Analysis and Application of BIM-Based District Heating Pipeline Network Digital Twin System

Guoshan Zhang[1], Yongxiang Fang[2,*], Quan Wen[1], Shijie Zheng[1], Yanmei Zhang[2]

[1]China Communications Construction Corporation Rail Transit Branch Beijing, Beijing 100088, China
[2]College of Pipeline and Civil Engineering, China University of Petroleum (Huadong), Qingdao 266580, China

*Correspondence: 2605858063@qq.com

Abstract. The traditional district heating network faces issues such as complex planning, barriers to information exchange, and excessive carbon emissions and energy consumption. Therefore, enhancing the intelligence of urban district heating network construction in China is essential. Firstly, this paper analyzes the current research status of Building Information Modeling (BIM) and digital twins in pipeline engineering. Secondly, combining the advantages of BIM supporting heterogeneous system data sharing and digital twins supporting bi-directional interaction, this study proposes a basic framework for a BIM-based district heating network digital twin system. Finally, based on the district heating network project in Jiangshan New City, Laixi City, a digital twin system was developed by integrating BIM, Geographic Information System (GIS), and Internet of Things (IoT) technology to create a pipeline network information carrier. The system demonstrates the feasibility of bidirectional interaction between the physical and virtual environments in district heating networks, enabling lean construction management, safety inspections, maintenance operations, and monitoring of carbon emissions and energy consumption.

Keywords: Building Information Modeling; Digital Twin; District Heating Network

1 Introduce

The thermal network is an important concealed infrastructure in northern municipal construction, and it is responsible for providing heating during the winter. As urban expansion continues, the design length of thermal networks has gradually increased. However, thermal networks are prone to cascading failures, where a single component failure can trigger a series of component malfunctions, potentially leading to heating interruptions [1]. In addition, external factors such as natural disasters, operational errors during construction, or accidental damage can also disrupt the normal function of thermal network components, compromising the integrity of the network system [2]. As the heat pipe network is laid deep underground, the traditional construction and inspection

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make it difficult to provide real-time feedback on the pipeline status, and personnel are required to conduct frequent on-site inspections. Once a problem occurs, it is difficult to troubleshoot promptly. Therefore, the construction of heat pipe networks urgently needs new technologies to improve the efficiency of construction and maintenance.

With the rise of intelligent technologies, the way urban services are delivered, monitored, and managed is undergoing significant changes. In large-scale, complex pipeline renovation projects and the construction of underground utility corridors, the use of Building Information Modeling (BIM) and digital twin technology for full lifecycle management can enhance the efficiency of pipeline construction and operation [3, 4]. As a result, improving the informatization and scientific management of pipeline construction has become an essential requirement for the efficient operation of cities [5]. This paper aims to summarize the complexity of current thermal pipeline construction and maintenance, highlight the necessity of digital construction, and explore the establishment of a BIM-based digital twin system for thermal pipelines. Additionally, it examines the application of digital twin technology in the thermal pipeline network project of Jiangshan New City in Laixi.

2 Problems in District Heating Network Construction

2.1 The Complexity of Thermal Pipeline Projects

Underground municipal pipelines are large-scale, diverse, complex projects with difficult management requirements due to their vast scope and intricate layouts [6]. The construction of urban district heating networks presents the following challenges: (1) the increasing scale of the network requires alignment with urban land-use planning. (2) The construction environment is complex, some sections of the pipeline cross the city center, and there are many influencing factors. (3) Involving multi-departmental coordination, conflicts exist between different management departments. (4) Updates and reconstructions need to take into account the original underground pipelines, and the operation of the original pipelines should be ensured when new pipeline sections are built.

As a key component of municipal pipelines, district heating networks not only face the aforementioned construction challenges but also require consideration of specific issues such as operational safety, improved thermal energy efficiency, and the management of thermal stress on the pipelines.

2.2 Obstacles in Network Informatization and Interaction

Urban district heating networks face challenges related to information interaction. If the data archives for urban pipelines are incomplete and the mechanisms for data sharing are inadequate, it becomes difficult to ensure the real-time availability, consistency, and accuracy of information [7]. The main issues currently identified are as follows: (1) The digital design level of municipal pipeline construction remains low, and there is a lack of fundamental mathematical and simulation models required for system development [8]. (2) New technology adoption is slow. The industry still relies on records management procedures and technologies from the last century [9]. (3) At each stage of pipeline construction, the participants only carry out phased information management, resulting in fragmented information, which is not conducive to information exchange and sharing throughout the pipeline life cycle.

