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Review

A Review of Life Cycle Construction Process and Cutting-Edge Technology in Prefabricated MEP Installation Engineering

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Abstract: Prefabricated installation, a pivotal study in the realm of contemporary construction practices, delves into the utilization of prefabrication within mechanical, electrical, and plumbing (MEP) systems. Despite its ascending prominence, the domain grapples with ambiguities in application pathways, uncertain developmental trajectories, and the absence of a holistic technical paradigm. This research endeavors to bridge these gaps by conducting a thorough and multidimensional investigation into the current landscape of prefabricated MEP installation initiatives. This study meticulously dissects the paradigm from five critical vantage points: historical evolution, standards and regulations, life cycle analysis, technological applications, and corporate implementation strategies. At present, there is still a lack of standards and specifications specifically for the field of assembled MEP installation. The analysis reveals a trend towards intelligent and sustainable installation practices in prefabricated MEP projects. The research predominantly focuses on the design, production, and installation stages. Notably, building information modeling (BIM) emerges as the most prominent technology, followed by the Internet of Things (IoT) and 3D laser scanning, with extended reality (XR) technologies gaining traction. Large, state-owned construction firms are spearheading innovative applications in this realm. In summary, this paper provides an overview and outlook for the development direction and the application of cutting-edge technologies in prefabricated MEP installation projects, with the aim of supporting the industry's advancement.

Keywords: prefabricated MEP; MEP installation; life cycle; cutting-edge technology; BIM

Citation: Yan, G.; Yang, Y.; Zhang, H.; Li, Z.; Chen, S.; Zhao, X.; Sun, Z.; Fan, X.; Zhang, M.; Huang, L.; et al. A Review of Life Cycle Construction Process and Cutting-Edge Technology in Prefabricated MEP Installation Engineering. *Buildings* **2024**, *14*, 630. https://doi.org/10.3390/buildings14030630

Academic Editors: Heap-Yih Chong and Sathees Nava

Received: 4 December 2023
Revised: 18 January 2024
Accepted: 23 February 2024
Published: 27 February 2024

1. Introduction

In our rapidly evolving contemporary society, the construction industry, as a vital foundation of human life, is facing an increasing number of challenges and opportunities. With the relentless advance of urbanization and the sustained surge in population, there has been a continuous expansion in the demand for construction. This has given rise to heightened expectations for construction projects to achieve enhanced levels of efficiency, rapidity, and sustainability. Given this background, "prefabrication" has emerged as a highly scrutinized innovative solution.

MEP installation engineering, often referred to as the "circulatory system" of a building, is an indispensable component. It provides essential supply and support to structures, ensuring the proper operation of various functions and equipment. Moreover, it profoundly impacts the sustainability, comfort, and safety of buildings. Traditional MEP installations often require a significant amount of labor, materials, and time. For instance, the shortage of skilled workers may lead to a rise in labor costs, as the imbalance between demand and supply drives up workers' wages. A lack of skills can cause project schedules to slip, as it may take longer to find qualified workers to complete specific tasks. Unskilled workers may not achieve the precision required for the installation of prefabricated components, which can affect the quality and safety of the final structure. In contrast, under the concept of prefabricated installation, core components like MEP equipment and pipelines can be prefabricated in factories and quickly assembled on-site [1]. This approach, which combines factory production with on-site prefabrication, significantly enhances construction efficiency, reduces resource wastage, and minimizes environmental impact, prompting the construction industry toward the direction of intelligence and sustainability [2,3].

The advantages of prefabricated MEP installation lie not only in time and resource savings but also in its remarkable adaptability and flexibility. Customized solutions can facilitate the rapid installation of various types of pipelines to meet the demands of different scenarios. Modular design also offers a more convenient option for the maintenance and upgrade of MEP equipment [4,5]. Specifically, prefabricated MEP installation boasts the following advantages to adapt to broader trends and challenges in the construction industry: Standardization: Prefabricated components can be standardized in a factory setting, reducing the complexity of on-site construction and the demand for specific skills. Automation: Automation technologies can be applied in the manufacturing process, reducing reliance on manual labor and easing the demand for skilled labor. Efficiency gains: Factory prefabrication can increase production efficiency and reduce the time required for on-site installation, thereby shortening construction periods and reducing the need for labor. Quality control: In a controlled factory environment, the quality of prefabricated components can be better ensured, minimizing the possibility of on-site corrections and rework, thus saving labor resources. Increased safety: Prefabrication reduces on-site work, especially in elevated and complex environments, thereby reducing the need for highly skilled safety operators.

However, achieving the modularization of MEP is not without its challenges. It necessitates the resolution of collaborative issues between engineering design and module manufacturing, ensuring module quality and reliability. Simultaneously, incorporating advanced digital technologies such as BIM, IoT, robotics, terrestrial laser scanning (TLS), and XR is essential to propel MEP installation into the digital era.

Numerous scholars have embarked on in-depth research endeavors concerning the intricacies of prefabricated MEP (mechanical, electrical, and plumbing) installations. Among them, Wu et al. [6] focused on the lack of clarity regarding MEP on-site installations, which can lead to conflicts in pipeline design and construction. They conducted extensive literature reviews and quantitative analyses and used questionnaires to quantitatively analyze and identify 24 factors that influence prefabricated MEP installations.

In terms of MEP model design, the absence of comprehensive 3D models has emerged as a pivotal challenge within the MEP installation domain [7,8]. Wang et al. [9] introduced a practical BIM framework aimed at streamlining MEP layouts from initial design through the construction phase. Within this framework, the BIM model is delineated into five distinct levels of detail: the 3D MEP preliminary design model, the 3D MEP detailed design model, the 3D MEP construction design model, the MEP construction model, and the MEP prefabricated model. They established a set of four coordination steps to address design and constructability issues effectively.

In the domain of MEP module optimization, Samarasinghe et al. [10] developed an automated and efficient modular algorithm by integrating fuzzy logic, dependency structure matrices, and hierarchical clustering. This algorithm calculates the optimal number of modules and module partition points based on the prefabrication and handling costs associated with each module, ultimately minimizing the overall installation cost. Furthermore, Tserng et al. [11] proposed a rational planning algorithm that employs spatial planning techniques to divide large and intricate MEP systems into several smaller prefabricated components. This approach enhances the efficiency of the installation process. An illustrative example was provided to validate the effectiveness of this algorithm.

To address issues related to clashes in MEP, Akponeware et al. [12] conducted an investigation into the fundamental causes of conflicts concerning the "clash avoidance" aspect of the UK's BIM design phase standards. They employed an interpretive sequential mixed-method approach to gather and analyze experiential data from BIM coordinators worldwide. On a similar note, Hsu et al. [13] utilized machine learning and heuristic optimization techniques to develop an artificial intelligence system tailored for resolving design conflicts of this nature. Additionally, Xie et al. [14] created an automated rule-checking system based on knowledge management and building information modeling. This system integrates model information extension, information extraction, system integrity checks, and component spacing inspections, thus enhancing efficiency in dealing with design conflicts.

Finally, in addressing the issue of quality assurance in MEP module installations, Guo et al. [15] introduced an automated geometric quality detection technique based on three-dimensional laser scanning. This method involves algorithmic fitting to scan data for detecting each MEP element within the module, tailored to the specific shapes of various element types. Furthermore, Chalhoub et al. [16] leveraged immersive augmented reality (AR) to identify discrepancies in the architectural information model within ceiling ventilation spaces. The results indicated that immersive AR can effectively be employed to inspect constructed building elements for compliance with the expected model, simultaneously improving the speed and accuracy of inspections.

However, prefabricated MEP installation engineering is a systematic and continuous construction technology [17], and most studies have only paid attention to one certain stage, one specialty, or one part of the project, lacking a holistic and systematic perspective. At the same time, the application maturity of different prefabricated MEP installation-related technologies varies significantly. The challenging integration of technology and engineering, along with data security and privacy and other issues [18], plagues the development of prefabricated building MEP. Therefore, what the enabling technologies for prefabricated MEP installation engineering are and how to build the technical system of prefabricated installation engineering while maintaining the advancement and coordination of the technical system are the main problems faced at present [19,20]. In addition, as the practitioner of project landing, the technology's research and development, as well as the innovation of MEP installation engineering of prefabricated buildings, are also issues that need attention.

Consequently, these aforementioned studies demonstrate the significant efforts made by numerous scholars in the field of MEP. However, there is currently no comprehensive overview of the research progress within the MEP domain. Therefore, this article aims to delve deeply into the current state of development, advantages, and challenges of modular MEP systems, analyze the prospects for the application of MEP installations, and discuss potential solutions for overcoming technical challenges. The goal is to make a meaningful contribution to the sustainable development of this industry.

2. Research Framework and Literature Analysis

2.1. Research Framework

In order to gain an in-depth understanding of the current research status of modular MEP installation projects in China, this paper follows the research framework outlined below:

1. Scope determination: First, the scope of the literature review for modular MEP installation projects is established.
2. Literature collection: Second, the relevant literature is collected based on defined search criteria. Suitable databases are selected for this purpose. Subsequently, the collected articles undergo keyword clustering analysis and timeline clustering analysis to identify current research hotspots in the field of modular MEP systems.
3. Analysis of research hotspots: Building on the results of the literature analysis, this research paper elucidates the current state of development in modular MEP instal-

lation projects from the perspective of both the entire construction process and the application of cutting-edge technologies.

