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Modular and Offsite Construction of Piping: Current Barriers and Route

Xiaodan Li [1], Zhongfu Li [1] and Guangdong Wu [2,*]

1 Department of Construction Management, Dalian University of Technology, Dalian 116024, China; gstslxd@126.com (X.L.); lizhongfu@dlut.edu.cn (Z.L.)
2 Department of Tourism and Urban Management, Jiangxi University of Finance & Economics, Nanchang 330013, China
* Correspondence: gd198410@163.com; Tel.: +86-791-8384-2078

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Abstract: To investigate current practices and identify challenges of piping prefabrication, this paper conducts a comprehensive survey to mechanical, electrical, and plumbing (MEP) contractors. This paper is performed in three main steps. First, the current state of piping prefabrication, the attitude of MEP contractors to piping prefabrication, and the challenges of piping prefabrication are identified through a comprehensive data collection process that included semi-structured interviews, case studies, site visits, and questionnaires. The second step included suggesting a pattern and roadway of piping prefabrication. The results showed that: (1) The attitudes to feasibility of piping prefabrication differ in piping systems, piping connector modes, and types of project; and (2) building information modelling (BIM) promotes the adoption of piping prefabrication. Integrated project delivery (IPD), and distributor's early involvement into projects have significant effects on the successful implementation of piping prefabrication. (3) The main barriers and challenges were identified including the low level of standardization of design, lack of preferential policy, economies of scale, low-skilled workers, as well as the availability of fittings and valves. In the final step, a four-phase route of piping prefabrication is suggested for MEP contractors to expand the prefabrication capacity incrementally. The main contributions of this paper include: (1) This paper proposes a route for MEP contractors to improve their piping construction through the Modular and offsite construction (MOC) method. (2) This paper finds that the level of feasibility of piping prefabrication differs in piping systems, connection modes, and types of project. Challenges and barriers of piping prefabrication are firstly identified.

Keywords: modular and offsite construction; piping prefabrication; building information modelling; challenges; route

1. Introduction

Modular and offsite construction (MOC) involves the process of designing, fabricating, transporting and assembling building elements for rapid site assembly to a greater degree of finish than in on-site construction. MOC, also called prefabrication or preassembly has been widely adopted by many countries and regions (such as the United States, the UK, Sweden, Australia, Malaysia and China) as a new construction method to improve the construction productivity [1–7]. Various benefits (e.g., quality improvement, waste reduction, and savings in construction time etc.) of prefabrication have been addressed in previous studies. Because of these proven benefits, mechanical, electrical, and plumbing (MEP) contractors adopted MOC as a new approach to strengthen its profitability and competitiveness.

Several studies were performed to analyze different management aspects of MEP construction. These studies include: construction schedule and planning [8,9]; safety and risk management in MEP construction [10,11]; coordination and integration strategies among various sub-systems and trades [12–14]; assessment of the built status of MEP works and quality inspection [15]; building information modelling (BIM)-based application in MEP layout design and construction [16–18]; and waste management of materials such as pipes used in MEP construction [19,20]. A few studies were performed to investigate the application of prefabrication in MEP construction. Mawdesley and Long [21] presented a case that has used prefabrication technology for the distribution of heating, ventilation, and air-conditioning (HVAC) systems. Wang et al. [22] presented the process of pipe spool fabrication in the industrial construction project. This study focused more on the value stream improvement in the spool fabrication shop. Court et al. [23] combined modular assembly with postponement strategy to improve productivity and reduce the on-site operations that involve risks of injury in MEP construction including cutting and drilling. Connor et al. [24] developed a method to design the modular standardized industrial plant. Ten types of advantages were identified when modularization and design standardization were combined. Mahdi et al. [25] proposed a quality management model for construction quality management that employs automated technologies such as photogrammetry and laser scanning to detect defects during piping prefabrication. The model has the potential to decrease the overall cost of a project by reducing the fabrication rework. Said [26] identified best practices in electrical prefabrication construction and improvement opportunities for electrical contractors' industrialization, and presented a prediction model of prefabrication feasibility for electrical contractors and found that prefabrication feasibility was dependent mainly on industry-related determinants. The surveys [27,28] have indicated that prefabrication was most widely adopted to manufacture structural components and building envelope of buildings, followed by MEP systems. Building superstructure, exterior walls, and ducts are the most prefabricated building components. Prefabrication of complicated ductwork can help reduce the space requirement on site. In addition, assembly off-site can positively impact the overall project schedule. As to how to make decisions and what challenges would be faced during implementation of modularization and off-site in MEP construction, a decision framework named prefabrication, preassembly, modularization, and off-site fabrication (PPMOF) [29] developed by the Construction Industry Institute (CII) needs to be concerned. This framework focuses on identifying the requirements for effective use of PPMOF on industrial projects. PPMOF contains a preliminary decision guide and a quantitative analysis as well as suggestions for tactical analysis in the PPMOF decision process [30]. In a case study conducted by Mawdesley and Long, some problems were encountered in the modular services installation. These problems have been ascribed to a lack of communication and training between the parties involved [21].

Previous research studies have identified challenges based on case studies. There were few quantitative investigations and comprehensive analyses of challenges and barriers to the successful implementation of piping prefabrication in building and construction projects. The research objective of this paper is to identify the challenges and barriers that MEP contractors may be confronted in the adoption of MOC by adopting qualitative and quantitative research methods and conducting a comprehensive data collection plan including semi-structured interview, questionnaires, and case studies. The organization of this paper is as follows. The paper begins with an introduction of piping construction profiles in China. Section 3 includes a discussion of the research methodology, questionnaire design and samples employed in this study. The results are presented and discussed in Section 4. Section 4 also presents the suggested pattern and route of piping prefabrication based on the results of this study. Finally, some conclusions are offered, and recommendations for further research are offered. The findings assist piping contractors in improving their piping construction through the MOC method.

2. Piping Construction Profiles in China

Piping is a system of pipes used to convey fluids (liquids and gasses) from one location to another. In domestic or commercial environments, the most familiar type of piping is plumbing. As to distinguish the meaning of piping and plumbing is not the scope of this research, we employed the term "piping" in this paper to refer to all the systems that consist of pipes, fittings, valves, and other devices inside buildings. As the fragmentation characteristics of building and construction industry, an MEP contractor is often in charge of one sub-system. That is, several MEP contractors are involved in a project. MEP construction in China is traditionally fabricated on site. Elemental units such as fittings and valves are fixed in place at the final site. Different trades often follow one another through the project fixing the particular units in place. For example, one of the contractors fix the ducts, followed by a second contractor or a gang of workers fixing the pipes and a third fixing the electrical cable runs. There could easily be as many as five different contractors or gangs with different resource requirement passing through all areas of a building.

