VAO CHECKER: ACCESSIBILITY STUDY FOR PIPELINE MAINTENANCE

Chu-Hsuan Lee, Meng-Han Tsai & Shih-Chung Kang
Department of Civil Engineering, National Taiwan University, Taiwan

ABSTRACT: *Pipeline maintenance is becoming an important issue in modern construction. An understanding of accessibility considerations in terms of operation and maintenance is essential for pipeline planning and management. Previous studies have highlighted the complexity of multi-pipes and the importance of visualization, but few have proposed a way to consider accessibility problems during operation and maintenance. Therefore, this study develops a systematic method to evaluate accessibility with respect to pipeline maintenance. We first divided pipeline accessibility into three categories: (1) visual accessibility—a pipeline visible to the inspectors; (2) approachable accessibility—a pipeline that is reachable; and (3) operational accessibility—a pipeline that can be operated by the inspectors. Therefore, we visually represent the intersection and union of these three levels to illustrate the varying accessibility of pipe elements. We then developed a user interface tool, VAO Checker, in which V, A and O stand for visual, approachable and operational, to display visual information about pipeline accessibility. Through instantaneous analysis, the system visualizes the accessibility of the pipelines. A usability consultation with experts will be conducted to validate the system's effectiveness. The results of the usability analysis show pipeline designers can benefit by using this tool to sketch a suitable traffic flow for engineers to investigate. Furthermore, the substantial amount of information saved in the layout database could be referenced for future optimization.*

KEYWORDS: *Building Information Model (BIM), Mechanical, Electrical, and Plumbing (MEP), Pipeline Maintenance, Pipeline Accessibility, Information Visualization*

1. INTRODUCTION

Pipeline design has become increasingly important in modern construction. Operation and maintenance requires consideration of accessibility in the design of the layout of plant pipelines. Previous research has noted that piping accounts for 20% of costs for the industry as a whole (Calixto et al., 2009) and over 50% of the total detail-design labor hours (Park and Storch, 2002). All other activities of following detail design depend on piping and massive savings are achievable by utilizing good layout design and engineering practices.

Mechanical, electrical, and plumbing (MEP) pipes used to be supplemental facilities in construction. However, they have become necessary facilities, especially in nonresidential construction, such as hospitals, fire stations, and plants. Coordinating a MEP system is a tremendous challenge in engineering fields such as advanced technology, health care, and biochemistry industries (Khanzode et al., 2008). Knowing how to arrange MEP systems appropriately is one of the most crucial aspects of the design phase (Riley et al., 2005).

Maintenance is a crucial phase in these types of construction. A poorly designed pipeline layout design wastes space and materials. Moreover, it can cause difficulty or even danger during manipulation and management.

2. LITERATURE REVIEW

The literature reviewed for this study included findings and recommendations related to piping that can be categorized into three main groups: a pipe-routing algorithm, the integration of multi-pipes, and the visualization of pipeline design.

2.1 Pipe-Routing Algorithms

Pipe-routing design is a subset of assembly design that conceives collision-free routes for pipes. A survey by Qian et al. (2008) categorized it into four fields: industrial plant pipeline layout design, circuit layout design,

Citation: Lee, C-. H., Tsai, M-. H. & Kang, S-. C. (2013). VAO checker: accessibility study for pipeline maintenance. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

aircraft design, and ship piping system design. Several studies have been devoted to routing algorithms, and mainly focus on physical constraints that connect the terminals of given locations and avoid all obstacles. They then use economic constraints to minimize the length of pipes and the number of pipe turns, which leads to an optimal specification. However, few, if any, solutions have considered pipeline accessibility in relation to operation and maintenance. Zhou and Yin (2010) emphasized that practical constraints, such as maintenance requirements and manufacturability, are not well recognized, and how humans still play an important role in guiding the computer to finish the design.

2.2 Integration of Multi-Pipes

An industrial plant typically has more than one kind of pipeline. Feng et al. (2012) indicated a large number of pipelines, multifarious design constraints, and numerous obstacles in layout complicates the design of a pipeline system. Recently, engineers have mainly used existing CAD software for design assistance, which has increased the problems associated with experts, such as complex operation, a long design cycle, and low efficiency. Feng *et al.* advocated a new layout space model to reduce high complexity and design interference in the automated design of pipeline systems. Kim et al. (1996) found the range and complexity of the constraints limits the possibility of automatic pipe route design, and demonstrated a more natural and effective representation for route optimization. The research of Kim *et al.* recognized the complexity in pipeline arrangement and proposed some methods to reduce it. However, in many instances the pipeline layout cannot be simplified, so the complexity should be taken into account.