4. Summary and future prospects: Finally, based on the findings of the literature analysis, this paper summarizes the current research status and outlines prospective directions for future research in modular MEP installation projects. Figure 1 illustrates the process of literature review analysis.

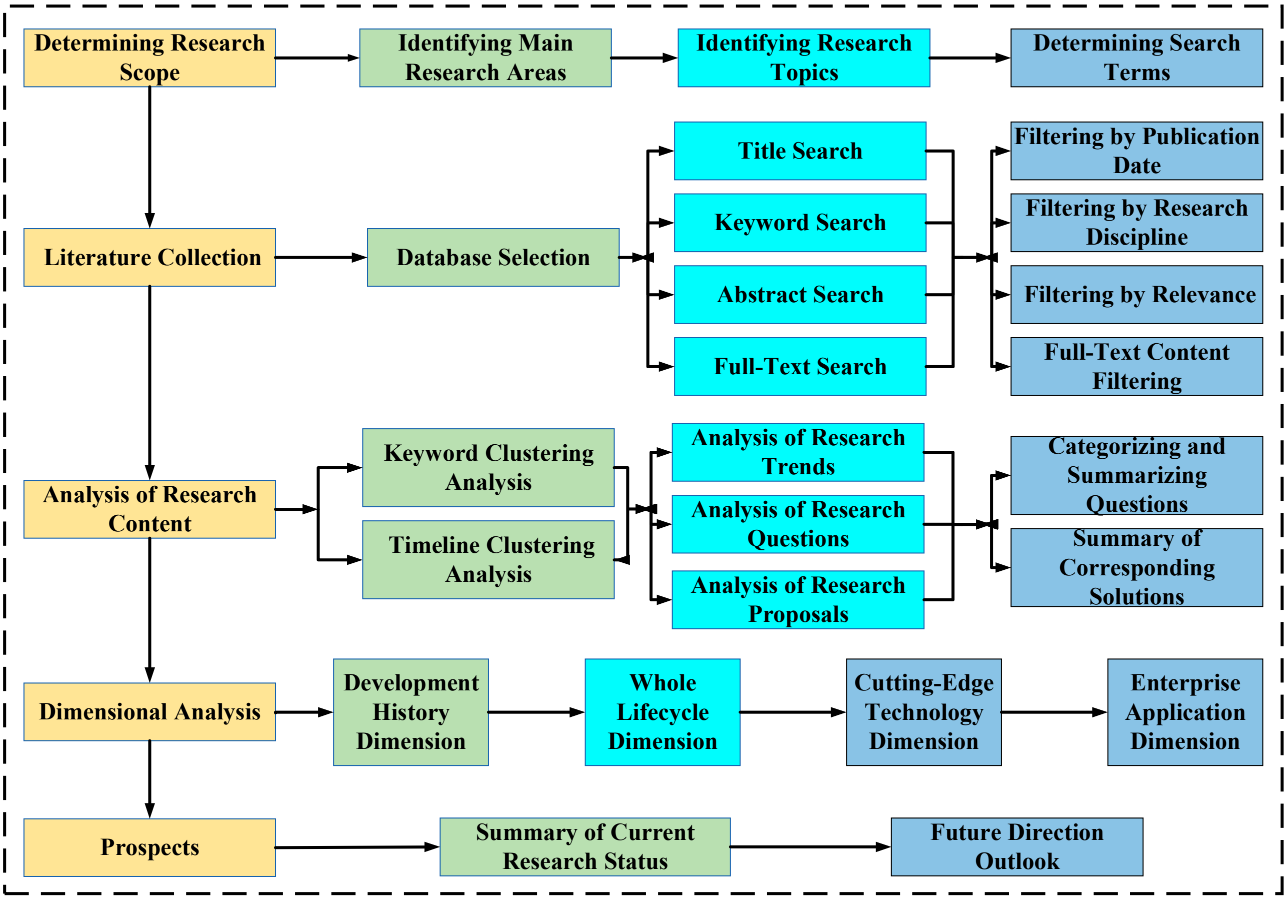


Figure 1. Document analysis framework.

2.2. Literature Analysis

2.2.1. Literature Retrieval and Screening Criteria

To ensure that the search results align with the research topic, specific literature search criteria (Table 1) and literature selection criteria (Table 2) have been developed. These criteria serve as guidelines for retrieving and screening the relevant literature effectively.

Table 1. Document retrieval standard (self-drawn).

Retrieval criterion 1	Focus on academic journals in the fields of civil engineering, and mechanical and electrical installation to ensure that the relevant literature is retrieved.
Retrieval criterion 2	Define search keywords and search structure.
Retrieval criterion 3	Limit the search to databases such as CKIN, Scopus, and Web of Science.
Retrieval criterion 4	Specify the time range for journal publications.
Retrieval criterion 5	Determine the search timeframe and the required types of articles, such as academic papers, review articles, and conference papers, to meet the research requirements.

Table 2. Literature screening criteria (self-drawn).

Screening criterion 1	Exclude literature that is unrelated to the field of modular MEP installation.
Screening criterion 2	Remove literature with research content related to other “modular construction” topics, such as “modular concrete structures” or “modular steel structures”.
Screening criterion 3	Eliminate literature classified as consultation, scientific awards, conference reports, engineering demonstrations, teaching materials, or training materials.
Screening criterion 4	Read the full text of articles and exclude those with superficial or lacking content.

2.2.2. Document Retrieval and Result Analysis

Before conducting literature searches, it should be noted that the field of literature review is within the civil engineering domain, with the research topic being modular MEP installation. The search terms and search structure are determined as follows: SU % = ‘modular MEP’ OR SU % = ‘MEP modularization’ OR SU % = ‘MEP installation’ AND KY % ‘modular MEP pipelines’ OR KY % ‘modular utility rooms’ OR KY % ‘modular support structures’ OR KY % ‘modular MEP equipment’ OR TKA % ‘modular installation technology’. Based on the specified keywords, literature searches were conducted in the CNKI (China National Knowledge Infrastructure) database, Wan Fang Database, and the Web of Science database for MEP installation-related documents. The selected document types were limited to journal articles, and the publication years were restricted from 2013 to 2023. This resulted in a total of 2702 articles. After an initial selection process, 520 articles were found to be related to modular MEP installation. Further refining the selection criteria, articles unrelated to the field of building MEP installation were removed, leaving 470 articles. Documents that focused on other modular objects such as “modular buildings,” “modular concrete structures,” “modular steel structures,” and “modular structural components” were excluded, resulting in 332 articles. Articles categorized as consultancy, technology awards, conference reports, engineering demonstrations, teaching, and training materials were then removed, leaving 310 articles. Finally, after reading the full texts of these articles, a manual selection process was carried out to retain documents that were highly relevant to modular MEP installation and had rich and specific research content. This yielded a final selection of 166 articles.

In addition, a keyword clustering and timeline analysis is conducted for the screened literature. Figure 2 illustrates that research in the field of modular MEP installation spans the entire process of MEP installation engineering, covering various phases from design to production, transportation, installation, and maintenance. It also encompasses research on modularization, integration, industrialization, and green construction in MEP installation. Through timeline clustering analysis, Figure 3 reveals that, starting from 2013, a significant portion of the research focused on the prefabrication and installation methods in building MEP systems. In 2015, there was a shift towards more in-depth design of MEP systems. By 2018, the research emphasis turned to the modular and standardized installation of building MEP systems. In 2020, there was heightened focus on green construction and industrialization in the research.

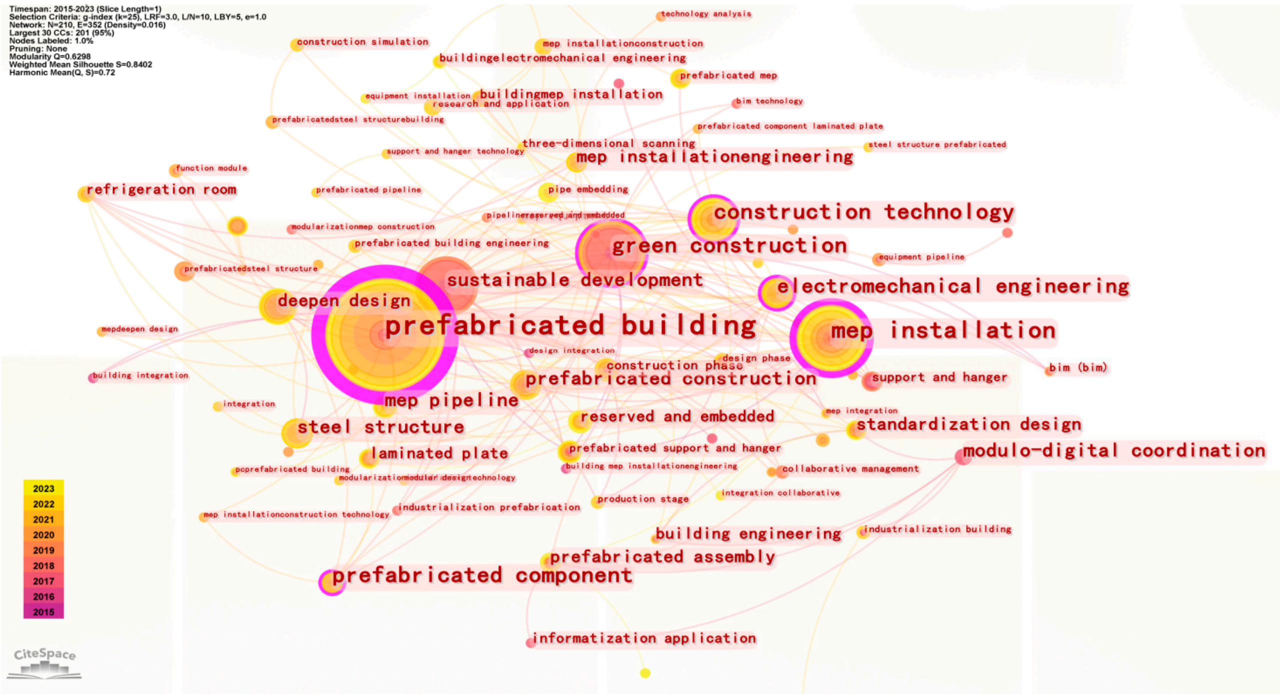


Figure 2. Keyword cluster analysis.

