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Challenges and Future of Prefabricated Pipe Spools

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Abstract: Prefabrication is a construction technique that is increasingly being applied to different building components due to its many benefits, including higher quality and lower waste. Despite these advantages, there are challenges in execution of these components on projects, due to transportation logistics, skilled labor requirements, and project management techniques. This paper investigates the current landscape of prefabricated pipe spools and potential solutions for minimizing these challenges. The scope of this research includes a proposed workflow, to standardize implementation of these components. Semi-structured interviews were conducted with industry professionals to assess current industry practices and the validity of the proposed workflow. Findings of this paper indicate that greater integration between design, fabrication and transportation is required to minimize inefficiencies when implementing prefabricated pipe spools on projects.

Key words: prefabrication, pipe-spools, transportation, construction, planning

1. PROBLEM STATEMENT

Prefabrication is defined as “a manufacturing process, generally taking place at a specialized facility, in which various materials are joined to form a component part of a final installation" [1]. It is a well understood methodology that provides many benefits when compared with conventional construction techniques, from reduced construction duration and improved quality to safer work environments [2]. Due to these benefits, prefabrication is widely used in different sectors, from applications in oil and gas to healthcare and for different components from mechanical, electrical, and plumbing (MEP) to structural and architectural building components [3].

Prefabricated pipe spools are defined as a collection of integrated prefabricated sections of piping systems. Among various types of building components, production and installation of pipe spools have been identified as a costly and critical process in construction projects because of their unreliable delivery which often results in construction delays [4]. This has resulted in pipe spools becoming one of the most commonly prefabricated components on construction projects [5]. These prefabricated piping systems can include threaded couplings, flange couplings, groove couplings and other sub components [6].

The most critical challenges of implementing prefabricated pipe spools should be understood by practitioners to determine suitability of these components on projects. Without an adequate plan, these components may suffer from cost overruns or delays during transportation, installation or planning. Currently there is no framework that incorporates these processes in a way that seeks to mitigate challenges. Existing studies have focused on transportation, zoning and minimizing deviations in pipe spool components, but have neglected to outline a comprehensive workflow that accounts for these inefficiencies. This study aims to identify and introduce common issues that arise as a result of implementing prefabricated pipe spools onsite, and potential solutions to mitigate these negative impacts through a literature review of 20 existing studies and interviews with industry experts.

2. BACKGROUND

To highlight the complexity of pipe spool installation, a brief description on their application, assembly, and installation follows. Pipe spools are used in many industrial facilities such as petroleum refineries, petrochemical plants, nuclear power plants, and off-shore oil/gas production facilities [7]. They are often made up of three components: pipes, flanges and fittings. First, a pipe is a tube of any specified material used to convey a liquid substance from one location to another. The flange connects piping and components in a piping system by use of bolted connections and gaskets. Finally, the fitting is used in pipe systems to connect straight sections of pipe or tube, adapt to different sizes or shapes, and for other purposes such as regulating or measuring fluid flow.

During the prefabrication process, the prefabrication shop receives specifications for the pipe spool assembly. Raw pipes are cut to the required sizes and moved with pipe fittings to a fitting table, where some of the components are temporarily fitted together. These sub-assemblies are welded before they go back to the fitting table to get fitted with other spool components. After the spool is assembled, it undergoes quality assurance (QA). During QA, a welded spool may need to undergo any or all of the following operations: stress relief, hydro testing, painting, and other surface finishing. Prefabrication is typically used where the working conditions are not suitable for the fabrication steps such as welding, fitting, etc [8].

To prepare for installation, every piece of the pipe spool is typically identified with a visible marker on the piece itself. This makes it easy to know where its destination is in the facility and/or where it belongs in a multi-spool system of pipes. The installer can then efficiently stage the piece after transportation and delivery of the material.

3. LITERATURE REVIEW

This section reports findings from existing studies on advances and challenges of implementing prefabricated pipe spools on construction projects. These studies highlight challenges during transportation and installation of prefabricated pipe spools. Improvements in project management techniques, including automation and skilled labor are also introduced.