2.3 Visualization Regarding Pipeline Accessibility

Some researchers have begun noticing the utility of information visualization for construction purposes as a means of improving the data-rich, but information-poor, problems of the construction industry (Kuo et al., 2011; Songer et al., 2004). Korde et al. (2005) and Russell et al. (2009) focused on the visualization of construction data, noting how it can help identify potential causal relationships among construction data. Gao et al. (2006) investigated colored construction drawing, which can increase the efficiency and accuracy of communication between designers and contractors. Chang et al. (2009) and Ya-Hsin et al. (2013) suggested a systematic procedure to determine the most suitable colors for effectively presenting the construction information. This procedure includes the selection, evaluation, and testing of colors to ensure they match the meaning of the construction information with the cognition of the users. With reference to pipeline arrangement, Deliang and Huibiao (2009) pointed out that visualization can help handle the detection and response to collisions between pipes and obstacles.

3. NEEDS ANALYSIS

We interviewed six experts in the field of plant pipeline design, including three engineers from a construction company, two managers from a microelectronics corporation, and one executive officer from the Building Information Modeling (BIM) research center.

We determined from the interviews that there are four main considerations in pipeline design: (1) the manufacturing process, (2) operation and maintenance, (3) cost, and (4) aesthetics. In a typical plant engine room, the engineers first have to deliberate how the pipelines go according to the manufacturing process, which will influence productivity and efficiency. They then contemplate how the workers will handle the equipment, meters, and valves during the operation and maintenance phase. Cost and aesthetics are aspects used to optimize the consequences of designs. Previous studies have proposed many algorithms by considering the cost factor, but maintenance is rarely discussed.

We mainly focused on operation and maintenance. Pipeline accessibility is the key factor to effective maintenance as it determines how easily the engineers can stretch to the accessories related to pipelines, including equipment, meters, and valves. Engineers can sometimes see pipelines from a distance, but cannot approach them due to the obstacles in the way of the pipelines. In other cases, engineers cannot read the meters in detail or operate the valves without difficulty, because these parts are mounted too high. We seek an easy way to illustrate pipeline accessibility with a view to engineers benefiting from this intuitive tool during the construction cycle (i.e., design, operation, and maintenance).

4. OBJECTIVE AND SCOPE

The aim of this study is to develop a systematic method to assist decisions about pipeline maintenance. One major challenge of coordinating MEP multi-pipes is identifying the spatial conflicts between systems. Through instantaneous analysis, the system automatically produces visual information indicating how much pipe access the engineers can have. This tool allows users to view, explore, and interact with the pipeline information via a direct manipulation interface in order to identify the spatial accessibility in a more intuitive manner. The user can thus obtain a comprehensive understanding of pipeline maintenance.

5. METHODOLOGY

We use a Venn diagram, a diagram that shows all possible logical relations between different sets, to differentiate three categories of pipeline accessibility. We then apply each section of the diagram to different scenarios. We further develop mathematical models and discuss the ergonomic details about each different category.

5.1 Overall Procedure of Pipeline Accessibility

We proposed three categories, *visual*, *approachable*, and *operational* to present the extent to which the pipe elements are accessible. As shown in Fig. 1, we use the intersection and union of these three categories to discuss different scenarios as follows:

Visual (V): determines how much of the pipe is directly visible for inspection.

Approachable (A): determines how far maintenance engineers can walk along the pipes.

Operational (O): checks how much of the pipes can be reached in order to operate valves or check surfaces.

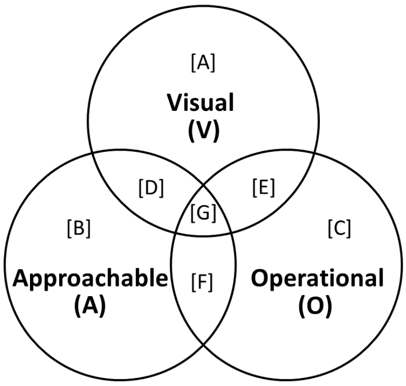

Fig. 1: Venn diagram of pipeline accessibility

In the Venn diagram, there are seven sections among the three circles. Each one is a variation of intersection and union. As listed in Table 1, we give the accessibility description of each variation from Fig. 1.