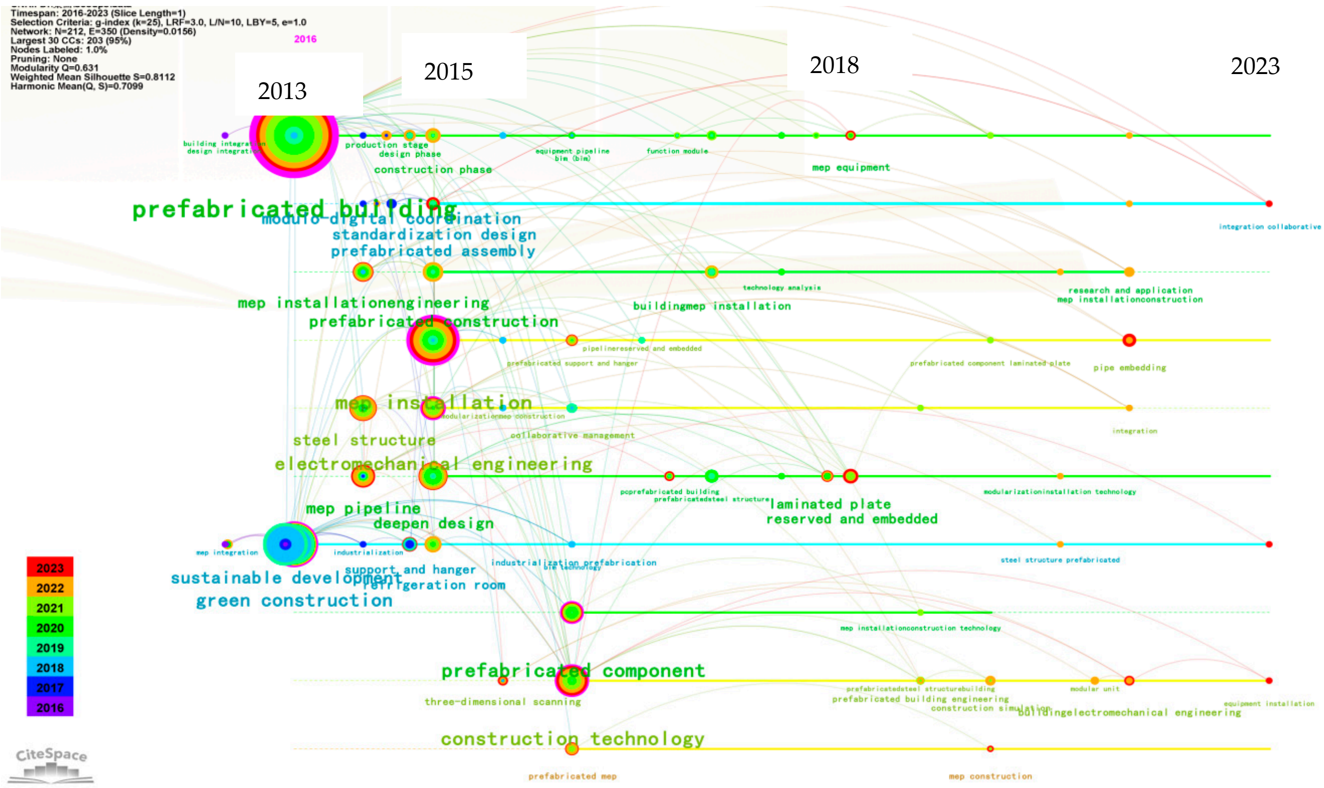


Figure 3. Timeline clustering analysis.

3. Overview of the Development History of MEP Installation Engineering in Prefabricated Buildings

Since the last century, prefabrication techniques have been continuously evolving, bringing revolutionary changes to the construction industry. Through prefabricated installation techniques, MEP components such as machinery, pipelines, and cable trays are processed, assembled, and tested in advance at factories. Subsequently, they are transported in whole or in part to the construction site for installation. Based on a review of the existing literature [21–29], the development of the modular MEP installation industry can be categorized into several stages, as illustrated in Figure 4:

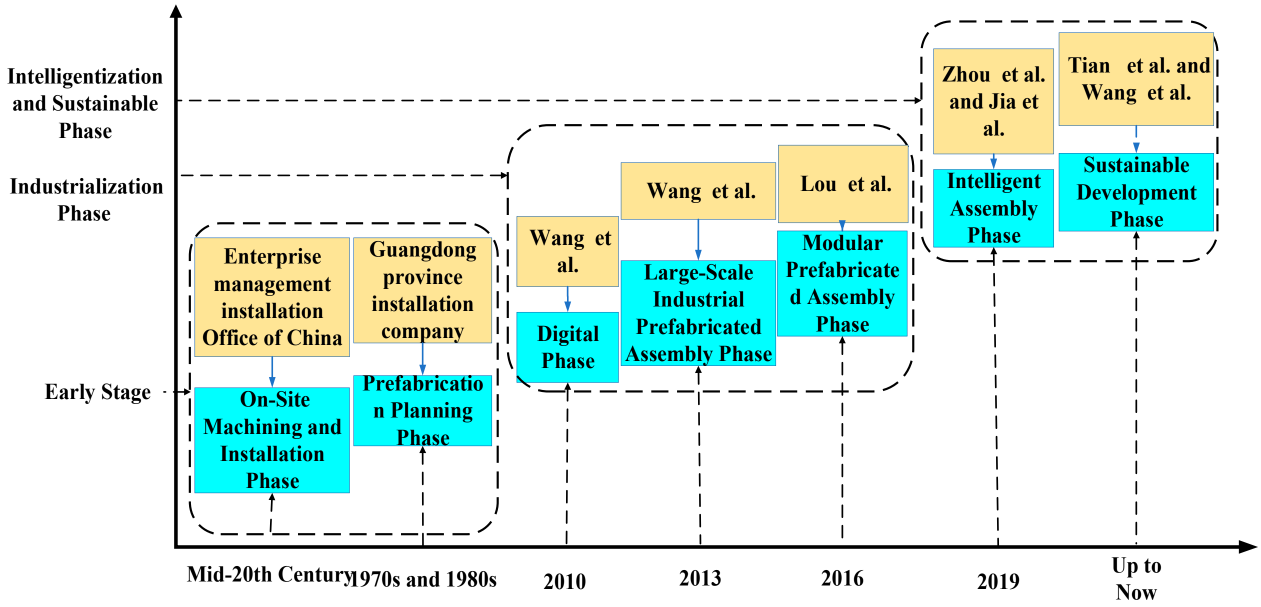


Figure 4. Development history of building MEP installation Engineering [5,30–36].

- Field processing and installation phase: In the early stages of prefabricated construction for MEP (mechanical, electrical, and plumbing) systems, the projects were relatively straightforward, primarily involving the prefabrication of basic MEP equipment such as ducts and water pumps. These components were usually fabricated on-site and installed there.
- Prefabrication planning phase: As the construction industry pursues efficiency and installation quality, prefabricated installation technology has further evolved. Many manufacturers have incorporated new technologies for component production and early prefabrication of parts, resulting in greater diversity in the quality and design of MEP components.
- Digital phase: With the continuous advancement of digital technology, prefabricated installation has entered the digital age. The advent of BIM technology, in particular, has brought new opportunities to MEP installation, with an emphasis on detailed MEP design. Through digital design and production, prefabricated installation has achieved a high level of precision and integration.
- Large-scale prefabrication and industrial prefabricated phase: As industrialization in construction advances, prefabricated MEP installation projects see further development. The application of industrial production techniques and prefabricated lines allows for the large-scale batch production of MEP equipment in factories, increasing efficiency and standardization in the prefabrication of MEP components and pipeline sections.
- Modular prefabrication and prefabricated phase: The modular installation phase is a critical stage of development. This phase focuses on assembling, connecting, and installing previously manufactured MEP equipment, components, or modular units at the target location following specific standards and procedures. Precision and quality of installation become paramount during this phase.
- Intelligent prefabricated phase: Intelligent installation emphasizes the use of digital, automated, and smart technologies to enhance construction efficiency, precision, and

sustainability. During this phase, advanced technologies such as sensors, data analytics, artificial intelligence, and machine learning enable real-time monitoring, predictive maintenance, remote operation, and optimized control, making prefabricated MEP installation more intelligent.

- Sustainable development phase: Prefabricated MEP installation increasingly emphasizes sustainability. Using prefabricated components can reduce the impact of on-site installation on resources and the environment, while prefabricated installation offers better control over material waste. Many scholars are now focusing on greener and more efficient prefabrication methods.