The participants in a traditional project include the owner, designers, general contractor and sub-contractors, manufacturers, and distributors. The process they collaborated to complete a project is shown in Figure 1. In the traditional supply chain, manufacturers produce standard components of different types. For example, they produce seamless steel tubes of six meters, while the distributor purchases material from manufacturers, then sells this material to local contractors. The piping contractor is responsible for the procurement of material such as pipes and fittings. After all the material in a piping system is transported to the construction site, a gang of workers will cut the pipe into pipe segments according to drawings. Some pipe segments need to be drilled to connect with a branched segment. Some segments need to be handled in the pipe-threading machine or roll-grooving machine. Finally, the handled pipe segments are connected with the corresponding fittings. This process is inefficient as the majority of time is consumed by calculating the length of the pipe segment and judging if the pipe end is threaded or grooved. To find the corresponding fitting from many packages of material also consumes too much time, because the worker must know the location and nominal diameter of the pipe. To improve the productivity and reduce waste, some MEP contractors try to adopt piping prefabrication with the application of BIM. In their project, pipes were cut ahead on site or in their fabrication shop based on the lengths exported from BIM software. Although more and more MEP contractors are interested in piping prefabrication, piping prefabrication is still in its infancy in China.

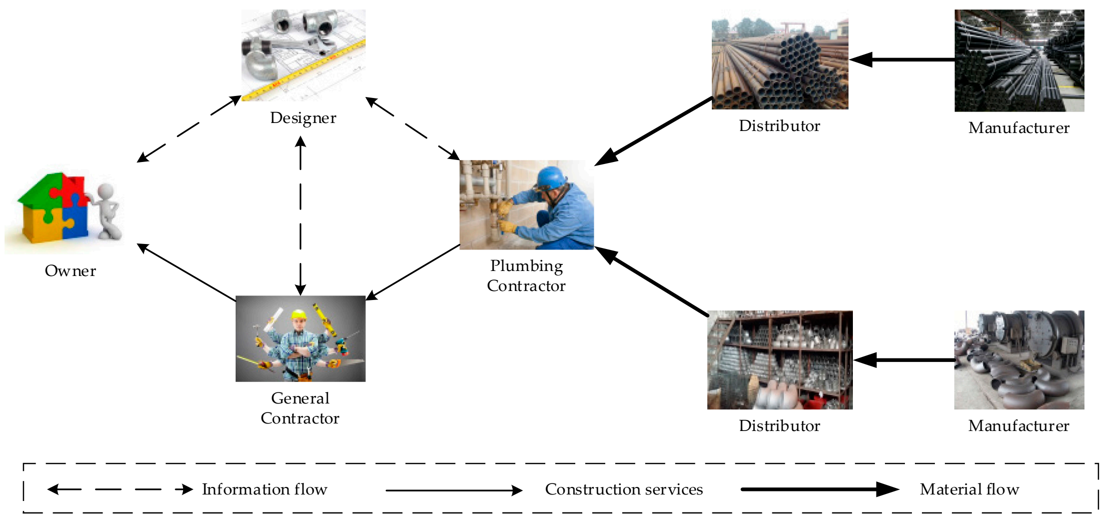

Figure 1. Supply chain of piping construction.

3. Methodology

Based on the study objective, which is to identify the feasibility of piping prefabrication, challenges and barriers, a comprehensive data collection plan was adopted to collect information that pertains to piping prefabrication. The research methodology is shown in Figure 2. Qualitative and quantitative research methods were adopted as methods of inquiry. The data was collected from four main sources: (1) semi-structured interviews; (2) acquisition of piping prefabrication case studies; (3) site visits to prefabrication facilities; and (4) online questionnaires.

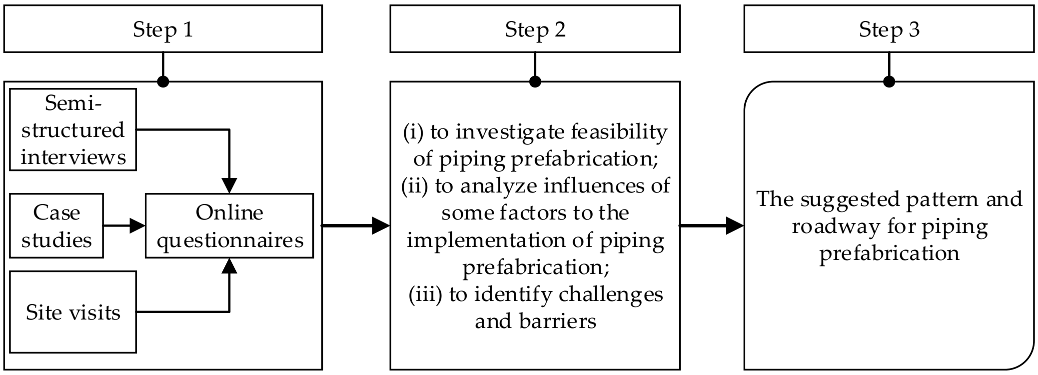

Figure 2. Research methodology.

3.1. Semi-Structured Interviews

To collect data relating to the adoption of piping prefabrication, semi-structured interviews were conducted with 10 experts, consisting of two academic, two on-site project managers, two designers, two pipe fittings suppliers, and two site foremen to understand the current practices, challenges, and opportunities of piping prefabrication. The reason for the combination of experts from different backgrounds was to provide a comprehensive review of the research topic. The interviews were either performed in person or on the phone. All these experts have sufficient project experience in the building and construction industry and sufficient knowledge of piping systems. These semi-structured interviews including the following six open-ended questions:

1. Do you agree on the following characteristics of piping prefabrication: It is the (1) off-site production of piping in a factory environment, (2) components such as pipe segments and fitting are pre-assembled as units or modules; (3) transportation of piping units to the project site; and (4) assembly and installation of the units to form a complete piping system?
2. Are there differences in the feasibility of piping prefabrication between different piping connection modes and different type of project?
3. What are the main challenges or barriers of piping prefabrication?
4. What are the roles of manufacturers and distributors in the piping prefabrication?
5. How the contractor, designer, and other participants collaborated in piping prefabrication?
6. What pattern and route will be developed in piping prefabrication?
7. Are there other items do you think that this research needs to be considered?