Table 1: Seven variations of intersection and union

Section	Math Representation	Accessibility Description
[A]	$V - A - O$	Only visible, but not approachable and operable. This happens when obstacles and other pipes prevent engineers from accessing equipment and pipelines.
[B]	$A - V - O$	Only approachable, but not visible and operable. This happens when obstacles and other pipes block displays and controls.
[C]	$O - V - A$	Only operable, but not visible and approachable. Although remote control is possible, we did not consider this variation.
[D]	$V \cap A - O$	Visible and approachable, but not operable. This happens when controls or valves are mounted too high, too low, or too far away to reach and operate.

[E]	$V \cap O - A$	Operable and visible, but not approachable. The same as [C]. We did not consider this variation.
[F]	$A \cap O - V$	Approachable and operable, but not visible. This happens when controls and valves are mounted behind the display, and engineers have to bend their arms to operate them. However, any blindness operation is not allowed in our assumption.
[G]	$V \cap A \cap O$	Visible, approachable, and operable—the ideal situation.

These three categories are expressed in a visual conception of information. We adopted the anthropometric data from the American Bureau of Shipping (ABS, 2003) to build the model for accessibility analysis. We made some modifications by considering the physical differences between Americans and Taiwanese, because the first case would be a semiconductor fabrication plant in Taiwan.

5.2 Approachable Accessibility

This level determines how far people can walk along the pipes. Walkways should have 2.1 m minimum clearance above the walking surface for the full length and width of the walkway. The analysis and mathematical model of approachable accessibility is different from the other two because it is a dynamic process. As shown in Fig. 2 and Table 2, we first use a bounding cylinder to represent a person, and bounding boxes in different sizes to represent a cart in different applications. If obstacles or other pipes block the box, it cannot go farther along the pipes.

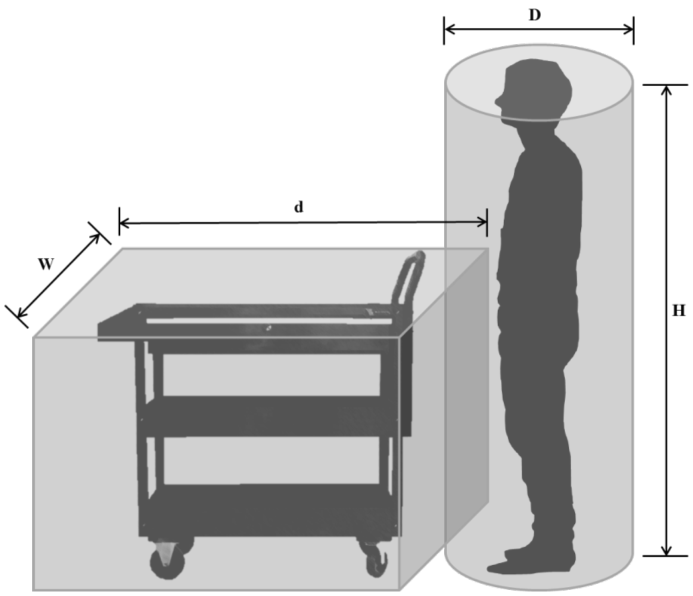

Fig. 2: Bounding cylinder and box representation

Table 2: Bounding box size for recommended walkway dimensions

Application	Box size *
One person traveling in an area with limited access	51×51×150
One person in unrestricted area, where two persons could pass	71×71×210
One person with a cart	71×120×210
Normal two-way traffic or any means of egress that leads to an entrance or exit	92×120×210
Corridor or passageway that serves as a required exit	112×120×210

* Size representation: W (cm) × (D+d) (cm) × H (cm)

The mathematical model of visual accessibility is then constructed as the equation:

$$A = (H, r, P) \tag{1}$$

As denoted in Fig. 3, $r = \frac{Max(W,D)}{2}$, and we used a cylinder with radius r and height H to simplify the bounding box. S means the start point, and T means the target point. P is the path from S to T:

$P = [S, p_1, p_2, \dots, p_n, p_{n+1}, \dots T]$, where the cylinder is not blocked.

