithm is applied for the measurement (Fig. 5).

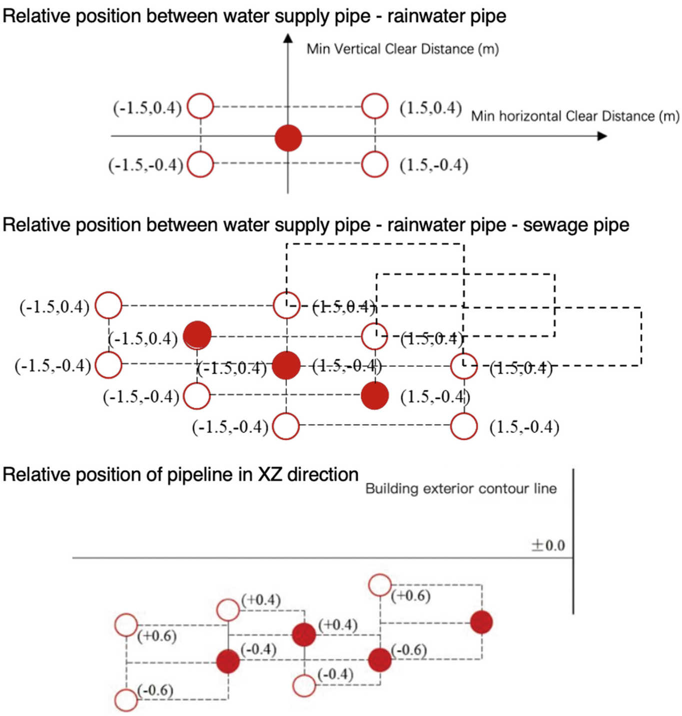

Fig. 5. Relative position between different kind of pipeline

In order to find the minimized distance objective function min(x, y), the mapping relationship with the fitness(x, y) function can be established through the following transformation, as follows:

$$fitness(x, y) = \begin{cases} Cmax - f(x, y), f(x, y) < Cmax \\ 0, f(x, y) \geq Cmax \end{cases}$$

Agentic algorithm battery within Grasshopper, the vertical spacing between pipelines is correlated with the vertical spatial distance of equipment pipeline system using Galapagos. The two ports Genome and Fitness correspond to the variable parameters in the function and the optimal solution, respectively. Through the selection, crossover and variation iterations of parameter configurations by the genetic algorithm, the gene parameter configurations with high utility function values in the results are retained. As the number of iterations continues to increase, the solution with the optimal value of the set objective function appears, and then stop the operation. The optimal configuration of the spacing parameters and the depth to be reserved underground can be obtained (Fig. 6). After the operation, the parameter condition that gives the optimized result is the value corresponding to the Genome port.

Fig. 6. Galapagos port output

4 Results

The above steps are integrated by creating a visualization plug-in through the human UI interface and displaying the final optimization results directly in the main rhino interface (Fig. 7).

4.1 Interaction Between Buildings and Equipment

The iterative relationship between pipelines and buildings is divided into two aspects: positive and negative. First, the building has an impact on the pipelines. Through the automatically generated ranking system, different kinds of pipelines are arranged in order according to the preliminary plan in the planning stage. Secondly, the impact of pipelines on buildings. Considering the grouped buildings, attention should be paid to maintain the building spacing requirements when planning in order to keep the building group pipeline system from crossing. In addition, when arranging motor lanes, combined with the flow of the park, it is not appropriate to arrange multiple lanes when the building spacing is constrained. If it has to, the building spacing should be widened to avoid pipeline crossings (Fig. 8).