2.3 Requirements for Green, Low-Carbon Emission Reduction

With the increasing frequency of extreme weather events worldwide, addressing carbon dioxide emissions has become more urgent [10]. The 14th Five-Year Plan for Housing and Urban-Rural Development Science and Technology designates low-carbon operational technologies for municipal infrastructure as a key priority, emphasizing the need for research on carbon emission reduction throughout the entire process of infrastructure construction and operation, including district heating systems [11]. This is because the construction of thermal pipeline networks involves the use of concrete materials, which generate significant pollution and carbon emissions. During the operational phase, energy losses in heat distribution also contribute to carbon emissions [12]. Although studies have demonstrated that digital technologies can reduce regional carbon emissions, the construction of district heating networks in China still primarily follows traditional methods, lacking precise data evaluation [13]. Furthermore, post-construction operation and maintenance are largely based on experience, leading to excessive resource consumption, which does not align with the "dual carbon" goals.

3 Current Research on the Digitalization of District Heating Networks

3.1 Current Applications of Building Information Modeling (BIM) Technology in District Heating Networks

Building Information Modeling (BIM) technology is regarded as the next-generation method for architectural design and information management within the construction industry [14]. BIM technology integrates information from multiple sources and decomposes it into various layers, creating an information model database for lifecycle management. It can be applied to all stages of pipeline construction and incorporates diverse data from design units into the operational management system [15]. BIM extends traditional 2D technical drawings of building design into 3D, sharing knowledge resources and providing information about facilities, thereby laying the foundation for decision-making throughout the facility's lifecycle [16]. The International Alliance for Interoperability released the IFC (Industry Foundation Classes) building data exchange standard in 1994, which provides standardized interoperability for BIM during project collaboration [17]. This standardized data model has made BIM technology widely favored, with numerous case studies accumulated in the construction industry.

Tian and Liang [18] presented successful global applications of BIM in the construction industry and addressed theoretical gaps in digital pipeline design by aligning BIM with the specific characteristics of pipeline construction projects. Han and Wang [19] introduced the time dimension by developing a BIM-4D model to optimize municipal pipeline construction schedule management. Guo [20] linked BIM models with schedule management to simulate the actual jacking process of thermal pipeline construction. Luo et al. [21] developed a sustainability-based multidisciplinary underground pipeline conflict optimization framework using BIM.

Although BIM technology has matured, its current model is relatively rigid and limited to the geometric attributes of the pipeline network. It lacks interaction with real-world entities and struggles to represent the physical characteristics of pipelines. Han et al. [22, 23] highlighted that BIM faces the challenge of "information silos." While BIM focuses on the forward design and construction process from "information" to "physical," it lacks systematic theoretical methods and technical strategies to support the reverse digitization process from "physical" to "information." Yang and Xing [24] proposed a new type of BIM that incorporates dynamic physical laws and interactive capabilities, extending building information into the physical world. However, existing BIM systems lack efficient reverse informatization technology and still rely on the on-site experience of construction personnel to identify and resolve discrepancies between the "physical" and "information" aspects of a building [25]. In summary, BIM technology remains constrained by traditional methods and has yet to fully enable digital pipelines to break free from these limitations.

3.2 Current Applications of Digital Twin Technology in District Heating Networks

The concept of Digital Twin was first introduced in 2003 by Professor Grieves during a Product Lifecycle Management course at the University of Michigan [26]. At its core, Digital Twin is a simulation technology that digitally mirrors a physical entity. It not only simulates the physical characteristics of the entity but also projects data streams into real-world space, enabling the physical object to perform functions based on specific commands. Digital Twin has been widely applied across industries, including manufacturing, energy, aerospace, engineering, urban development, healthcare, and agriculture [27-30].