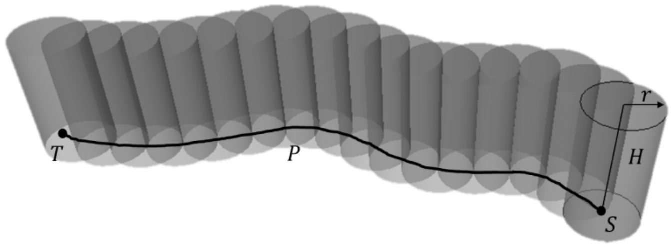

Fig. 3: Mathematical model of approachable accessibility

5.3 Visual Accessibility

This level determines how much of the pipe is directly visible for inspection. We further divide it into two levels: visible and legible. The former includes those used for normal operations and those not requiring accurate readings, whereas the latter includes those used frequently, for obtaining precise readings, and in emergencies. The mathematical model of visual accessibility is constructed as the following equation. Fig. 4 indicates the parameters.

$$V = \left(S,\ H,\ L_{min},\ L_{max}, \theta,\ H^v_{min}, H^v_{max}\right) \tag{2}$$

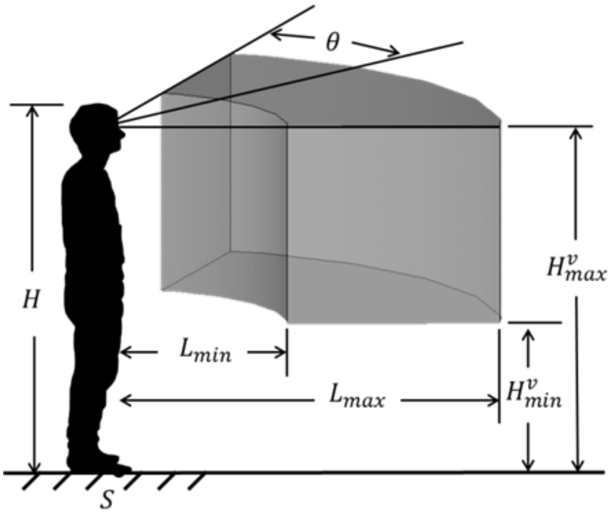

Fig. 4: Mathematical model of visual accessibility

Table 3: Suitable field-of-view and vision range (multiple of H) for legible and visible levels

Posture	L (cm)	θ (degrees)	Standing (C)	Kneeling (D)	Squatting (E)	Overall
Visible Maximum	200	60	1.0114	0.8239	0.7102	1.0114
Legible Maximum	71	35	0.9375	0.7500	0.5795	0.9375
Legible Minimum	33	0	0.7216	0.5398	0.4261	0.4261
Visible Minimum	0	0	0.5909	0.3977	0.2955	0.2955

The two parameters regarding people's field-of-view are the distance from eyes (L) and the viewing angle from the central line (θ). Based on ABS research, as shown in first two columns of Table 3, people can see the details of pipes at distances between 33cm and 71cm, and a viewing angle within 35 degrees, where the legible level should be located (provided obstacles or other pipes do not block the pipes and displays). The distance for the visible level can be up to 200cm, with the viewing angle up to 60 degrees. The visual heights (H^{v}) for displays in different postures are illustrated in Fig. 5: standing (C), kneeling (D), and squatting (E). The rest of Table 3 shows the maximum and minimum heights for the legible and visible levels, based on personal height (H). Because the range of these three postures overlapped, we integrated the data. The legible level should be located within the multiple 0.4261-0.9375, but the visible level can be broader, 0.2955-1.0114.