3.2. Case Studies and Site Visits

Cases were acquired to provide exploratory examples of piping prefabrication practices. Technical documentation including project profile, construction pictures and videos, design drawings, specification sheets, and component assembly drawings was obtained from two cases that have adopted prefabrication technology. One project has been completed and another one is in progress. These cases helped to provide general understanding and specific illustrations of piping contractors' prefabrication solution and collaboration with designers and manufacturers.

Except for the cases, prefabrication facilities of a piping contractor, the site of an office building project, and a piping distribution center were visited to identify current prefabrication practices.

Two prefabrication facilities in China (one in Beijing and another in Xi'an) were visited; one for large piping contractors (revenue of more than $1.2 billion one year) and one for small piping contractors (revenue less than $0.3 billion one year). These visits enabled diverse observations of prefabrication and supply chain approaches in low and large production volumes. A distribution center of a pipes and fittings distributor was visited to investigate the sufficiency of various fittings. An office building project that was using the prefabrication technology was visited to learn the quality of a fire sprinkler system and challenges during piping installation.

3.3. Questionnaire

A questionnaire was designed to explore the feasibility, challenge and barrier of piping prefabrication. The questionnaire was used to verify the generality of the findings from the semi-structured interviews, case studies, and site visits. The objective of this questionnaire includes: (1) general attitude toward the feasibility of piping prefabrication; (2) the influence of some factors on the successful implementation of piping prefabrication; and (3) critical challenges or barriers of piping prefabrication.

The questionnaire included a total of 18 questions organized into 4 main sections, as shown in Table 1. This questionnaire was distributed to a sample of piping contractors. A brief introduction on piping prefabrication and descriptions of some terms were also attached to the questionnaire to ensure that all the respondents were informed of and were using the same definition and description for each question. These questions were formulated in a neutral way without implying any set propositions.

Table 1. Questionnaire Design.

<table>
<tr><th>Category</th><th>Questions</th><th>Provided Values</th></tr>
<tr><td rowspan="3">General information</td><td>General information of those people surveyed that works in MEP firms.</td><td>For example, four options (<3 years, 3–5 years, 5–10 years, and >10 years) were provided for work experience.</td></tr>
<tr><td>The number of piping projects participated?</td><td><3, 3–5, 5–10, and >10</td></tr>
<tr><td>Does the designer provide the BIM model in the project participated?</td><td>Yes/No</td></tr>
<tr><td rowspan="3">Level of the feasibility of piping prefabrication</td><td>The feasibility of piping prefabrication in different piping systems.</td><td rowspan="6">Likert scale (1–5)</td></tr>
<tr><td>The feasibility of piping prefabrication using different piping connection method</td></tr>
<tr><td>The feasibility of piping prefabrication in different types of project</td></tr>
<tr><td rowspan="3">Level of the influence of some factors to piping prefabrication</td><td>Influence of BIM to piping prefabrication</td></tr>
<tr><td>Influence of integrated project delivery method such as EPC to piping prefabrication</td></tr>
<tr><td>Influence of early involvement of manufacturers and distributor in the project.</td></tr>
<tr><td>Challenges and barriers</td><td>The challenges and barriers of piping prefabrication.</td><td>Multiple-choice questions with ten options such as standardization of design, policy, and availability of fittings and valves.</td></tr>
</table>

During a period of three months, the questionnaire was distributed to 411 respondents. All the respondents are practitioners come from piping contractors. A total of 48 responses were received, all answers were checked to verify the completeness and validity. Therefore, these 48 samples were used for the analysis. These figures represent a valid response rate of 11.7%, which is adequate for the data analysis. Time and resource limited the increase of response rate. A similar survey also reported low response rate (response rate of 2.9%) because of the large population of possible respondents [31]. However, the diversity of the collected sample can be considered representative for the piping contracting industry. The respondents cover large, small and medium piping contractors such as China Construction Industrial & Energy Engineering Corporation, Shanghai Installation Engineering

Group Corporation, and Dalian Zhongying Mechanical, Electrical & Plumbing Corporation. Figure 3 shows the work experience and the number of piping projects participated of respondents. 58% of respondents have a work experience above three years. 73% of respondents have completed more than three piping projects. The rich experience accumulated in practice will give a result of high quality.

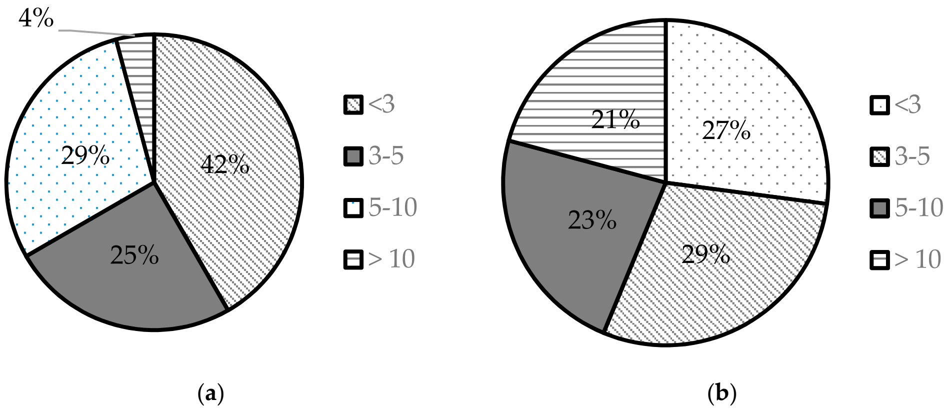

Figure 3. Overview of the respondents. (**a**) the respondents' work year of experience; (**b**) the number of piping projects participated by respondents.

4. Data Analyses, Discussion and Findings

4.1. Prefabrication Scope Identification

We divided questions into three groups to survey and discuss the level of the feasibility of piping prefabrication in different piping systems, different connection modes, and different types of project. The results are shown in Figure 4. A 5-point Likert scale (with 1 being the least feasibility and 5 being the most feasibility) was used to elicit respondents' opinions about the level of feasibility of prefabrication. The average score, which was weighted by the 5-point of Likert scale, represents respondents' general attitude to each question.