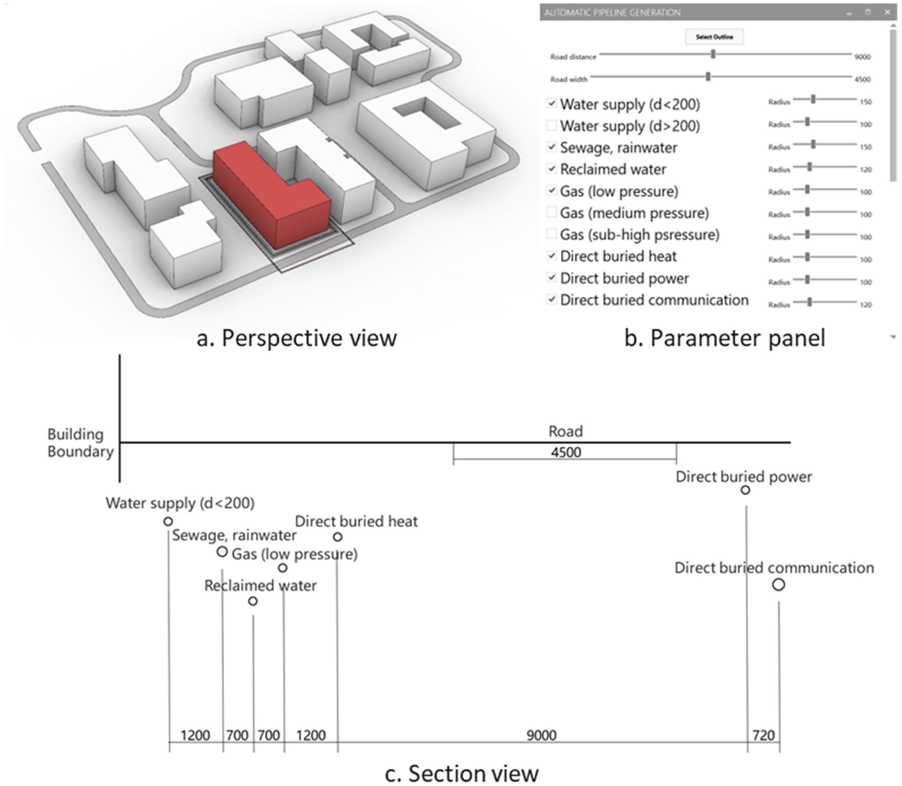

Fig. 7. Toolkit plug-in interface

4.2 Interaction Between Landscape and Equipment

Because of the overburden restriction, plants with root depth requirement cannot be arranged above the pipeline, which will cause damage to the service life. After determining the horizontal vertical distance to be reserved, the plant landscape and detailed site design can be reasonably arranged (Fig. 9).

4.3 Validation Experiments and Practical Applications

Applied to several different building blocks to verify the feasibility of the method in different situations. The results can be used as a reference when optimizing the solution. Firstly, two buildings in the virtual biological park were selected for the validation experiments. Building A, located in the northwest side of the park, is adjacent to the motorway on the north side. Building B, located in the middle group of the park, is adjacent to the motorway on the west side and has an old tree on the north side. The diameter of the type of pipeline is set and the resulting pipeline arrangement is checked. The resulting optimization was found to be feasible and could meet the planning and design requirements (Fig. 10).