Prefabricated MEP installation, as a critical part of construction projects, is rapidly evolving, providing new possibilities for future building development while meeting the growing demands and challenges of the construction industry.

4. Standards and Regulations Related to Prefabricated MEP Installation

Standards and regulations play an essential role in the design, production, and installation of prefabricated MEP Installation. They not only ensure the quality and safety of the systems but also promote the development and innovation of the industry. While standards and regulations for prefabricated construction have been preliminarily established, a corresponding regulatory system for prefabricated MEP installation is yet to be developed. This chapter will review the standards and regulations related to prefabricated MEP installation projects at the national and industry levels and elaborate on the stipulations set forth for prefabricated MEP installation in these regulations.

4.1. Chinese National Standards and Atlas

Chinese National Standards atlases provide requirements for the design and construction drawings of piping systems in modular MEP installation projects. These standards help ensure the correct installation and operation of piping systems. Tables 3 and 4 show China's national standards and atlas standards, respectively

Table 3. Chinese National Standards related to modular MEP.

Standard Name	Number	Content
"General Technical Requirements for Prefabricated Supports and Hangers" [37]	GB/T 38053-2019	Specifies the requirements for connecting components, channel steel, and other support and hanger accessories in prefabricated supports and hangers, including test methods, inspection rules, marking, packaging, transportation, and storage requirements.
"Technical Specification for Prefabricated Composite Risers" [38]	GB 50682-2011	Stipulates the design, manufacturing, installation, testing, and acceptance requirements for prefabricated composite risers.
"Assessment Standard for Prefabricated Buildings" [39]	GB/T 51129-2017	Specifies the assessment of prefabricated buildings, using the prefabrication rate to determine the degree of prefabrication of the building, and prescribes the calculation method for the pipeline separation ratio.

Table 4. Chinese National Standards atlases related to modular MEP.

Atlas Name	Number	Content
"Prefabricated Building Electrical Design and Installation" [40]	20D804	Illustrates detailed installation and connection diagrams for prefabricated electrical equipment, electrical conduits, lightning protection, and grounding devices, specifying requirements for reserved embedding, node structure, and operational space.

Table 4. *Cont.*

Atlas Name	Number	Content
"Selection and Installation of Prefabricated Indoor Pipe Supports and Hangers" [41]	16CK208	Presents prefabricated connectors between supports, hangers, and steel structures; offers comprehensive support and hanger design examples for various pipelines; introduces methods and precautions for selecting and installing prefabricated supports and hangers.
"Prefabricated Pipe Supports and Hangers (Including Seismic Supports and Hangers)" [42]	18R417-2	Depicts detailed installation and connection diagrams for prefabricated electrical equipment, electrical conduits, lightning protection, and grounding devices, specifying reserved embedding, node structure, and operational space requirements.
"Metal and Non-Metal Air Duct Supports and Hangers (Including Seismic Supports and Hangers)" [43]	19K112	Details various types of air duct supports and hangers, including prefabricated and seismic supports and hangers, systematically presenting types, installation illustrations, applicable conditions, and material specifications.

4.2. Industry Standards

Industry standards are set by relevant industry associations or organizations to guide specific practices in modular MEP installation projects. These standards can more specifically meet the needs of particular industries. For example, the HVAC industry might develop specialized HVAC standards. Table 5 shows the industry standards related to MEP.

Table 5. Industry standards related to modular MEP.

Standard Name	Number	Content
"Technical Standard for Modular Facilities on Construction Sites" [44]	JGJ/T 435-2018	Specifies the application of modular facilities on construction sites, including design, construction, and acceptance requirements for modular MEP projects.
"Technical Standard for Prefabricated Steel Structure Residential Buildings" [45]	JGJ/T 469-2019	Regulates the full life cycle design, production, construction installation, quality acceptance, use, maintenance, and management of equipment and pipeline systems in prefabricated steel structure residential buildings.
"Design and Selection Standard for Prefabricated Residential Buildings" [46]	JGJ/T 494-2022	Guides the design and selection of equipment and pipeline systems in prefabricated residential buildings.
"Technical Standard for Prefabricated Interior Decoration" [47]	JGJ/T 491-2021	Regulates the design, production, transportation, construction installation, quality acceptance, and maintenance of equipment and pipelines in prefabricated interior decoration. Follows the principle of pipeline separation, coordinating equipment and various systems.
"Building Inspection Technical Standard for Prefabricated Residential Buildings" [48]	JGJ/T 485-2019	Regulates the inspection of equipment and pipelines in prefabricated residential buildings.
"Technical Specification for Modular Indoor Greywater Integrated Systems" [49]	JGJ/T409-2017	Regulates the design, installation, commissioning, acceptance, and maintenance of modular indoor greywater integrated systems.
"Modular Air Conditioning Room Equipment" [50]	JG/T447-2014	Specifies terms and definitions, classification and marking, general requirements, requirements, test methods, inspection rules, marking, packaging, transportation, and storage for modular air conditioning room equipment.

Although China has made progress in standardization in the construction field, the lack of comprehensive standards and regulations specific to prefabricated MEP leads to uncertainties in design, manufacturing, and installation, and the level of standardization still needs improvement. This is particularly true in the modular design, installation, and acceptance of prefabricated MEP, and other related regulations. To achieve long-term development in this field, more comprehensive and detailed standards and regulations need to be developed to improve internal coordination within the industry.

5. Life Cycle Analysis of the Research Progress Regarding Prefabricated MEP Installation Engineering

Prefabricated MEP installation is a highly systematic and continuous construction technique, yet most research has focused only on specific phases, disciplines, or parts of the project, lacking a comprehensive approach [30].

This section, primarily oriented around the entire project life cycle, provides an overview of the development of modular MEP installation projects throughout the construction process. It delves into the issues and challenges encountered at various stages. Figure 5 demonstrates that the majority of research has concentrated on the design, production, and installation phases of modular MEP installation, with limited studies on the transportation and maintenance phases.

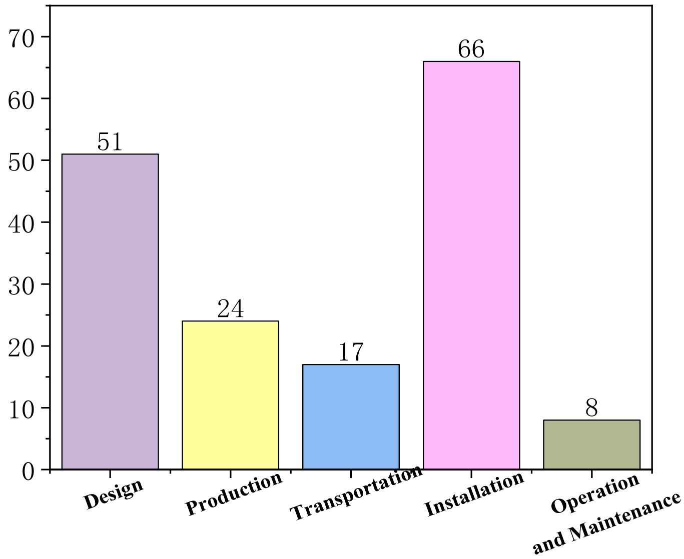
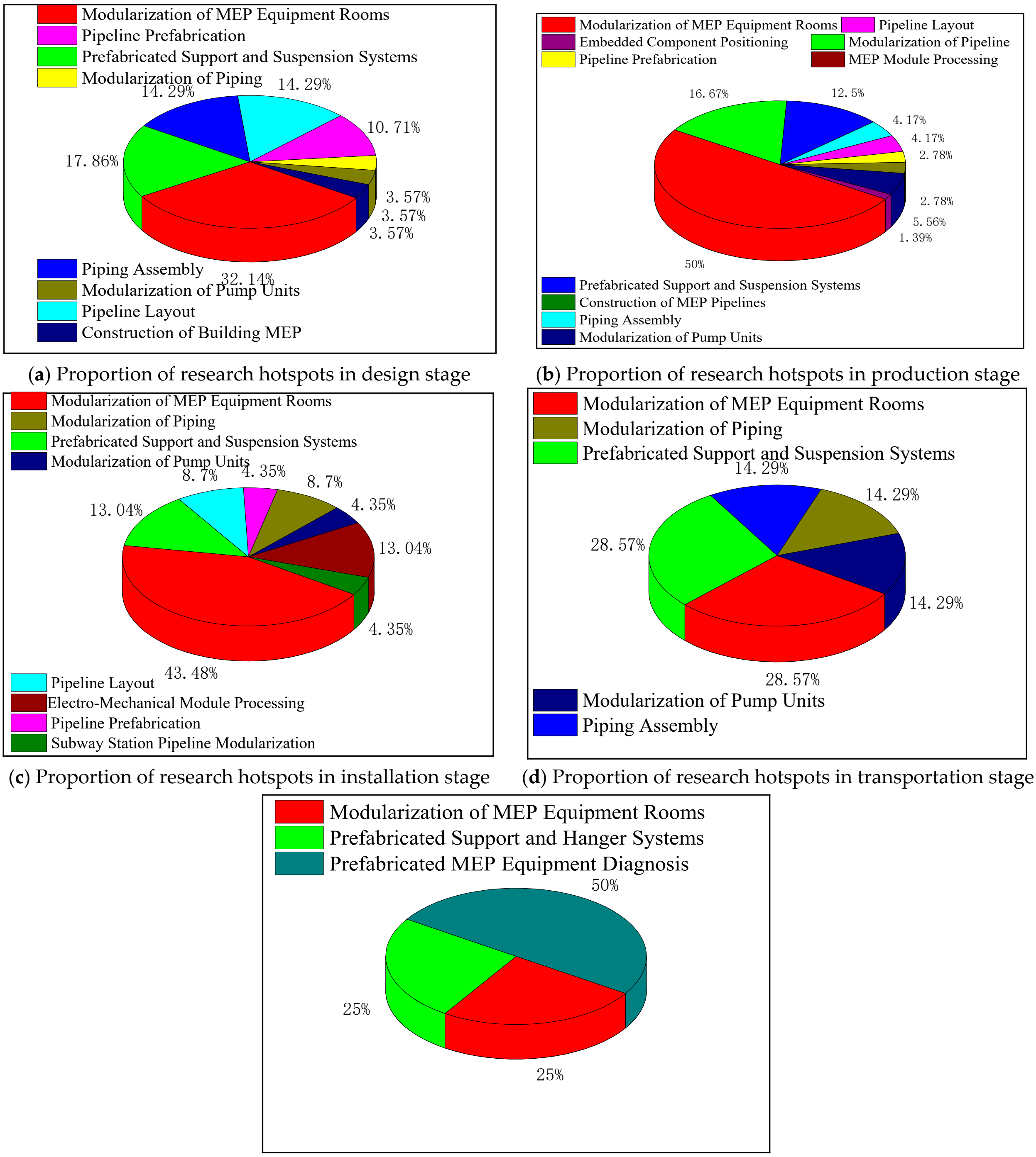