The levels of feasibility in the main and branch pipe prefabrication of different piping systems and pipes in the pump room such as fire sprinkler system, water supply system, air conditioning water system, heating system, and drainage system were surveyed and the result is shown in Figure 4a. The feasibility of pipe prefabrication in pump rooms has a higher average score (average score of 4.25) than the prefabrication of fire sprinkler system (3.71), air conditioning water system (3.54), heating system (3.5), and water supply system (3.46). According to the collected case studies, the successful implementation of pipes in pump rooms has some difficulties. For example, if the equipment is not procured by contractors, the accurate sizes of connectors impede the developed of BIM. The verticality of pipes will have a significant effect on the operation performance of the piping system. The compensation method of deviation needs to be considered in advance. The successful implementation of prefabrication of pump rooms needs the integration of the distributor, manufacturer, and designer. The feasibility of pipe prefabrication in drainage systems is lower than others as the average score is only 2.5. This is because the pipes in a pump room are often installed by only one MEP contractor. There is no need to coordinate with other MEP contractors. The drainage system in a building is sloped. The slopes depend on the pipe diameter. For example, the recommended slope for pipes of diameter 50 mm is 25‰. The small slope increases the risk of prefabrication.

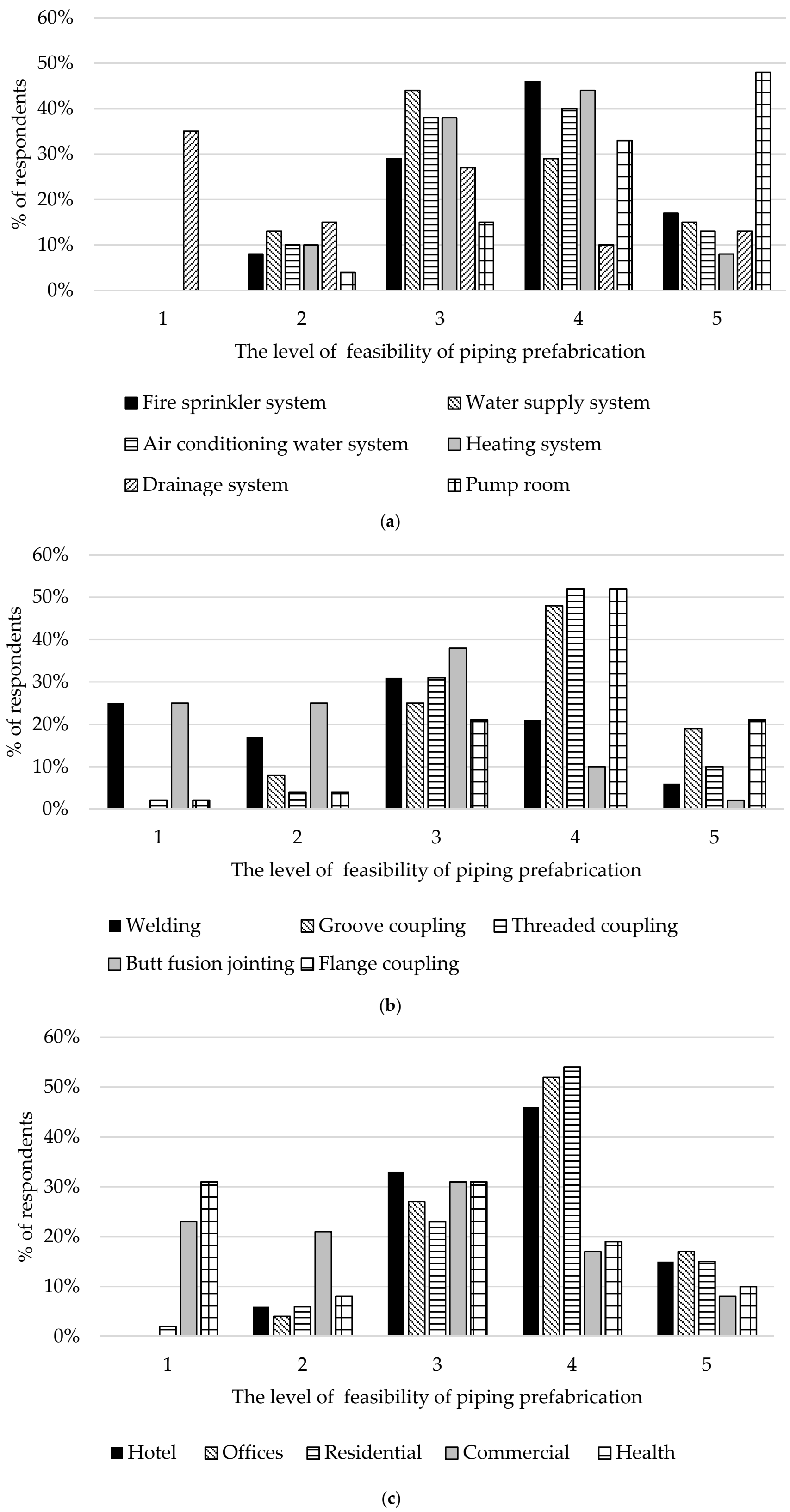

Figure 4. Level of feasibility of piping prefabrication. (**a**) the level of feasibility of prefabrication in different types of piping systems; (**b**) the level of feasibility of prefabrication in different connection modes of piping; (**c**) the level of feasibility of prefabrication in different types of projects.

The connection modes of the piping system are various, depending on the type of system, the line pressure, the pipe diameter, the connected valves or equipment, and the availability of material. According to the construction specification in China, the threaded coupling can be used in the pipe, of which the diameter is less than 80 mm. When the pipe diameter is larger than 100 mm and less than 150 mm, the groove coupling, welding, and flange coupling are applicable. The butt fusion jointing is used when the pipe is PPR. The welding and flange coupling are recommended when the pipe diameter is larger than 150 mm and the pressure in the piping system is big. In some circumstances, the connection mode depends on the available valves, for example, if the connector in the valve is a flange, the corresponding connection mode must be the flange coupling. As shown in Figure 4b, the welding and butt fusion jointing modes have a low average score for prefabrication feasibility. It seems that the piping system is not detachable using these two connection modes. When a length of pipe is welded with an elbow, they form a whole that is difficult to disassemble. By comparison with other connection modes (for example, groove coupling), groove coupling is not only detachable but also is easy to learn. As mentioned above, in some circumstances, the welding can be replaced by the flange coupling or the groove coupling.

The level of feasibility of piping prefabrication in different types of projects is surveyed. It can be indicated in Figure 4c that MEP contractors have a positive attitude to the piping prefabrication in residential, office, and hotel projects as the average scores of the three types of project are higher than the others (the average scores of 3.73, 3.81, and 3.69). The level of standardization in residential, office, and hotel projects is higher. In most cases, these buildings in China are tall and consist of typical floors and standard units. Therefore, the pipes in these projects are appropriate to be mass produced in the fabrication store. The commercial buildings are uniquely shaped. Besides, various pipes in fire sprinkler systems, water supply systems, and air conditioning systems are all required in commercial buildings. Pipes in commercial buildings are numerous in size and diameter. The health project is one of the most complex public projects for its special function requirements in consulting rooms, operating room, and diagnostic laboratory. The medical buildings consist of some special MEP systems such as sewage system, medical gas system. The average scores of commercial buildings and health projects are 2.67 and 2.69 respectively. The characteristics of these two types of projects increase obstacles for piping prefabrication.