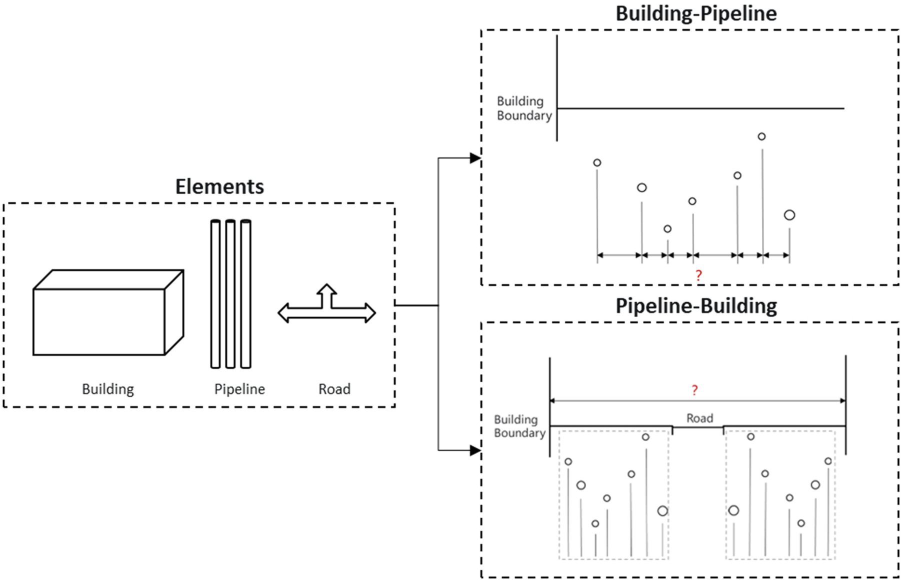

Fig. 8. Interaction influence of building design and pipeline

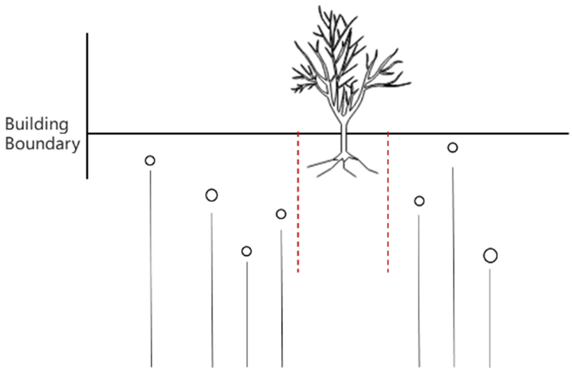

Fig. 9. Adjustment of pipeline design based on landscape planning

The validation scheme is located in Nanhu, Jiaxing, China, a campus with a site area of 95,000 m^2. As a bio-innovation laboratory, the complex pipeline systems were required to be considered throughout the entire process from planning to construction. Optimize the position of the manhole cover corresponding to the pipeline at the ground level, avoid the square in front of the entrance of the building and the car road of the park, and try to arrange it in the green landscape area.

The pipeline has two directions of movement, upward and downward, while meeting the vertical clearance requirements. The maximum vertical distance between all pipelines is set to 10,000 mm with an accuracy of 50 mm (Fig. 11).