Figure 5. Proportion of the number of MEP documents of prefabricated buildings in each stage after screening (units–copies).

To gain a deeper understanding of the research hotspots within each stage, the selected literature is categorized into various focus areas. These include modularized equipment rooms, design and installation of modular supports and hangers, pipeline layout, and pipeline prefabrication, among others. As seen in Figure 6, modularized equipment rooms hold the highest prominence across the various phases of the MEP construction process. Additionally, the proportion of attention given to each research object varies across stages, with modularized equipment rooms receiving the highest attention, followed by modular supports and hangers, pipeline layout, and pipeline prefabrication. The priority of focus areas varies according to the characteristics of each stage.



(**a**) Proportion of research hotspots in design stage

(**b**) Proportion of research hotspots in production stage

(**c**) Proportion of research hotspots in installation stage

(**d**) Proportion of research hotspots in transportation stage

(**e**) Proportion of research hotspots in operation and maintenance stage

Figure 6. Proportion of MEP research hotspots in the life cycle of prefabricated buildings.

In order to gain a deeper understanding of the characteristics, key issues, main solutions, and considerations at each stage of MEP construction, this section provides an analysis from five aspects: modular design, prefabricated production, logistical transportation, modular installation, and intelligent operation and maintenance.

5.1. Modular Design

Modular design in MEP construction involves using specific modeling tools and plugins to divide various components into different modules. Each module is prefabricated and processed separately, and then transported to the construction site for installation. This design approach is applied throughout the entire construction cycle of MEP modules. It can be categorized into modular design for equipment rooms and modular design for pipelines. The following analysis explores the main research topics in MEP modular design, focusing on these two aspects.

5.1.1. Design Tools

To enhance the efficiency of modular design in MEP construction, various research and development organizations have developed modular design plugins with diverse functionalities. Table 6 provides a comparative analysis of the functionalities of these design tools.

Table 6. Comparative analysis of design tool functions.

Analysis Dimension	**Supporting Design Dimension**				**Engineering Quantity Estimation Dimension**	**Analysis and Calculation Dimension**	
Tool Name	**Automatic Break and Connect**	**Automatic Layout**	**Automatic Division**	**Automatic Numbering**	**Component Report Statistics**	**Support and Hanger Verification**	**Calculation Sheet Generation**
BIM Master (Mechanical and Electrical)	●	●	●	●	●	●	○
Oliveshan MEP	●	○	●	○	○	●	●
PM Hibim MEP Software (V3.5.4)	○	●	○	○	○	●	●
BIMspace MEP	●	●	●		○	●	●
BIM Modeling Assistant	●	●	●	●	○	○	○

Note: ● indicates that the tool has the functionality for that dimension, ○ indicates that the tool does not possess that functionality.

5.1.2. Modular Design

Modular Design for Equipment Rooms

Modular design for equipment rooms is a crucial aspect of the entire lifespan of MEP installation. It significantly impacts module production, transportation, and installation. The principles of modular design for equipment rooms serve as the basis for the feasibility, cost effectiveness, safety, and convenience of dividing MEP modules.

For instance, Zhu et al. [30] discussed modular design and construction of equipment rooms using a hospital data center as an example. Design principles for newly constructed equipment rooms were presented, along with the differentiation between components suitable for modular prefabrications and other construction elements. Yu et al. [31] based on high-precision 3D segmentation design, analyzed and discussed the application of prefabricated construction technology for pipeline modules in large-scale refrigeration equipment rooms using the Shanghai Museum East Pavilion as a case study.

Additionally, when designing modular equipment rooms, interchangeability and compatibility of modules should be considered, enabling flexibility in combining and replacing different modules to meet varying project requirements and changes.

Modular Design for Pipelines

The modular design of pipeline segments involves various considerations. This includes the layout of pipeline modules in a two-dimensional plane, transitioning to three-dimensional space, and determining the connection methods between modules. It is essential to take into account building structure and functional requirements throughout the design process. Moreover, a focus on the characteristics of the pipeline system and operating environment is essential to ensure the successful implementation and performance of modular design.

The key step in the design of modular pipeline segments is the division between standard segments and free segments [32]. Liu et al. [33] based on high-precision 3D segmentation design, analyzed and discussed the application of prefabricated construction technology for pipeline modules in large-scale refrigeration equipment rooms. Practical experience has shown that the proper arrangement and use of free segments aid in the smooth prefabrication and splicing of different pipeline module units on-site. Furthermore, modular design for pipeline systems must avoid conflicts with other equipment or structures, ensuring clear access and maintenance space for pipelines.

In terms of connecting pipeline modules, the design of pipeline modules should focus on factors such as the trajectory of the pipeline, elbows, and connection points. Efforts should be made to minimize pipe bends and corners, ensuring that different pipeline module segments can be closely connected within a two-dimensional plane. This reduces energy losses and flow resistance, ensuring efficient layout and connection of pipeline systems in a modular design. Additionally, for different connections between pipeline module segments, such as threaded connections, flange connections, or socket connections, the tightness and sealing of connections should be ensured to prevent water leakage. For specific locations, the selection of suitable materials and anti-corrosion measures is necessary to ensure the long-term stability of pipeline modules.

Lastly, the modular design of pipeline segments should also consider the convenience of construction and maintenance. Modular design should facilitate on-site prefabricated and non-prefabricated components, enabling construction and maintenance personnel to perform their tasks with ease. This increases construction efficiency and reduces maintenance costs.

5.2. Prefabricated Production

Currently, the production of prefabricated MEP installation primarily involves advanced, standardized product manufacturing processes in automated facilities, such as robotic cutting, laser welding, automated painting, and prefabrication line operations. These processes aim to enhance production efficiency, quality, and cost-effectiveness while aligning with modern production techniques and management methods to meet market demands for MEP building products. In this context, Yu et al. [31] conducted a thorough analysis of production methods in the building MEP installation sector, elaborating on the holistic process of prefabricated machining, including grooving, threading, cutting, perforating, piercing, intersecting line cutting, pair prefabrication, and welding. This approach significantly improves machining efficiency. Furthermore, Liu et al. [34] incorporated BIM technology into the prefabrication phase, establishing a construction process that covers rearward production, intermediate process transportation, and on-site prefabrication, effectively reducing on-site operations.

5.3. Logistics Transportation

Transportation of prefabricated MEP components plays a vital role in the entire process, aiming to enhance transportation efficiency, reduce costs, and ensure product quality. It is essential to conduct advance planning for logistical solutions, determining transport routes, choosing transport methods, and establishing a logistics schedule. Tailoring the transport approach according to the characteristics of various MEP modules and equipment is crucial. Furthermore, the introduction of digital technology and logistics management systems can enhance logistics efficiency and enable visual monitoring, optimizing the logistics transportation process. This ensures the smooth delivery of prefabricated MEP equipment to the construction site and shortens the overall project timeline.

However, the safety of MEP component transportation remains a major concern. Large-sized and complex-shaped prefabricated MEP equipment may introduce risks during transport, especially on narrow roads and under complex traffic conditions. Key solutions include rationalizing the size of MEP modules and devising suitable transportation plans. Li et al. [35] meticulously planned the transportation of prefabricated pump units, enhancing the safety of transporting oversized, super-wide, and super-tall components. Additionally, long-distance logistics transportation can lead to additional energy consumption and carbon emissions, affecting the environment. Therefore, adopting low-carbon, eco-friendly transportation methods is a primary research direction for the future of logistics transportation.

5.4. Prefabricated Installation

Prefabricated MEP installation requires a high level of precision, particularly during on-site prefabrication and junction processes. Any deviations in dimensions during manufacturing or inaccuracies in measurements during prefabrication can result in poor component alignment, causing gaps or inadequate junctions or gaps that lead to quality issues. Moreover, errors are an inherent part of MEP installation, stemming from various factors, including equipment installation errors, instrument measurement errors, processing precision errors, and human operation errors. Implementing effective methods to control errors is a significant challenge in modular installation. Yuan et al. [36] and others proposed a BIM-based method for detecting errors in building MEP Installation, improving installation accuracy. Therefore, prefabricated MEP installation necessitates the adoption of suitable pipe connection techniques. The proficiency of workers in these techniques and quality control are crucial for the success of component junctions.