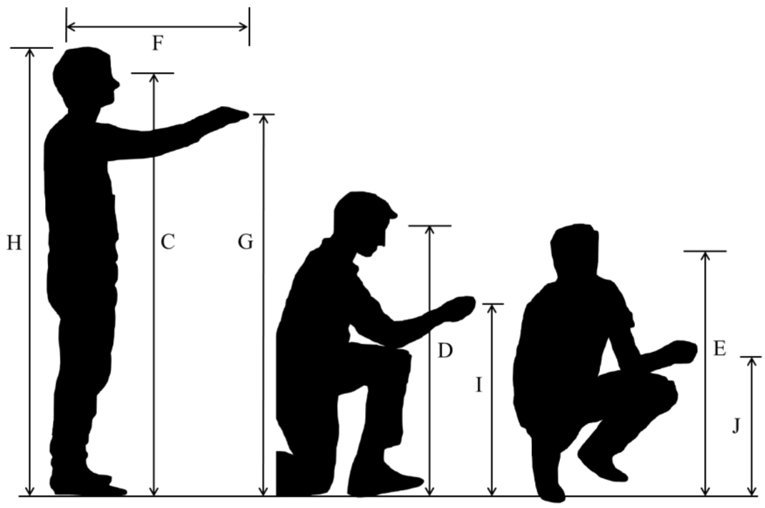

Fig. 5: Related height in different postures

5.4 Operational Accessibility

To facilitate the operation of valves or the checking of surfaces, this level checks the accessibility of pipes. It is derived from the arrival accessibility level, and shows the ease with which people can operate within the pipe layout. We further divided it into two levels: general control and precise control. The former includes those used for normal operations and those not requiring accurate manipulation, whereas the latter includes those used frequently, for obtaining precise performance, or in emergencies. The mathematical model of operational accessibility is constructed as the following equation. Fig. 6 indicates the parameters.

$$O = (S,\ H,\ F,\ H^o_{min}, H^o_{max}) \tag{3}$$

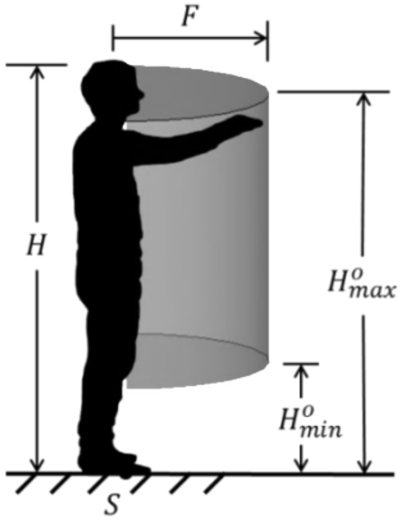

Fig. 6: Mathematical model of operational accessibility

People's forward functional reach from behind the shoulder to the tip of the extended finger (F) and the operable heights (H^o) for controls in different postures are illustrated in Fig. 5: standing (G), kneeling (I), and squatting (J). Table 4 shows the maximum and minimum forward functional reach and heights for precise and general controls, based on personal height (H). Frequently used controls should be located within a radius of multiple 0.2614 from the operator's centerline, whereas less frequently used controls should be located within a radius of multiple 0.4545 from the operator's centerline. Because the range of these three postures overlapped, we integrated the data. Precise control should be located within the multiple 0.2273-0.7670, but general control can be broader, 0.2045-1.0966.

Table 4: Suitable forward functional reach and heights (multiple of H) for precise and general controls

Posture	Forward (F)	Standing (G)	Kneeling (I)	Squatting (J)	Overall
General Maximum	0.4545	1.0966	0.8239	0.7102	1.0966
Precise Maximum	0.2614	0.7670	0.6136	0.4545	0.7670
Precise Minimum	0	0.4886	0.3068	0.2273	0.2273
General Minimum	0	0.4318	0.2614	0.2045	0.2045

6. IMPLEMENTATION

This study developed a system, VAO Checker, which integrated the user interface and visualization information as a tool, to implement the proposed methodology. The following sections describe the software used for the development environment and the system design.

Programming Platform: This study used Microsoft Windows Presentation Foundation (WPF) for the display of the user interface. WPF was chosen because it allows programmers to easily unify multimedia data, and change the appearance or the function of display controls for customization. Furthermore, the WPF application functions by off-loading to graphics processing units (GPUs) rather than central processing units (CPUs), which facilitates smoother graphics and better performance (Nathan, 2006).

Graphics Engine: The framework developed for the visualization information was based on the Microsoft XNA Game Studio 4.0. This tool assists the development of video games and the improvement of software management. XNA has ample performance for the development of 2D and 3D games. It offers users the capability to build the operating system and visual images with ease (Grootjans, 2009; Miller and Johnson, 2010).