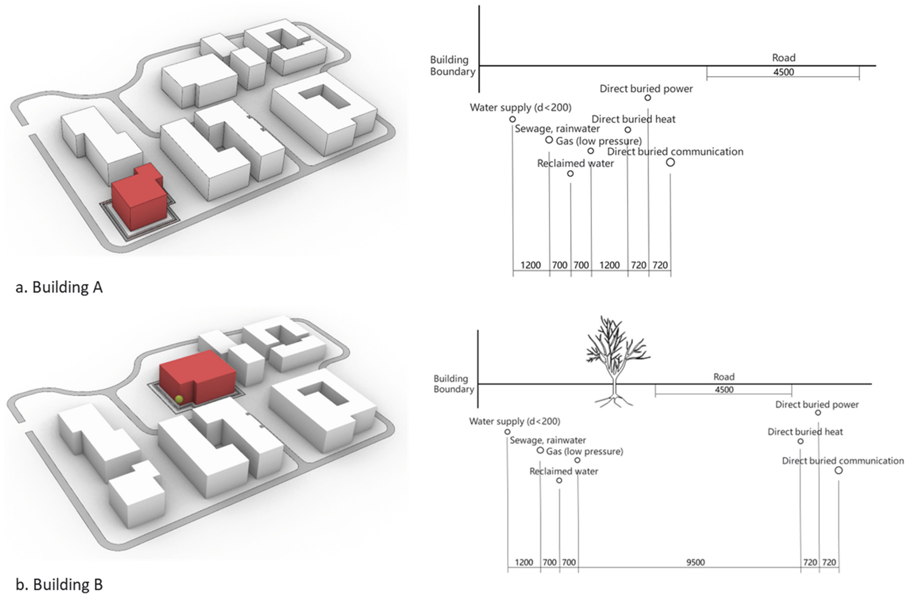

Fig. 10. Validation experiments

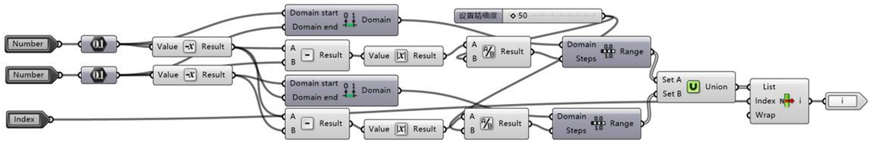

Fig. 11. Create a concatenation of the two directions of movement

The Genome port connects the vertical distance thresholds between the control lines, and the Fitness port connects the vertical distance simulation results of the ductwork system. In order to obtain the minimum vertical spatial distance of the pipe heterogeneous system, the vertical net distance control end of Cluster is continuously changed. It gradually leveled off after the 19th iteration and stopped after the 131st iteration of the operation, yielding a required vertical distance of 500 mm for the equipment pipeline system. The result of pipeline distance and the iterative relationship of the visual toolkit are as follows (Table 3, Fig. 12).

5 Conclusion and Discussion

This study developed the application of a digital-twin model to simulate smart park site plan and equipment pipeline system. The horizontal and vertical space required for the equipment pipeline system can be derived based on the input of building exterior contour lines, pipe types, pipe diameters, motorway widths, and engineering specifications. A platform for digital-twin model can be built to provide a reference for space reservation

Table 3. Vertical distance between pipelines

Pipeline type	Vertical distance (mm)
Water supply—sewage	400
Sewage—rainwater	400
Rainwater—reclaimed water	200
Reclaimed water—gas	200
Gas-direct buried heat	500
Direct buried heat—direct buried power	150
Direct buried power—direct buried communication	500

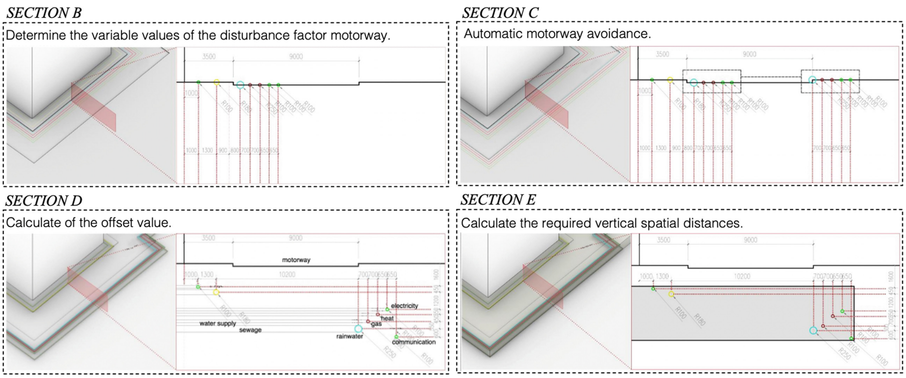

Fig. 12. Results of pipeline space minimization and optimization

of the pipe header system at the early stage of the scheme and facilitate the general drawing design.

Of course, there are still some limitations to this study. First, the application experience in real projects is insufficient. To address this issue, the feasibility of the tool was first verified by assuming several virtual environments, and then the actual application was performed in a project. There is a possibility of incomplete consideration due to the diversity in the construction of the project. Second, the optimal pipeline layout in this study is measured in terms of spatial economy rather than construction cost. However, the equipment pipelines in the actual project may be complex and extensive, and there are situations that are different from the visualization model. If we add a cost comparison module, we can balance the construction cost and spatial cost of different pipeline layout methods from multiple perspectives.

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