4.2. BIM

The degree of influence of BIM to the piping prefabrication is shown in Figure 5, in which 5 means the highest degree of influence. It can be seen in Figure 5 that BIM has a significant influence to the piping prefabrication. In most cases, the designer provides 2D drawings to the piping contractor. These drawings can only give a general information of the piping system. Some information that is important for procurement and construction is insufficient in these drawings. Some designers may provide a design model for the contractor (about 23%). However, the level of detail (LOD) for this design model is commonly LOD 300 [32], according to the definition of LOD by American Institute of Architects (AIA). In this circumstance, some piping contractors develop the BIM model for construction. In China, as the piping contractor is responsible for the procurement of pipes and fittings, the piping contractor will supplement more information such as the length of the pipes, the type of the fittings into the BIM model. In the process of developing this BIM model, some design errors can be fixed. However, the quality and precision of the BIM model are dependent on the quality of materials provided by the distributor. The contractors need to develop a BIM model above the level of LOD 400. As observed from interviews with some piping engineers, the main challenges when developing the BIM model for prefabrication are in two aspects. On one hand, it is difficult for the contractor to choose the optimum connection solution of pipes as the shortage of appropriate fittings. On the other hand, it is difficult for the contractor to set the parameters of components as lacking size of some devices. Figure 6 shows a case of a prefabricated fire sprinkler system that the writer has visited. In this project, the contractor developed a detailed BIM model. Then 2D drawings were exported from BIM model to workers on site.

The distributor is involved in this project when developing the BIM model. Therefore, the accurate sizes of the fittings including elbows, branches, reducers, flanges and so on to provide a chance for pipe prefabrication.

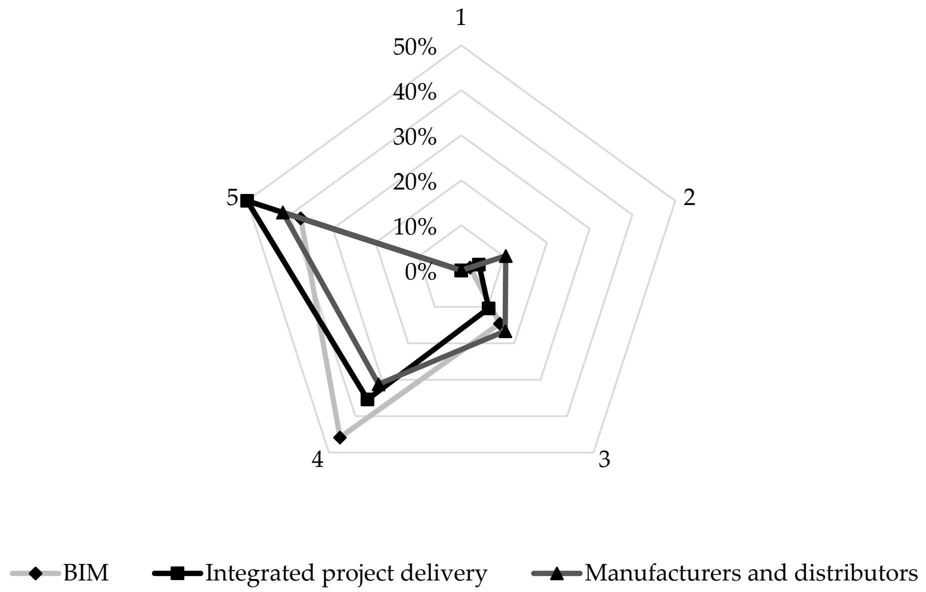

Figure 5. The degree of influence of building information modelling (BIM) to the piping prefabrication.

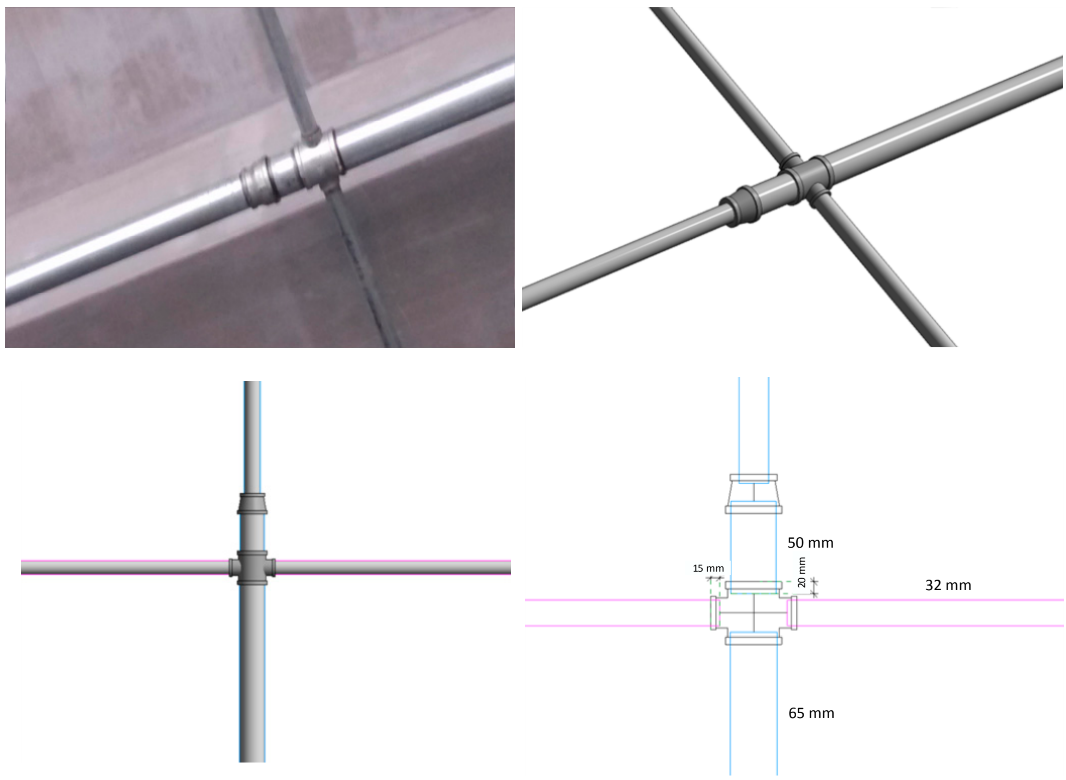

Figure 6. Detailed BIM model of a fire sprinkler system developed by the contractor.