Furthermore, prefabricated MEP installation plays a pivotal role in both subcontracting and main contracting management of projects, enhancing the efficiency and quality of engineering works while introducing new challenges and opportunities to project management [51]. David et al. [52] addressed issues such as timeliness of payments, the subcontractor selection process, retainage, construction insurance, on-site safety, partnering arrangements, and productivity. Through surveys conducted among subcontractors, general contractors, and building owners, the study revealed the existence of these issues and made recommendations to mitigate their negative impacts. Shumank et al. [53] created a reliable and validated scale for analyzing these relationships from the subcontractor's perspective, utilizing quantitative methods like reliability testing and confirmatory factor analysis to develop a decision-making framework.

The main contractor is required to effectively coordinate and control various aspects of the project, whereas subcontractors need to provide high-quality professional services. Close collaboration between the subcontractors and the main contractor is essential to jointly ensure the success of the project.

5.5. Intelligent Operation and Maintenance

Effective operation and maintenance are essential to ensure the stable operation of prefabricated MEP equipment, prolong equipment lifespans, reduce failure rates, and enhance equipment reliability and safety. The application of MEP maintenance primarily relies on sensors and IoT technology, combined with data analysis and mining using big data and artificial intelligence (AI). This approach enables fault prediction, equipment status assessment, and maintenance optimization. Zhang et al. [54] introduced an intelligent application technology for prefabricated smart pump modules, enabling streamlined production and smart operation and maintenance.

In the future, MEP system maintenance will harness machine learning and automation technologies for automatic fault detection and diagnosis. Additionally, utilizing robots for the inspection of prefabricated MEP equipment to reduce the workload of manual inspections is a key development direction for MEP maintenance. However, the inclusion of information technology poses several challenges, including the real-time accuracy of data. Smart operation and maintenance hinge on the fundamental issue of data integrity, as the intelligence derived from outdated or irrelevant data is meaningless. Lastly, the transmission and handling of a substantial volume of sensitive data pose privacy and security concerns, necessitating appropriate protection measures.

5.6. Life Cycle Analysis Enhancement

Prefabricated MEP installation offers significant advantages in sustainability and long-term operational efficiency. The sustainability benefits of prefabricated MEP installation stem from their efficiency in material use and manufacturing processes, as well as their minimized environmental impact. Specifically, these systems exhibit superiority in the following aspects:

Efficient resource utilization: The production process of prefabricated MEP components significantly reduces material waste through precise design and manufacturing. Compared to traditional on-site construction, production in a controlled factory setting allows for more accurate material cutting and usage, thereby maximizing the use of raw materials. Additionally, the mass production and standardization of components also reduce the surplus and storage needs of materials.

Environmental friendliness: Transferring the majority of production activities to factories means a substantial reduction in noise, dust, and waste at construction sites. Moreover, reducing on-site construction activities also leads to fewer trips by construction vehicles, consequently lowering carbon emissions associated with construction.

Energy efficiency: At the design stage, prefabricated MEP installation can integrate the latest energy-saving technologies, optimizing energy consumption. For instance, the integration of efficient heating, ventilation, and air conditioning systems, as well as optimized layouts for piping and cabling, reduces energy loss during transmission.

In terms of long-term operational efficiency, prefabricated MEP installation demonstrates advantages in maintenance, reliability, and operational cost:

Ease of maintenance and replacement: The modular design of prefabricated MEP installation facilitates more convenient and efficient maintenance and replacement. This design allows for quick identification and replacement or repair of faulty components, significantly reducing the time and cost required for maintenance.

Durability and reliability: MEP components produced in a controlled factory environment exhibit higher manufacturing quality and consistency. This not only enhances the overall performance of the system but also reduces long-term maintenance needs caused by installation errors or material damage on-site.

Optimization of operational costs: The efficient energy use and reduced maintenance requirements of prefabricated MEP installation lead to a significant decrease in overall operational costs. In the long run, these systems provide economic benefits to building owners and users by reducing energy consumption and maintenance expenses.

In summary, the advantages of prefabricated MEP installation in sustainability and long-term operational efficiency not only reflect their positive environmental impact but also provide an economically efficient model for long-term operation. These characteristics make prefabricated MEP installation an indispensable element in contemporary architectural design and construction, offering a vital pathway to achieving more environmentally friendly and efficient building goals.

6. Application Analysis of Cutting-Edge Technology in MEP Installation Engineering of Prefabricated Buildings

In this section, we analyze the current state of application of advanced technologies in prefabricated MEP installation. Figure 7 presents the distribution of research articles based on the predominant advanced technologies applied in prefabricated MEP installation. The chart reveals that there are 61 articles (36.1% of the total) primarily focusing on BIM. Additionally, there are 42 articles (24.8% of the total) addressing topics related to IoT technology, radio frequency identification (RFID) technology, and QR code tracking. Furthermore, 32 articles (18.9% of the total) discuss the application of 3D laser scanning and point cloud technology. A total of 21 articles (12.4% of the total) explore the use of augmented reality (AR) technology, with 3 articles discussing virtual reality (VR), 13 articles exploring augmented reality (AR), and 4 articles delving into mixed reality (MR). Lastly, there are 10 articles (5.9% of the total) focusing on robotics technology. Further, Figure 8 shows the proportion of application scenarios of each cutting-edge technology.

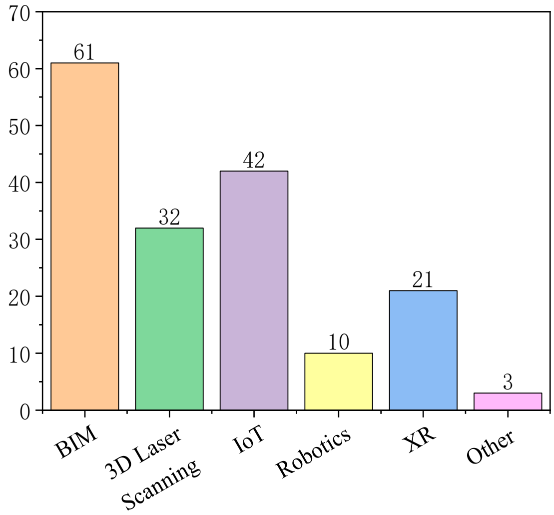
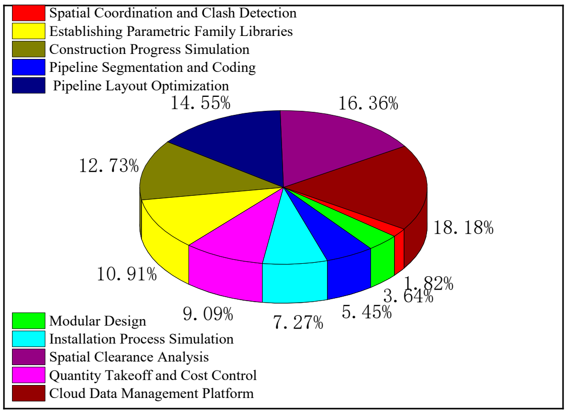
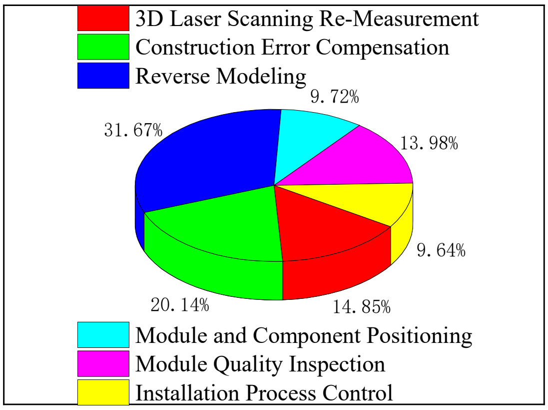


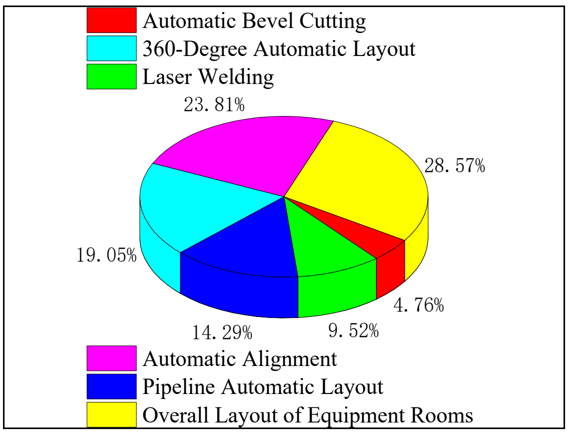
Figure 7. Distribution of different cutting-edge technologies (units–copies).