3.1 TRANSPORTATION OF PREFABRICATED PIPE SPOOLS

Due to numerous factors, such as low labor cost and convenient procurement of materials like steel, prefabricated pipe spool modules are typically undertaken by overseas vendors in East Asia, such as South Korea and China [9]. After manufacturing, modules will then be shipped to construction sites in North America. The result is significant cost and schedule delay incurred to the overall construction process via transportation of materials. Hong et al. [10] reported that transportation costs account for 10% of the cost of typical prefabricated components. As the size and weight of prefabricated pipe spools can be significant, the transportation cost is mainly dependent on the number of transport trailers or cargo holds. Ideally, the modules will be trucked to site, either directly from the module yard or from a staging location, and then offloaded directly onto prepared foundations.

A complicated material supply chain makes just-in-time delivery practically impossible for prefabricated pipe spools [11]. This has led some experienced project managers to believe that buffers can provide flexibility to uninterrupted installation during construction [12]. Material buffers can be used to reduce transportation variability from upstream suppliers. Interviews conducted by Song et. al [13] confirm that pipe spools can accumulate and be stored in a constructor's laydown yard as early as 5 to 6 months prior to scheduled installation. Laydown yard personnel will locate, identify, and stage the pipe spools when the fitting crew makes a requisition. Oftentimes in this process, there are misplaced pipe spools, which require additional time and cost to relocate. The authors have also reported that RFID technology is effective in tracking pipe spools in laydown yards through field tests and statistical analysis. This approach reduces time required to identify and locate pipe spools, reduces misplaced pipes and search time, and increases reliability of pipefitting schedule.

During transportation, deformations may occur due to vibrations and other unfavorable movements despite assemblies being braced, making installation more complicated. If these assemblies are not identified and replaced before installation begins, then adjustments and alignments required to overcome out-of-tolerance erection can be costly. According to Akinci et. al [14], approximately 10% of the total required rework is due to late defect detection.

To further optimize transportation of these components, configuration of pipe spools should be considered in the transport medium. A large-scale integer optimization model was developed by Yi et. al [15] to optimize for the least number of cargo holds to transport prefabricated components. The study assumed that the shape of a typical prefabricated product is a rectangular prism. Song et. al [16] has developed a methodology to formalize the smallest workface boundary of a pipe component using an LOD 400 model. Using this methodology, the rectangular boundary of a pipe spool can be more accurately determined, allowing the optimization to be performed to a higher degree. Lee et. al [17] has developed a methodology which ultimately reduced the number of transport trailers required to transport wall panels. Extending the scope of the study to include pipe spool components may attain similar results in cost reduction when trailers are used as the transportation medium.

3.2 SKILLED LABOR

In addition to transportation barriers, skilled labor requirements and lack of onsite automation are barriers to adoption of prefabricated pipe spools in construction. Prefabricated pipe spools require specialized skilled labor, such as machine oriented skills both on-site and in the manufacturing process, as installation is different from in-situ construction.

Automating QA processes of pipe spools can result in decreased reliance on skilled labor, and will result in supply chain and productivity improvements as current approaches lack a sufficient level of control [18]. Nahangi et. al [18] has performed an automated deviation analysis using laser-scanned point clouds to the as-is BIM. The study employed a distance-based analysis for defect and inaccuracy detection, which were validated for pipe spools The proposed framework enables defect detection in a timely manner which, therefore, has the potential to improve construction productivity.

3.3 PROJECT MANAGEMENT

In conjunction with automation of existing processes, project management techniques can aid in the efficient installation of prefabricated pipe spools.

Lean construction techniques such as pull driven scheduling and flow production are rarely used by spool fabricators for industrial applications, as spool fabrication lacks suitable tools for modeling and analyzing system changes and improvements. A study by Wang et. al [19] explored a simulation-based approach to compare a traditional batch-and-queue fabrication shop to one using a flow production technique. The results highlighted that the "flow" technique can result in an improved production performance of pipe spool fabrication shops.