4.3. Manufacturer and Distributor

The survey indicates that the information provided by the manufacturers and the early involvement of distributor are beneficial for piping prefabrication (as shown in Figure 5). The manufacturer or distributor may provide a product brochure in which vibrant pictures and professional introductions are given for contractors. This information is sufficient when the contractor develops the BIM model based on products in the brochure. However, developing the product brochure based a BIM model is a time-consuming task, especially when many products will be used a project. The interoperability between the software used by the manufacturer and the BIM software in the building and construction industry is a challenge. To achieve this issue, some manufacturers, including the equipment manufacturers and the fitting manufacturers, develop the BIM model that can be used directly by the contractors. For example, Daikin, one of famous HVAC product suppliers, provides the comprehensive library of a high quality BIM models for its HVAC products in support of our building owner, architect, MEP and contractor customers using Autodesk Revit platforms. Another example is Victaulic, the originator and world's leading producer of mechanical pipe joining solutions and grooved pipe joining systems, provides certified content in 21 native software platforms including BIM software such as Revit MEP, Bentley AutoPlant and PipeDesigner 3D. In case studies provides by Victaulic, a company wins the bid for a major hospital expansion project by creating a BIM model using Victaulic grooved mechanical piping systems to save time and costs.

4.4. Integrated Project Delivery Method

As shown in Figure 5, most contractors suggested that the integrated project delivery (IPD) method is more appropriate for piping prefabrication. As the majority of projects use design-bid-build (DBB) method, several MEP contractors in the same project only sign contracts with the general contractor or even with the owner. Beyond that, no contractual relationship exists between any two MEP contractors. Conflicts of interest exist during the installation stage. The installation schedules of different MEP systems are not well communicated before construction. Therefore, the piping prefabrication is risky when the installation space of pipes is occupied by other MEP contractors. The IPD method, which seeks to improve project outcomes through a collaborative approach by aligning goals of the project team through shared risk and reward, early involvement of all parties, and a multiparty agreement [33]. This application of IPD method in piping prefabrication will decrease the risk of rework. The interests gained through the successful implementation of piping prefabrication can be shared by the manufacturer, distributor and the MEP contractor.

4.5. Challenges

Through semi-interviews and case studies, ten challenges of piping prefabrication including the standardization of design, the economies of scale, the prefabrication function of BIM software, insufficient information of the contractors, unavailable of fabrication shop, the quality and the availability of fittings and valves, authority of the procurement of some equipment, the capacities of workers, the design and construction specification, and policy were summarized. Then these challenges were surveyed through a questionnaire. All the 48 respondents provided valid answers to this question. More than 60% of respondents have selected at least three challenges. Meanwhile, some new challenges are supplemented during this survey. According to Figure 7, the five biggest challenges are the low level of standardization of design (58.3% of respondents), lack of preferential policy (52.1% of respondents), low-skilled workers (50% of respondents), the economies of scale (47.9% of respondents), as well as the availability of fittings and valves (41.7% of respondents). The design of piping systems is the last design activity after the building design and structural design. Therefore, the layout of the pipes and equipment in piping system is subject to the location and size of the column, the beam, and other building components. It is an inevitable result that a variety of elbows, branches, and reducers existed in the system. The design is separate from construction. The constructability is not in the scope of the objective of design. Through the interview with one of the largest MEP contractors in China, more than 100 thousand types of material were used in piping systems. The policies in recent years are more about prefabricated building and green building. However, policies related to the prefabricated building were limited primarily to the prefabrication of structural components such as slabs and walls. While the policies related to green building focus on the energy-saving in the operation and maintenance phase. There is a lack of policies to promote the piping prefabrication. The prefabrication and installation of pipes need smaller tolerances as the rework cost is high. Therefore, high skilled labors are needed. As the fierce competition among MEP contractors, it is difficult to achieve economies of scale. The availability of appropriate fittings and valves is a challenge to pipe prefabrication as different fittings and valves use different connectors, with different sizes. Other challenges are related to the BIM software for piping prefabrication, the support of the related specification, and the availability of fabrication shop. The result indicated that these challenges are easy to overcome.

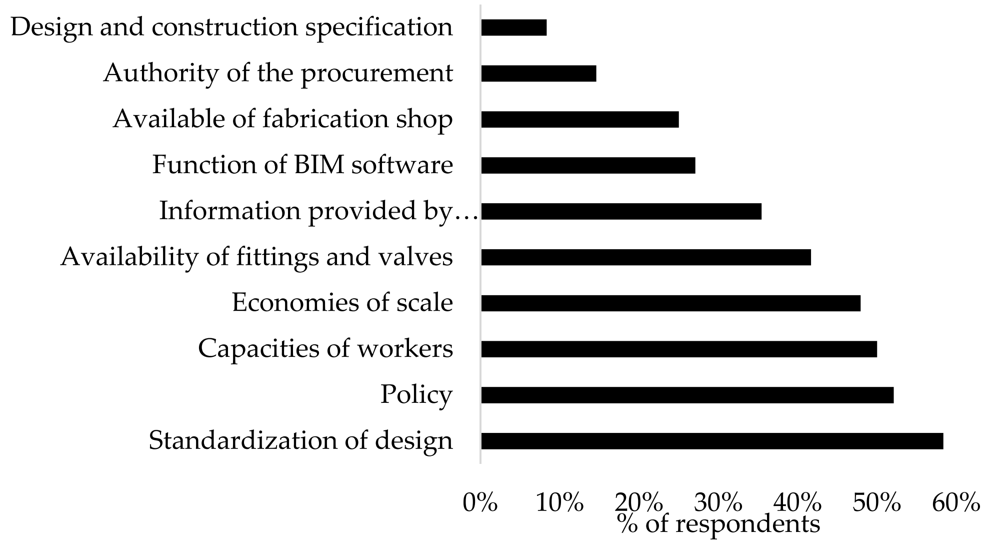

Figure 7. Challenges of piping prefabrication.