The pipeline engineering industry has also taken notice of Digital Twin technology. Li et al. [31] believe that Digital Twin can effectively support the accurate perception of underground engineering features, high-fidelity modeling, virtual-physical mapping, and multi-physics simulations. Hlady et al. [32] proposed the creation of Digital Twin models during the pipeline construction phase to improve construction quality and pipeline integrity. Xiong et al. [33] integrated technologies such as aerial photogrammetry, 3D laser scanning, terrain modeling, oblique photogrammetry, and 3D modeling into Digital Twin to reduce operational costs and enhance safety management in pipeline systems. Liu et al. [34] integrated Digital Twin with BIM to display the dynamic spatial positions of excavators and buried pipelines in 3D, helping to avoid potential collisions and improve excavation safety in urban areas. Wang and Chen [35] used ANSYS Twin Builder software to create a smart pipeline network Digital Twin model. Kwag et al. [36] applied Digital Twin for fault prediction and health management of pipeline systems subjected to earthquakes and arbitrary loads. Guo et al. [37] proposed using the urban underground comprehensive utility corridor as the physical entity and applying Digital Twin throughout its entire lifecycle. Brahmbhatt [38] introduced a Digital Twin framework with modeling and calibration capabilities for monitoring water quality and locating leaks in water pipelines. Li et al. [39] utilized Digital Twin technology based on 3D-GIS (Geographic Information System) for smart control of district heating systems.

In summary, Digital Twin technology offers unique advantages in advancing the informatization and digitalization of the pipeline engineering industry. However, its application in district heating networks remains limited and is still in the exploratory phase. Current challenges include a lack of comprehensive solutions for real-world problems, the absence of standardized model components, and the inability to fully replicate the actual conditions of pipeline engineering projects.

4 Analysis of the Application of BIM-Based Digital Twin Technology

4.1 BIM-Based Digital Twin Framework for District Heating Networks

The Digital Twin technology provides a viable approach for achieving intelligent construction of district heating networks, addressing the limitations of BIM's bidirectional information interaction capabilities. Digital twins leverage the advantage of BIM in supporting data sharing between heterogeneous systems, overlapping and integrating building information with multimodal data to unify the underlying data structure expression. Therefore, this paper proposes a Digital Twin system for district heating networks based on BIM (shown in Figure 1). According to the characteristics of Digital Twin [40], the system offers two main functions: (1) Perception, where the system senses and analyzes the network entity and its surrounding environment, mapping a replica of the network entity in the information space. (2) Agency, where the twin projects data flows into the physical space of the network, enabling it to influence the surrounding real-world environment.

The perception and mapping capabilities of the Digital Twin rely on the integration of BIM and the perception system. BIM generates 3D models based on the design and construction drawings of the network, creating an information carrier that transforms physical entities into digital twins. The perception system utilizes Internet of Things (IoT) technology, deploying sensors at network nodes to collect dynamic data, which is pre-processed at the terminal and transmitted to the Digital Twin platform to update the physical state of the BIM model. The agency function is implemented by the control system. Through IoT technology, actuators are deployed at network nodes, converting data commands into control actions that alter the operational state of the physical network.

The digital twin system collects pipeline data to construct an information model, visualizing the environmental space and state data of the thermal pipeline. Staff can observe the construction and operation of the pipelines in real-time through the thermal pipeline twin, reducing the time delay in the inspection process. At the same time, with the projection function of the twin, staff can adjust the operating status of the pipeline network, achieving remote control. The digital twin system transforms the unidirectional feedback model into a bidirectional interaction, enhancing the interactive efficiency of construction and maintenance for district heating networks.