Similarly, a study by Tommelein [5] compared three probabilistic models for pipe spool installation using a simulation based approach, where a pull driven scheduling model ultimately resulted in smaller material buffer, earlier project completion and increased productivity. These studies show that lean techniques can be applied to achieve improvements in fabrication system performance.

4. DISCUSSION

In the following section, recommendations to increase success of prefabricated pipe spool implementation are provided. A combination of studies and workflows are utilized to outline an "ideal" strategy for practitioners.

In most industrial projects that utilize pipe spools, the designer provides 2D drawings to the piping contractor which only contains general information of the piping system [6]. However, a 3D model that includes information such as the length of the pipes and the type of the fittings can be used to reduce material waste and improve design efficiency [20]. An LOD 400 model provides sufficient detail to capture this information.

After a model is developed, close coordination between the fabrication crew and modeling crew can help identify misalignments and promptly implement any new design modifications. Through the use of lean techniques such as the Last Planner System (LPS), increased production and efficiency is expected.

As previously mentioned, deformations are likely to occur during transportation. Using methods such as automated deviation analysis, practitioners can quickly identify deformations and begin the rework process immediately. Safa et al. found that 3D laser scanning and photogrammetry techniques can be successfully used in QA systems for post fabricated pipe spools, substantially improving efficiencies over current QA processes [21].

A common issue with prefabricated components, that extends to pipe spools, is the relationship between transportation of the material and zoning onsite for storage. Without adequate zoning consideration, storage onsite may not reflect the relationship between production quantity of prefabricated components and jobsite installation requirements. This can result in delayed installation and cost overruns [22]. Shih et al. developed an optimization model as a function of total storage capacity and transportation costs. A mixed zoning mechanism was recommended as a means to preserve space and planning practicality.

The authors have outlined a process, shown in Figure 2, which demonstrates the recommended implementation for prefabricated pipe spools. This workflow outlines the importance of developing a fabrication level BIM, and introduces a feedback loop between the BIM and detected defect. In addition, emphasis is placed on the means of transportation, by considering reshuffling and stacking efforts. Current implementation processes neglect these additions, and often rely upon static design drawings to begin fabrication. This can result in fabrication of outdated components which lends to rework and increased delay.

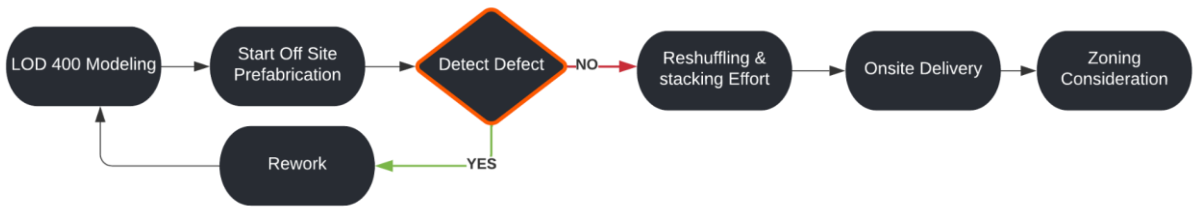

Figure 1. Ideal prefabricated pipe spool implementation process. This process is meant to reduce the cost overruns and schedule delays.

To verify prefabricated pipe spool process improvements highlighted in Figure 1, semi-structured interviews were conducted with 2 industry experts that have 15 years of experience on average. These experts have sufficient experience with procurement and installation of pipe spools and are currently working at market-leading companies. Interviews were conducted over a phone call and the interviewees were asked the following questions:

1. What are the biggest issues to successfully implementing prefabricated pipe spools on projects?
2. How do you manage these challenges?
3. What role do different stakeholders play in the manufacturing and installation of prefabricated pipe spools?
4. How does your ideal prefabricated pipe spool implementation process flow look?