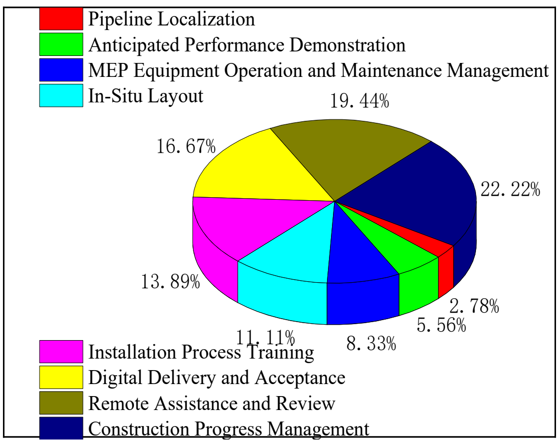
(**a**) Proportion of BIM technology application points



(**b**) Proportion of application points of three-dimensional laser scanning technology

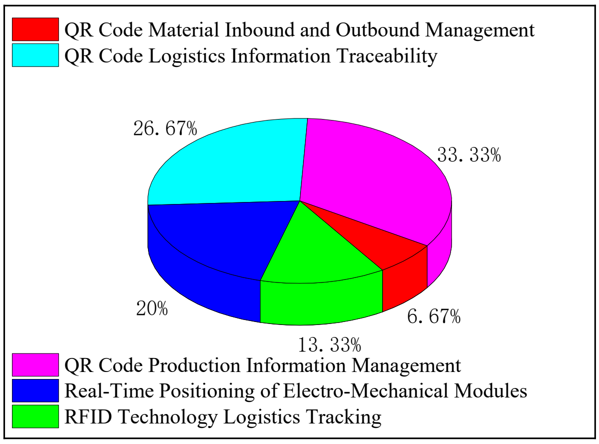


(**c**) Proportion of robot technology application points



(**d**) Proportion of application points of extended reality technology

Figure 8. *Cont.*



(**e**) Proportion of Internet of Things technology application points

Figure 8. Proportion of cutting-edge technology application points.

6.1. BIM Technology

Figure 9 illustrates the distribution of application points for cutting-edge technologies. From the analysis results, it is evident that BIM technology finds the most extensive application in prefabricated MEP engineering [55], particularly in the areas of spatial coordination and conflict detection (22.15%), modular design [56,57] (15.37%), and pipeline layout optimization (11.59%). Presently, BIM technology exhibits relative maturity in its application throughout the entire life cycle of MEP installation. However, the future direction of BIM technology lies in its deeper integration with other emerging technologies and application models [58].

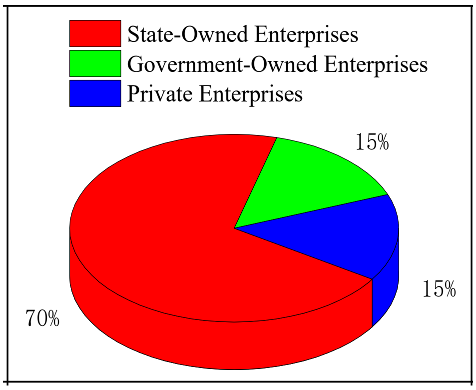


Figure 9. Distribution of enterprise types.

Furthermore, during the application of BIM technology, adjustments in design or other requirements may arise. Wang et al. [9] addressed discrepancies between architectural structures and MEP layouts during the installation process by developing a pragmatic BIM framework for the integration of MEP layouts from the initial design to the construction phase. BIM coordination facilitates the identification of potential clashes in pipeline design and construction. However, due to a lack of identification of influencing factors and to fill this research gap, Wu et al. conducted an extensive literature review and quantitative analysis to ascertain the influencing factors on mechanical, electrical, and plumbing installation and production. Consequently, strategies and recommendations were proposed to encourage and implement productive BIM applications.

Han et al. [59] studied the development of monitoring and management of MEP installation in smart buildings. Given the increasing complexity of MEP design and the rules governing them, manual rule checking has become prohibitively expensive. Xie et al. developed an automated rule checking system that integrates a knowledge-based management system (KBMS) with building information modeling (BIM). This system facilitates model information expansion, information extraction, system integrity checks, and pipe spacing checks, thereby streamlining the automation of MEP system rule checking. Ensuring timely updates to the BIM model to reflect such changes and ensuring that all relevant parties have access to the latest information is a current challenge that needs attention.

Additionally, given the variety of BIM software available, ensuring seamless data conversion and sharing between different disciplines and addressing compatibility issues among different software platforms are pivotal and require close collaboration among stakeholders.

6.2. Three-Dimensional Laser Scanning Technology

Three-dimensional laser scanning technology efficiently and comprehensively captures the complexities of construction sites and allows for thorough comparison with design models [60]. This technology significantly aids in quality checks and project acceptance. The application approach for 3D laser scanning mainly revolves around the integration of BIM models with 3D laser scanning devices for forward or reverse applications [61,62] To enhance the management efficiency of highly complex MEP installation, Wang et al. [63] proposed a novel method for an MEP scenario integrated with BIM reconstruction. This method takes full advantage of the rich semantic information provided by images and the precise geometric information provided by 3D LiDAR point clouds. Compared to previous BIM reconstruction methods, the proposed technology is more accurate, more efficient, and has a broader application scope.

Prefabricated MEP modules are one of the off-site construction technologies that can significantly enhance production efficiency. The traditional manual inspection process is inaccurate and time consuming. To address this issue, Guo et al. [15] introduced an automated geometric quality detection technology that uses 3D laser scanning to estimate the geometric characteristics of MEP modules. Experiments conducted on two prefabricated MEP modules validated the accuracy and efficiency of the proposed method.

Data analysis results indicate that 3D laser scanning is widely used in on-site remeasurement (14.85%), comprehensive compensation for construction errors (20.14%), and reverse modeling for comparative analysis (31.67%). This emphasizes the importance of 3D scanning technology in precision control and on-site revalidation.

6.3. IoT Technology

IoT technology is extensively applied to provide end-to-end logistics tracking for MEP products and the prediction of the MEP running status. For instance, to better provide maintenance strategies for building facilities, Cheng developed a data-driven FMM predictive maintenance planning framework based on BIM and IoT technologies. By integrating data collection and data integration between BIM models, FM systems, and IoT networks with machine learning algorithms at the information layer, it is possible to effectively predict the future state of MEP equipment components, providing a basis for maintenance planning. Data analysis reveals successful applications involving RFID (13.3%) and QR code technology for logistics information tracing (26.7%) and production information management (33.3%). However, the use of QR code technology relies on scanning using cameras or scanning devices, and poor-quality or damaged QR codes may result in scanning failures or errors. Moreover, complex installation processes can lead to issues such as missed scans, which can significantly impact the management of the entire installation process. Therefore, in practical applications, appropriate QR code solutions should be selected based on specific circumstances, and they should be combined with other technologies and methods to enhance the efficiency and reliability of the MEP construction process.

Apart from QR code technology, RFID technology, due to its higher cost and susceptibility to interference from the surrounding environment, is less commonly adopted by stakeholders.

6.4. Robotics Technology

Robotics technology is increasingly being employed in prefabricated of MEP installation, resulting in significant improvements throughout the process. Yeo et al. [64] employed robotics to inspect the production of mechanical, electrical, and plumbing elements, considering four robot inclusivity design principles: mobility, accessibility, safety, and observability. Certain robotics applications in building MEP installation have achieved a high degree of automation, including automatic bevel cutting, laser welding, and automatic layout. However, many aspects still require manual intervention, especially under complex on-site conditions. The autonomy and adaptability of robots are areas in need of improvement. Although the application of robotics technology can enhance efficiency and quality, it is associated with relatively high costs in certain aspects. In the MEP installation industry, stakeholders must balance the investment cost and benefits of robotics technology and identify suitable application scenarios. Despite some challenges, as technology continues to advance and experience accumulates, robotics technology is expected to progressively find broader applications in building MEP installation, contributing to more innovation and development within the industry.

6.5. Extended Reality Technology

Extended reality technology encompasses mixed reality (MR), augmented reality (AR), and virtual reality (VR). XR technology is primarily applied in areas such as expected outcome visualization (15.25%), on-site layout (22.18%), construction progress management (16.59%), and installation process training (11.96%), Table 7 shows the application of XR in MEP installation engineering. The conflict in MEP systems is a complex issue characterized by multidisciplinary coordination and limited axial bearings. Given the practical problems caused by deviations from the plan, on-site inspection and further adjustments of the pipes are inevitable. Tsai et al. [65] developed an on-site pipe inspection and automatic coordination method using AR and a grid-based path planning algorithm. This method enables practitioners to compare newly added pipe layouts with existing ones and re-plan in the event of conflicts, thereby obtaining conflict-free solutions.

Table 7. Application of extended reality technology in MEP installation engineering.

Extended Reality Technology	Engineering Application			
Augmented reality (AR)	In situ layout	Pipeline positioning	Expected outcome presentation	Installation process training
Mixed reality (MR)	Digital delivery and acceptance	In situ layout	Construction progress management	Remote assistance and review
Virtual reality (VR)	Remote assistance and review	Digital delivery and acceptance	Installation process training	MEP equipment maintenance management

In the actual construction process, ensuring the consistency of the model with reality is crucial. Chalhoub et al. [16] proposed a methodology requiring participants to use immersive AR to identify deviations in the BIM of ceiling ventilation spaces. The results indicate that AR enables users to effectively identify significant deviations and missing architectural elements.

7. Analysis of Enterprise Application

7.1. Enterprise Applications

In recent years, with the enhancement of policy-driven and market endogenous power, with the active promotion and practice of enterprises and institutions in the industry, the MEP engineering of prefabricated buildings gives full play to the comprehensive advantages of prefabricated construction methods, and effectively improves and enhances the environmental, social, and economic benefits of MEP installation of prefabricated buildings.