4.6. Pattern and Route

According to the survey, piping prefabrication is feasible in most cases, especially when using the threaded coupling, groove coupling, and flange coupling modes. Piping prefabrication is applicable for the most type of projects such as offices and hotels. However, the challenges and barriers that each contractor may face are different depending on the characteristics of projects. Under the promptings of successful cases, MEP contractors who want to adopt piping prefabrication in their projects need to validate and evaluate its feasibility again. Contractors should expand the prefabrication capacity incrementally in a keen competition environment. Based on the result of semi-structured interviews, case studies, site visits, as well as the questionnaire, a four-phase route is suggested for MEP contractors.

In the first phase, the MEP contractors are suggested to learn to develop BIM model above LOD 300 based on the real size of the fittings and valves. BIM is beneficial to identify the prefabrication scope and to communicate the scope with supply chain participants. The virtual BIM model is useful to avoid conflicts with other MEP systems. BIM can provide rich data for prefabrication. Take the fire sprinkler system as an example, BIM provides the accurate length of pipes. To achieve this goal, a lot of components information need to be stored in the BIM software, for example, stored as families in Revit. This information needs to be reconfirmed and updated with the distributor and manufacturers. This is helpful to develop BIM model of high quality in a very short time. In this phase, the BIM model that contains accurate data can be used to produce the detailed drawings with dimensioning automatically for workers on site. The contractors need to evaluate the benefit of BIM in improving the productivity of piping installation through clear observations of the piping installation process.

In the second phase, piping contractors should collaborate with a local fabricator to implement prefabrication in a pilot project. Piping contractors provide detailed shop drawings to the fabricator, then the components are transported to site according to the installation plan. In this phase, the main question should be settled is how to manage these prefabricated components. The management includes components labeling, packaging, transportation, and installation to the right place. From the experience of the case, it is difficult to find the right one from a pile of components. The production productivity of fabricator is higher than installation productivity on site. Therefore, the more quantity of prefabricated components conveyed to the site, the less efficient when picking out the component one by one according to the installation sequence. Besides, the label posted on the component cannot reflect the accurate location of it. As shown in Figure 8, the prefabricated pipes laid in a disorderly pile. The information exported from the BIM model developed in Revit such as the pipe length, the pipe ID was marked on pipes. Meanwhile, the plans of sprinkler system developed in Revit automatically were printed to workers for installation on site. Although the ID of a pipe can distinguish this pipe from other pipes, the ID cannot explicitly infer the location of this pipe. In other words, the worker needs to analyze the location of the pipe manually in the drawing according to the information marked on the pipe.

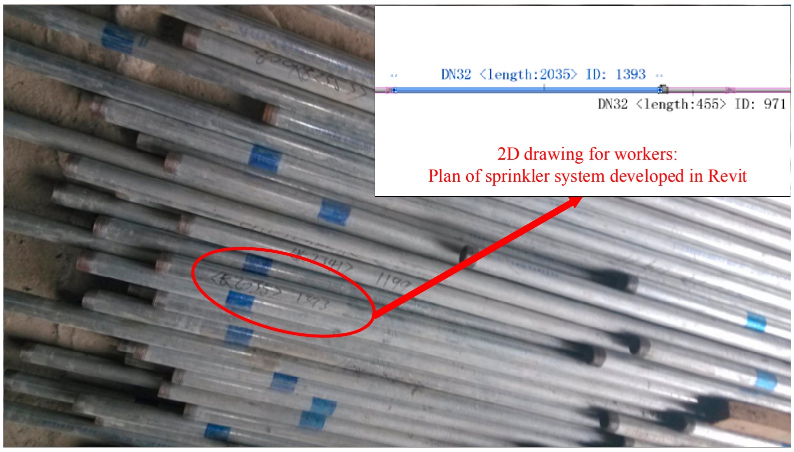

Figure 8. Prefabricated pipes marked with information exported from BIM model.

In order to integrate the prefabrication activity into the business process of the piping contractor, it is suggested for contractors in the third phase to set up a small prefabrication production line to produce standard components such as pipe spools. The production process and the management process in the facility shop should be planned carefully based on the experience obtained in the second phase. The production process includes cutting, threading, beveling, welding (for example, the flange need to be weld to a corresponding pipe), conveyor handling, pre-assembly, labeling, and packaging. As shown in Figure 9, the basic configuration of the pipe fabrication production line consists of one set of fixed-type high-speed pipe cutting machine, one sets of fixed-type pipe end beveling machine, many sets of the piping prefabrication fast fitting-up machine, many sets of piping automatic welding machine, and a set of the automatic conveying system. Besides, in some projects, the pipe coating machine is needed to distinguish different piping systems. The management process ranges from communication with BIM group, procurement planning, production planning and control, transportation, and coordination with the site. Some information technologies based on BIM should be developed to improve the efficiency of prefabrication. For example, after the detail design of prefabricated components, explicit information (e.g., system name, size, ID) and implicit information (the location of the pipe, the connected fittings) can be marked in the drawing. The size of pipes that planned to be prefabricated in the facility can be exported from BIM software to the central database, then be imported into the computer numerical control (CNC) machine. Moreover, some information in the BIM model can be used for procurement. In the production process, the quick response (QR) code can be labeled on the pipe. Then the QR code is used to search the information in the BIM model automatically.