System Design: The proposed tool called VAO Checker was built for this study to consider the three categories of pipeline accessibility. As shown in Fig., the operation interface displays a plan view of the space, including the equipment and pipelines. The user can use this tool to find a collision-free path through the space and to examine the different levels of visual and operational accessibility.

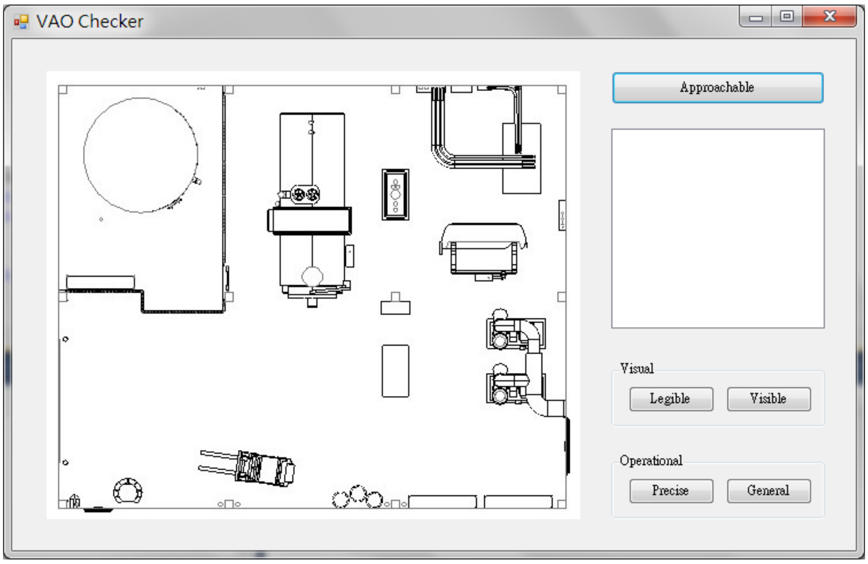

Fig. 7: Operation interface of VAO Checker

7. VALIDATION

In order to verify how VAO Checker could help users explore and understand relevant accessibility information, we conducted a usability test. We also solicited expert consultation to verify the usability and how the users can interact with the pipeline accessibility information.

7.1 Test Plan

For the usability test, we built a typical machinery room project with equipment and pipelines. There were 10 accessibility problems in this case. All users had to identify the problems in three individual tasks, each task using different mediums, 2D plan drawing, 3D model and our system, VAO Checker. Besides, we also conducted the NASA Task Load Index (NASA-TLX) test. As shown in Fig. 8, the test plan began with the NASA-TLX weight assessment, in which the user compared the factors pairwise based on their perceived importance. After the user finished the identification of accessibility problems via one information medium, the user had to rate each factor of task load within a 100-points range. The final NASA-TLX score was calculated based on the weight distribution, which was decided at the initial phase.

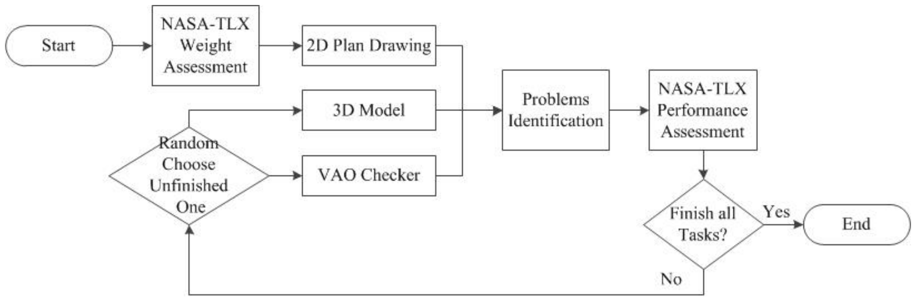

Fig. 8: Usability test procedure

7.2 Test Result

An α level of 0.05 was used for all statistical tests and analysis, and we calculated the p-value between groups in analysis of variance (ANOVA), where $p < 0.05$ means statistically significant. The test results assessed how quickly and accurately participants performed the task when using different mediums. There is also an analysis of NASA-TLX score, which shows how the participants evaluated the ergonomics performance of each medium. They are summarized as follows:

Correctness: VAO ≧ 3D > 2D

Table 5 presents means and standard deviations of success rate of each medium, and the p-value shows the data between 2D and VAO Checker is statistically significant. As the data indicates, the success rate of VAO Checker (64.3%) is 1.6 times higher than 2D plan drawing (40.1%) and 1.14 times higher than 3D model (56.4%).