In order to analyze the R&D and project application of prefabricated MEP installation technology of enterprises, this section sorts out the scientific and technological progress award-winning projects of China Installation Association from 2017 to 2023 (no awards were set in 2018 and 2021). Among them, there are 107 projects related to MEP installation and 20 MEP projects of prefabricated buildings. Table 8 sorts out the names of enterprises and key technologies declared. From the number of awards, the award-winning projects of MEP installation increased year by year from 2017 to 2022. From the proportion of MEP installation of prefabricated buildings in the whole MEP installation project, prefabricated MEP installation is still in the initial stage of development. In addition, as can be seen from Figure 9, large-scale construction central enterprises are at the forefront in the innovative application of assembled MEP products.

Table 8. Combing the key technologies of the award-winning projects of each enterprise.

Year	Enterprise Name	Names of Key Technologies
2017	China Construction Third Engineering Installation Engineering Co., Ltd.	Key technology of DPTA-assembled refrigeration room
2019	China Construction Eighth Bureau First Construction Co., Ltd.	Complete set of MEP installation technology of modular prefabricated building based on BIM +
2019	China Construction Installation Group Co., Ltd.	Research and application of prefabricated construction technology of refrigeration room
2019	Jiangsu huansheng construction engineering Co., Ltd.	Research on deepening design and prefabricated construction technology of MEP engineering
2019	China Construction Fifth Bureau Third Construction Co., Ltd.	Research on standardization implementation of MEP construction technology in prefabricated buildings
2021	China Construction Installation Group Co., Ltd.	Research and application of modular construction technology of MEP engineering based on BIM
2021	China Construction Fifth Bureau Third Construction Co., Ltd.	Mechanical and electrical engineering construction technology of prefabricated intelligent standard computer room
2021	Shanxi sijian group Co., Ltd.	Research and application of complete sets of prefabricated construction technology for MEP installation engineering
2022	Shanghai Baoye Group Co., Ltd.	Research and application of mechanical and electrical installation construction technology of fully assembled buildings in confined space
2022	China Construction Fifth Bureau Third Construction Co., Ltd.	Development, research, and application of assembled digital module high-efficiency computer room and MEP industrialization products
2022	China Construction Second Bureau First Architectural Engineering Co., Ltd.	Comprehensive construction technology for installation of large-scale prefabricated convention and exhibition center
2022	Zhongtian Northwest Construction Investment Group Co., Ltd.	Research and application of key technologies of prefabricated MEP based on BIM
2022	Guangzhou MEP Installation Co., Ltd.	Application of integrated collaborative platform in modular design and construction of computer room
2022	China Construction Installation Group Co., Ltd.	Research on modular construction technology of assembled pipeline in refrigeration room based on DFMA
2022	China Construction Eighth Bureau Second Construction Co., Ltd.	Key technologies of MEP installation and prefabricated construction of urban large-scale medical complex
2023	China Construction Second Bureau Second Architectural Engineering Co., Ltd.	Installation technology of adjustable prefabrication support and hanger in various environments

Table 8. *Cont.*

Year	Enterprise Name	Names of Key Technologies
2023	China Construction Third Bureau First Construction Engineering Co., Ltd.	Research on the application of modular building MEP prefabrication equipment
2023	Shanxi Yijian Group Co., Ltd.	Research and application of modular prefabricated construction technology for equipment and pipeline in computer room
2023	CCCC No. 1 Public Bureau Group Co., Ltd.	Construction technology of prefabricated computer room based on BIM modeling AR positioning
2023	China Construction Second Bureau First Architectural Engineering Co., Ltd.	Standardization of MEP system in prefabricated residence

7.2. Application of the Project

This section, from a project perspective, analyzes the application scenarios of prefabricated MEP installation. Figure 10 shows that prefabricated MEP installation projects are most commonly applied in commercial complexes, followed by super-tall buildings, factories, and substations, with relatively fewer applications in venues and hotels.

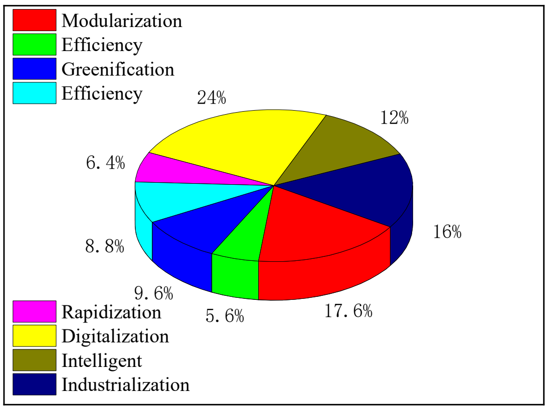


Figure 10. Application distribution map of MEP installation project of prefabricated building.

Furthermore, to align with "dual-carbon" goals and promote smart construction and intelligent management, guiding the high-quality development of China's prefabricated MEP industry, various enterprises have developed a rich set of prefabricated construction technologies. Figure 11 reveals that most enterprises focus on environmentally friendly, fast, and efficient installation methods in their project applications. Smart, modular, standardized, digitized, and factory-based approaches have become the primary research directions for the development of prefabricated MEP projects. From the number of award-winning projects and development trends, it is evident that research in various directions is still in the early stages but is showing growth. Achieving high-quality development in the prefabricated MEP industry requires research institutions and enterprises to strengthen collaboration, facilitating technology research and development and the practical implementation of innovations.

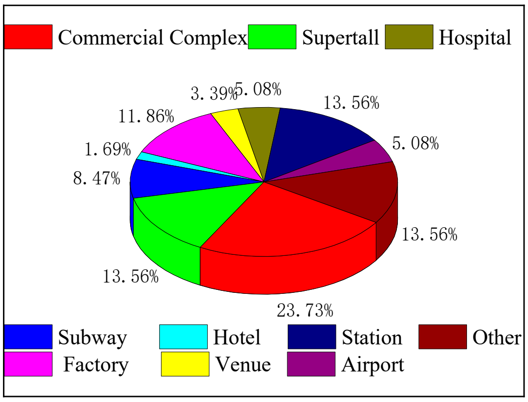


Figure 11. Distribution of application and development of installation technology in prefabricated building MEP projects.

8. Conclusions and Prospects

8.1. Conclusions

In summary, this article provides an in-depth analysis of the research progress and technological applications throughout the life cycle of prefabricated MEP installation projects, outlining the overall status. However, the analysis reveals several challenges within these projects:

1. The depth of advanced technology application in the field of prefabricated MEP is insufficient. The collaborative capabilities among advanced technologies need further enhancement, and there is a lack of integrated application models for multiple technologies.
2. The construction process throughout the entire life cycle lacks close coordination, often proceeding independently without a unified construction model. Furthermore, the optimization of prefabricated construction has not fully realized its true potential in the field of MEP installation.
3. Low standardization of MEP module components: Divergent developments among different companies and discrepancies in technical applications among professionals necessitate more collaboration and knowledge sharing. The industry as a whole has not reached a unified level of development and requires standardization and regulation.
4. Currently, there is a lack of comprehensive standards specifically targeting prefabricated MEP installations and acceptance. This implies that industry participants may lack clear guidance and standards throughout the design, manufacturing, installation, and acceptance processes.

8.2. Prospects

In the long-term perspective, the future of prefabricated MEP installation appears promising and transformative. Several key developments and trends are expected:

1. Full life cycle efficiency: Utilize building information modeling (BIM) tools for designing MEP systems. This technology allows for precise planning, clash detection, and integration from the outset. Incorporate predictive maintenance algorithms to extend the life cycle of installations.
2. Sustainability and green practices: Sustainable and environmentally friendly practices will become central to prefabricated MEP installation. There will be a strong focus on reducing carbon emissions, conserving energy, and using eco-friendly materials.
3. Standardization and collaboration: Develop industry-wide standards for prefabricated MEP components. This could involve creating universal specifications and dimensions, as well as establishing common practices for installation and maintenance. Encourage collaboration through joint ventures or partnerships between companies to share knowledge and best practices.

4. Cost efficiency: Invest in automation and robotics for the production of prefabricated MEP components. This reduces labor costs and increases production speed. Analyze the total cost of ownership to understand the long-term financial benefits of investing in advanced technologies.
5. Developing and implementing standards and regulations specifically for prefabricated MEP is crucial to ensure they cover the entire process from design to manufacturing, installation, and maintenance. Additionally, aligning these standards with international norms is essential to facilitate global exchange and collaboration.

Overall, the future of prefabricated MEP installation is expected to be more sustainable, efficient, and technologically advanced. These changes will likely lead to a more streamlined and environmentally conscious construction industry.

Author Contributions: Conceptualization, Y.Y.; methodology, G.Y. and H.Z.; software, Z.S. and M.Z.; validation, S.C. and L.L.; formal analysis, Z.L.; investigation, G.Y., Y.Y. and H.Z.; resources, X.Z.; data curation, X.Z., L.H. and M.Z.; writing—original draft preparation, X.F.; writing—review and editing, L.L.; visualization, X.F. and L.H.; supervision, G.Y. and X.Z.; project administration, X.Z.; funding acquisition, G.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the sub-committee of teaching guidance for engineering management and engineering cost of Ministry of Education of the People's Republic of China, grant number CMPC202129.

Data Availability Statement: Dataset available on request from the authors.

Conflicts of Interest: Authors Gangwen Yan, Yinghui Yang, Huizhong Zhang, Zhenwei Li, Song Chen were employed by the company Beijing Urban Construction Group Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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