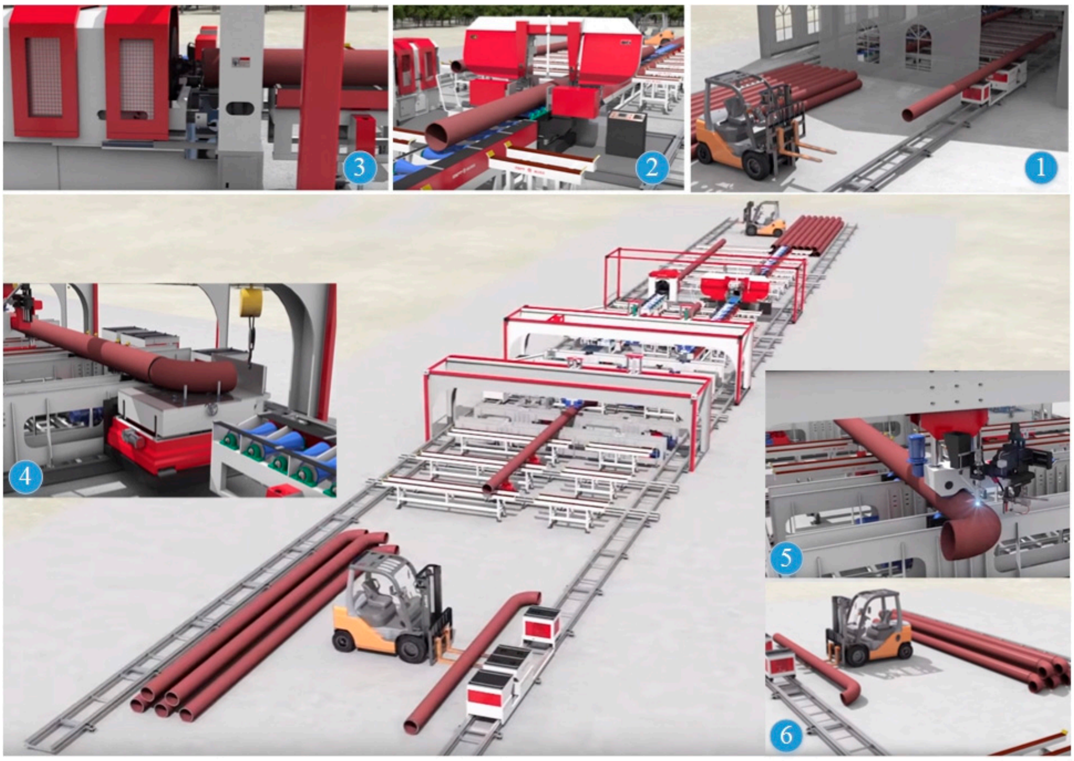

Figure 9. Configuration of a pipe fabrication production line. (**1**) the arrival of standard pipes; (**2**) high-speed pipe cutting machine; (**3**) the beveling machine; (**4**) the piping prefabrication fast fitting-up machine; (**5**) piping automatic welding machine; (**6**) the prefabricated pipe spools.

The fourth phase is an improvement and expansion of the third phase. The contractors can attempt to fabricate and assemble larger and more complex components (standard and nonstandard) such as pump sets and prefabricated packaged pump rooms. Take the pump room for an example, although the result of the survey indicates that the prefabrication of pipes in pump rooms is highly feasible, the successful implementation of piping prefabrication in pump rooms need to expand another production line. The pump room is characterized by a variety of different types of system, fittings, and valves, crosswise of horizontal and vertical pipes, and large-scale equipment. These characteristics increase the complexity and challenge for prefabrication. A number of components of special-shape in the pump room need to be prefabricated. The detailed design and pipe splitting of the pump room consume more time than a single system as the pipes are set closer. The location of large-scale equipment has a significant effect on the pipes layout and the prefabrication solution. Therefore, the production line used to produce standard components is not applicable for these nonstandard components. If the facility is expanded, higher productivity and applicability can be obtained in this phase. The simpler the prefabricated components, the more interfaces between the components. If the complex component is prefabricated in the facility, there will be few construction activities on site. This results in higher efficiency and less working space requirement on site.

5. Conclusions

MOC is a new technology for MEP contractors to improve productivity, especially in piping construction. Few MEP contractors have adopted this technology in their pilot project. More and more contractors in China want to adopt this new technology in their projects. Based on the information collected from the contractors, interviews with some professors in MEP area, and a comprehensive survey, the levels of the feasibility of piping prefabrication in different piping systems, different connection modes, and different types of project were analyzed. The influences of BIM, the IPD method, and early involvement of manufacturers or distributors were then surveyed. The top five challenges to implement piping prefabrication successfully were identified and summarized. Finally, the suggested pattern and route of piping prefabrication was proposed.

To get a comprehensive understanding of the current practices and challenges during piping prefabrication, several data collection methods were used. Ten experts were interviewed then fabrication facilities as well as project site were visited. Two case studies were collected and analyzed carefully. Based on the data collected from these three methods, a comprehensive survey was conducted.

According to the results, the levels of the feasibility of piping prefabrication differ in connection modes, type of piping systems and projects. The prefabrication of the piping system with a threaded coupling, flange coupling, or groove coupling modes has a higher level of feasibility, as the pipe component connected by the three methods are detachable. The higher standardization of design in the hotels, offices, and residential projects increases the feasibility of piping prefabrication in these projects. The significant effects of BIM, integrated project delivery, and the early involvement of manufacturers and distributors were verified from the result. The development of a detailed BIM model needs accurate information from the manufacturers and distributors. This BIM model is a basis for piping prefabrication. The IPD method is beneficial to the coordination of the detailed design, installation of the whole piping systems. The integrated plan made by all the participants would decrease the risk from prefabrication. As piping prefabrication is still in its infancy in China, challenges and barriers exist in various aspects. According to the result of survey, the biggest challenge is the low level of standardization of design, followed by the lack of preferential policy, low-skilled workers, the economies of scale, as well as the availability of fittings and valves. Other challenges related to the function of BIM software, the production information provided by manufacturers and distributors are easy to overcome and improve. The present design and construction specifications have little restriction to the piping prefabrication according to the semi-interviews and the result of survey.

Finally, a four-phase route of piping prefabrication for MEP contractors was suggested, taking account of the abovementioned results related to the levels of feasibility and challenges. MEP contractors should firstly learn to develop the BIM model above LOD 300 with real size of fittings. Productivity needs to be evaluated when the BIM model is used to provide accurate dimensions of pipes. Then MEP contractors should collaborate with a fabrication facility to adopt piping prefabrication in a pilot project. In this second phase, the management process started from detailed design of BIM model to installation of pipe components to the right place will be learned and analyzed. Based on the experiences obtained in the former two phases, the MEP contractor should invest a fabrication facility to get more interests. The first production line should focus on assembling the standard components such as pipe spools. In the fourth phase, the facility can be expanded to assemble both the standard and nonstandard components. Especially, the more complex the component assembled in the facility, the fewer construction activities on site. Therefore, higher productivity will be gained.

This paper provides valuable information for practitioners in the MEP field, especially for these MEP contractors that want to adopt piping prefabrication. This paper can hopefully contribute to MEP contractors by identifying that the levels of feasibility of piping prefabrication in offices and residential projects with the threaded coupling mode are the highest. Although piping prefabrication has several advantages, the successful implementation of it needs to lay a solid foundation of BIM ahead and overcome other challenges in various aspects. For example, the first step of piping prefabrication should be started from an office or residential project using the threaded coupling mode. Then the business of MEP contractors can be expanded according to the suggested pattern and route. The contribution to the body of knowledge and researchers is that this paper finds that the level of feasibility of piping prefabrication differs in piping systems, connection modes, and types of project. Challenges and barriers of piping prefabrication are firstly identified that include internal factors such as standardization of design and external factors such as policy, availability of skilled workers and fittings and valves of high quality. Future research includes the identification of best practices in piping prefabrication.

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