The interviewee's answers were collected through these interviews and distilled by the authors. The respondents unanimously agreed that skilled labor is a critical component to successfully manufacture and implement prefabricated pipe spool components. Skilled labor is especially required in the fabrication shop during manufacturing, as utilizing fabrication grade equipment takes time and experience to master. Employees who are skilled in this area often stay with the same firm for an extended period of time, and are difficult to recruit externally. In order to be accurate with cutting and prepping material, an LOD 400 model is recommended. These models require intense collaboration with other trade partners to ensure accuracy. Training, through experience and education, remains the primary action in which to manage challenges of skilled labor deployment and retention.

Currently, across most manufacturers there is no formalized methodology for orientating pipe spools onto trailers for transportation. Trailers are generally limited to 50 spools, barring especially large components that require separate trailers, while the smaller components are placed using last-in first-out lean principles. By optimizing pipe spool orientation during trailer transportation, it is possible to achieve cost reduction by increasing the number of pipe spools per trailer.

Once pipe spools arrive onsite, they are hoisted into place depending on their size. Working with a general contractor that allows for pipe activity in the project schedule and allows installers the flexibility to get onto site early, is a benefit in navigating logistical challenges that arise. It allows pipe spool installers to move piping components through the facility with minimal obstacles, and install larger components before other trades. Slight field modification can be performed to pipe spools onsite. If the LOD 400 model changes substantially before pipe spool manufacturing completes, there is generally an opportunity to accommodate the new design provided there is enough buffer in the schedule.

It was agreed by respondents that a formalized framework for evaluating prefabricated pipe spool success is required for their successful implementation. Without metrics or an evaluation process, facility owners and pipe spool manufacturers may not understand the challenges of implementing prefabricated pipe spools and whether they were successful in their efforts. Implementing the proposed workflow can allow for more control over the manufacturing, and delivery process which would increase the likelihood of achieving project goals with prefabricated pipe spools.

5. CONCLUSIONS, LIMITATIONS, AND FUTURE WORK

This study consists of a review and discussion of research pertaining to prefabricated pipe spools on construction projects. It was determined that improvements in transportation, skilled labor, and project management techniques can be performed to increase success of implementing these prefabricated elements. Through combining methodologies from existing studies, a new ideal workflow was developed which was confirmed through expert interviews.

The ideal process outlined in Figure 1 is consistent with the desires of pipe spool manufacturers. It seeks to eliminate inefficiencies that arise with implementing prefabricated pipe spools, by creating a feedback loop that allows all stakeholders to manage and rapidly respond to issues. The process can reduce cost overruns, by reducing deviations in pipe spools that are delivered onsite and optimizing their delivery.

It is recommended that more sophisticated 3D modeling, defect detection, restacking and reshuffling efforts, and transportation optimization should be considered to enhance current workflows. In addition, close collaboration between the general contractor and pipe spool installer is beneficial when developing the project schedule. Skilled labor remains the largest challenge for pipe spool manufacturers in retaining knowledge and level of sophistication.

Current practice does not truly account for pipe spool orientation within trailer transportation, which can cause inefficiencies and unoptimized deliveries. An effort to evaluate stacking and reshuffling is necessary to improve the pipe spool implementation process.

Further research into different modes of transportation for prefabricated pipe spools is needed to broaden the investigation. The reviewed studies focused on cargo holds, however other forms of transportation include truck and rail. These alternative methods may have different lead times, implementation strategies, and constraints. Additionally, the reviewed studies focus on prefabrication of pipe spools across Canada, USA and China. A comparison with the pipe spool manufacturing and delivery across different countries would provide a more holistic view of challenges with their implementation.

Sustainability efforts can also be considered while optimizing transportation of material. A comparison of embodied carbon associated with prefabricated and in-situ pipe spools should be performed to understand lifecycle costs associated with either technique. Insights from these studies can better inform practitioners how prefabricated pipe spools affect environmental sustainability benefits.

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