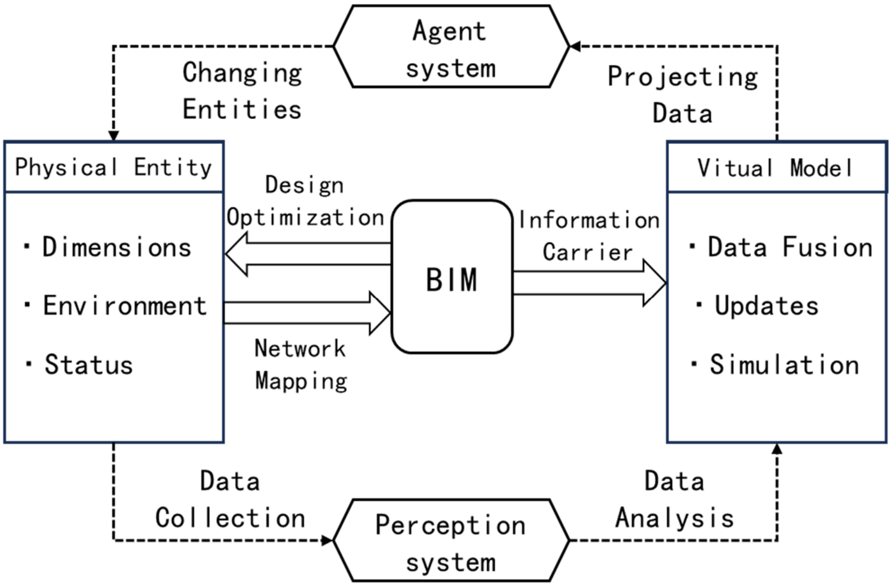

Fig. 1. The framework of digital twin pipe network system

4.2 Application of BIM-Based Digital Twin Technology in District Heating Networks

The district heating network project of Jiangshan New Town in Laixi City is situated in the Jiangshan Industrial New Town area of Laixi City. The pipeline route follows existing roads and crosses several intersections, and there are many underground pipelines within the construction scope of the pipeline network route. The project's critical points include three sections of pipe jacking, involving three working shafts and three receiving shafts. The challenges include the prohibition of excavation near newly constructed roads, limited space for foundation excavation, and difficulties in determining the underground conditions of the pipelines. Therefore, leveraging the Digital Twin system to map real-time construction scenarios facilitates more precise and efficient construction management for the project team.

The digital system for the Laixi City heating network, driven by BIM, integrates digital twin technology into the construction and operation of the heating network. This system creates a digital twin of the pipeline in a virtual space, enabling functionalities such as construction management, operational inspections, and carbon emission monitoring.

Fig. 2. Digital Twin Construction Management Module for District Heating Networks

Fig. 3. Digital Twin Operation and Maintenance Inspection Module for District Heating Networks

During the construction phase of the heating network, the digital twin system maps the project through its twin model, integrating data to evaluate critical project elements such as construction difficulty, progress, and cost. The system is connected to the personnel management system, enabling real-time location tracking and efficient allocation of workers (shown in Figure 2). When on-site construction is underway, the digital twin system connects to on-site monitoring devices, providing real-time feedback on operational status. By visualizing the virtual twin, managers can gain a comprehensive understanding of the project, guide on-site operations, quickly identify construction risks, implement corrective measures, control progress, and ensure quality.

Fig. 4. Digital Twin Carbon Emission Monitoring Module for District Heating Networks

During the operation and maintenance inspection phase of the pipeline network, the digital twin system relies on sensors embedded at network nodes to detect anomalies in pipeline status and issue alerts. These alerts are prioritized based on their severity. The inspection system tracks the status of alert resolutions to prevent oversights or missed inspections (shown in Figure 3). Additionally, the system can compile statistics on the frequency of alerts over the month and analyze inspection efficiency within a given time frame.

The digital twin system is also equipped with a thermal mapping feature. During pipeline operation, sensors can collect real-time data on temperature variations in the hot water within the network, monitor pipe pressure, and measure hot water flow rates (shown in Figure 4). Additionally, the system integrates big data technologies, enabling the analysis of localized heating performance. By applying algorithms, it assesses heating efficiency and thermal losses, supporting management in controlling carbon emissions.

5 Conclusion

This paper summarizes the challenges currently faced in the construction and operation of district heating networks. It reviews the application status of BIM and digital twin technologies in such projects and proposes a framework for building a district heating network digital twin system based on BIM. Using the district heating network project in Jiangshan New City, Laixi, as a case study, the implementation of a BIM-based digital twin system is demonstrated. The key findings are as follows:

(1) Due to the complexity of district heating network planning, barriers to information infrastructure, and the need for low-carbon emission reductions, there is an urgent need for a digital construction and operation mode for district heating systems.

(2) By integrating the advantages of BIM and digital twin technologies, a BIM-based district heating network digital twin system was constructed. This system allows construction managers to capture the physical and functional attributes of the heating network, enabling bidirectional interaction between the real and virtual environments.

(3) The Jiangshan New City district heating network project, through the use of the BIM-based digital twin system, achieved lean construction efficiency, ensured safe inspections, and promoted green, low-carbon emissions reduction.

(4) The functions of the digital twin system are primarily focused on mapping the pipeline status. The virtual twin has limited control authority over the physical pipelines, which hinders further optimization of bidirectional interaction capabilities. Future research could focus on enhancing the digital twin system's ability to optimize and reconstruct physical pipelines, gradually achieving proactive interaction between the twin and the physical entities.

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