Table 5: Statistical analysis of correctness

Medium	Mean (%)	Std. Deviation (%)	p-value (* means significant)	
2D plan drawing	40.1	16.3	2D & 3D	0.002*
3D model	56.4	25.3	2D & VAO	0.000*
VAO Checker	64.3	24.5	3D & VAO	0.139

Performance: 3D > VAO > 2D

Table 6 presents means and standard deviations of NASA-TLX score of each medium, and the p-value shows the data between each pair of these three groups is statistically significant. The score of 2D plan drawing is the lowest (36.0), whereas the score of 3D model is the highest (53.8). The score of VAO Checker (48.0) is 1.33 times higher than 2D plan drawing.

Table 6: Statistical analysis of performance

Medium	Mean (points)	Std. Deviation (points)	p-value (* means significant)	
2D plan drawing	36.0	13.5	2D & 3D	0.000*
3D model	53.8	17.0	2D & VAO	0.004*
VAO Checker	48.0	17.3	3D & VAO	0.020*

7.3 Discussion

Most of the participants have a background of civil engineering, and they can get on track quickly when they check 2D plan drawing or 3D model. Based on the observation during the usability test, participants would spend some time to get used to the user interface of VAO Checker, because it is a new tool for them. However, in the analysis of correctness, the success rate of VAO Checker is the highest. This means, although users might spend more time when they first contact with the user interface of VAO Checker, they still can achieve the goal of high correctness.

In the analysis of performance, the NASA-TLX score of VAO Checker is higher than 2D plan drawing, and 3D model is higher than VAO Checker. We also interviewed the participants about their feeling when they manipulated VAO Checker. Many of them pointed out that the manipulation of VAO Checker had a sense of reality, unlike 2D plan drawing. They could look around the environment, and perceive the size of equipment and pipelines. The visual effects made it like playing a game. However, due to the unfamiliarity with the overall pipeline design, they sometimes got confused with the direction in the virtual environment. That is the reason some participants evaluated the NASA-TLX score of 3D model higher.

Despite the participants needed some time to be familiar with the manipulation interface of VAO Checker, they all agreed that they could identify the accessibility problems very easily via this tool, because it provided sufficient information for them to judge the level of pipeline accessibility. They expected the path generated from analysis of approachable accessibility could be used for inspection or judgment, and the engineers would have a certain understanding of pipeline maintenance of the entire environment if they could move along this path.

VAO Checker would serve as a useful tool for the designers who are conscious of the design, and they would benefit from this tool to correct any design errors. Experts suggested that VAO Checker is suitable for planning a more complex environment, such as chiller machinery room. The sizes of pipelines are bigger, and there are more relevant systems. Formerly only experienced designers could plan a pipeline layout which is acceptable enough. Through VAO Checker, designers could save a lot of time in analyzing and planning.

8. CONCLUSION

This research developed a systematic method to evaluate the accessibility of pipeline maintenance. During the early stage of this research, we interviewed six experts to determine the requirements of pipeline design. After combining the opinion of experts with a literature review, we mainly focused our research on pipeline accessibility during operation and maintenance, which is rarely discussed in previous studies. We first divided pipeline accessibility into three categories, developed mathematical models, and discussed the ergonomic details of each different category. We then developed a system called VAO Checker, which integrated the user interface and visualization information as a tool to implement the proposed methodology. VAO Checker used a simple motion-planning algorithm to find a path with acceptable approachable accessibility, and programmed the mathematical models into visualization information indicating the visual and operational accessibility. We created an example case to validate the practicality of VAO Checker, and the result showed that it is a useful system for pipeline designers and engineers. It considered the pipeline accessibility within multi-pipes and enhanced the spatial comprehension. The system can be further integrated into BIM software as an API, extended to pipe assembly planning areas, or even referenced for future optimization.

9. ACKNOWLEDGEMENT

This research was supported in part by Taiwan's Ministry of Economic Affairs, under contract 101-EC-17-A-15-S1-223. The authors are grateful to Mr. Chien-Chih Lai of L&K Engineering CO., LTD., Mr. Ching-Yang Kao and Mr. Ming-Fa Lin of United Microelectronics Corporation (UMC), Mr. Yuan-Fu Liao and Mr. Yi-Ti Tsai of CTCI Corporation and Mr. Ching-Hsien Lee of Research Center for BIM, National Taiwan University for their kind support and assistance in this research. We like to express our appreciation to the interviewees of these corporations and organizations.

10. REFERENCES

The American Bureau of Shipping (ABS) (2003). *Guidance notes on the application of ergonomics to marine systems*, Houston, USA, American Bureau of Shipping.

Calixto E. E. S., Bordeira P. G., Calazans H. T., Tavares C. A. C. and Rodriguez M. T. D. (2009). Plant design project automation using an automatic pipe routing routine, *Computer Aided Chemical Engineering*, Vol. 27, 807-812.

Chang H. S., Kang S. C. and Chen P. H. (2009). Systematic procedure of determining an ideal color scheme on 4D models, *Advanced Engineering Informatics*, Vol. 23, 463-473.

Deliang L. and Huibiao L. (2009). Interfere-check applying to 3D automatic pipe route arrangement, *Proceedings of International Conference on Computational Intelligence and Software Engineering*, Wuhan, China, IEEE, 1-3.

Feng H., Fu Y. and Li L. (2012). Layout space modeling for automation design of pipeline system, *Proceedings of 2012 International Conference on Mechatronics and Automation (ICMA)*, Chengdu, China, IEEE, 881-886.

Gao Z., Walters R. C., Jaselskis E. J. and Wipf T. J. (2006). Approaches to improving the quality of construction drawings from owner's perspective, *Journal of construction engineering and management*, Vol. 132, 1187-1192.

Grootjans R. (2009). *XNA 3.0 Game Programming Recipes: A Problem-Solution Approach*, Apress.

Khanzode A., Fischer M. and Reed D. (2008). Benefits and lessons learned of implementing building virtual design and construction (VDC) technologies for coordination of mechanical, electrical, and plumbing (MEP) systems on a large healthcare project, *Journal of Information Technology in Construction*, Vol. 13, 324-342.

Kim D., Corne D. and Ross P. (1996). Industrial plant pipe-route optimisation with genetic algorithms, *Lecture Notes in Computer Science*, Vol. 1141, 1012-1021.

Korde T., Wang Y. and Russell A. (2005). Visualization of construction data, *Proceedings of 6th Construction Specialty Conference*, Toronto, Ontario, Canada, University of British Columbia.

Kuo C. H., Tsai M. H. and Kang S. C. (2011). A framework of information visualization for multi-system construction, *Automation in Construction*, Vol. 20, 247-262.

Miller T. and Johnson D. (2010). *XNA Game Studio 4.0 Programming: Developing for Windows Phone 7 and Xbox 360*, Addison-Wesley Professional.

Nathan A. (2006). *Windows presentation foundation unleashed*, Sams Publishing.

Park J. H. and Storch R. L. (2002). Pipe-routing algorithm development: case study of a ship engine room design, *Expert Systems with Applications*, Vol. 23, 299-309.

Qian X., Ren T. and Wang C. (2008). A survey of pipe routing design, *Proceedings of 2008 Chinese Control and Decision Conference*, Yantai, China, IEEE, 3994-3998.

Riley D. R., Varadan P., James J. S. and Thomas H. R. (2005). Benefit-cost metrics for design coordination of mechanical, electrical, and plumbing systems in multistory buildings, *Journal of construction engineering and management*, Vol. 131, 877-889.

Russell A. D., Chiu C. Y. and Korde T. (2009). Visual representation of construction management data, *Automation in Construction*, Vol. 18, 1045-1062.

Songer A. D., Hays B. and North C. (2004). Multidimensional visualization of project control data, *Construction Innovation: Information, Process, Management*, Vol. 4, 173-190.

Ya-Hsin C., Meng-Han T., Shih-Chung K. and Chin-Wei L. (2013). Selection and evaluation of color scheme for 4D construction models, *Journal of Information Technology in Construction*, Vol. 18, 1-19.

Zhou C. and Yin Y. H. (2010). Pipe assembly planning algorithm by imitating human imaginal thinking, *Assembly Automation*, Vol. 30, 66-74.