Factors Affecting Productivity of Pipe Spool Fabrication

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Abstract: Pipe spool fabrication is an early stage in industrial construction projects and is crucial for the successful delivery of a project. Pipe spool fabrication is a complex and uncertain process due to the uniqueness of its products. The productivity of the fabrication process and the factors affecting productivity are therefore of great importance to project managers and construction researchers alike. Being able to identify all of the significant factors affecting productivity is critical to the ability to accurately estimate productivity and ultimately improve the fabrication process. This paper introduces the factors that affect the productivity of the pipe spool fabrication process that are not accounted for in the production unit of spools. In addition, the impact of each factor on productivity is illustrated, and different methods for modeling these factors are proposed. This paper provides a framework for a more comprehensive approach to estimating the productivity using the production unit of spools.

Keywords: Diameter inch, factors, pipe spool fabrication, productivity

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1 INTRODUCTION

Pipe spool fabrication falls under the category of industrial construction processes. The term “industrial construction” is used to describe a wide range of facilities for basic industries, such as petroleum refineries, petrochemical plants, nuclear power plants, and oil/gas production facilities (Barrie and Paulson 1992). Pipe spools are normally built in a fabrication shop through a series of cutting, fitting, welding, and other processes according to the engineering designs (Song et al. 2006). Final products are either assembled, and form large modules, or are shipped directly to a construction site for installation.

At a higher level, the piping process can be divided into four phases: design, pipe spool fabrication, module assembly, and site installation. Pipe spool fabrication directly affects module assembly and site installation, therefore it is a critical stage not only in a piping project (Hu and Mohamed 2011), but also in an overall industrial construction project. As a result, the productivity of the spool fabrication shop has always been of great interest to researchers.

Fayek and Oduba (2008) introduced many factors that affect the productivity of field pipe rigging and welding processes on an industrial construction project. These factors can be categorized into three groups: attributes of the spool, attributes of the crew, and environmental conditions. In this study, Fayek and Oduba developed a fuzzy expert system to estimate labour productivity, defined as manhours per unit quantity, using, as inputs, the introduced productivity factors. Three models were developed to estimate the productivity of pipe rigging, carbon steel butt welding, and alloy steel butt welding. These models had a numerical accuracy of 38%, 49%, and 41%, respectively, and a linguistic accuracy of 86%, 75%, and 50% respectively.

Tommelein (2006) investigated the effects of using standardized spools, both in the fabrication shop and for on-site installation processes. According to her definition, a “specific” material refers to a material that is a one of a kind, which means the facility’s design only has one of it. In contrast, a “standard” material refers to materials that are identical and have been used more than once in the facility. She used a simulation model to measure the effect of using standard materials for piping projects. Her model indicated a reduced cycle time in the fabrication of standard materials, in comparison to specific materials.

Sadeghi and Fayek (2008) used a work breakdown

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structure approach for modeling the pipe spool fabrication and assembly process. They developed a simulation model capable of both estimating the productivity of the fabrication shop and indicating potential bottlenecks in the fabrication process. The results of this model were satisfactory, as it was capable of estimating the productivity of the fabrication shop with less than 5% error. Also, it used statistical analysis to determine resources with a high waiting time that create bottlenecks in the process.

Wang et al. (2009) studied the effects of shop layout and their proposed Flow Production System (based on lean production practices) on the productivity of the fabrication shop. The study showed that changing the shop layout to a flow production layout resulted in a significant reduction in spool cycle time.

Hu and Mohamed (2011) studied the effects of the assembly sequence (i.e., cutting, fitting, and welding) on the spool fabrication process. A simulation model of the pipe spool fabrication shop was used to test the effects of changing the sequence of steps. There are many alternatives approaches to build a spool from its raw material. The spool can be fitted and roll welded in various sequences to make the intermediate spool assemblies and eventually the final spool. The simulation model demonstrated that changing the sequence of activities can reduce the cycle time and amount of handling by an average of 10%.

In this paper, first the processes of pipe spool fabrication are briefly introduced, and the diameter inch standard for measuring unit cost, production, and productivity is explained. Then, the important productivity factors that are not considered in the diameter inch standard and their effect on the fabrication process are explained. In addition, methods for modeling the effect of these factors on productivity of the fabrication process are presented. This research is based on a case study in a major industrial fabrication facility in Alberta, Canada.

2 PROCESSES IN PIPE SPOOL FABRICATION

Before a project is started, the required materials, such as pipes, flanges, fittings, and valves are shipped to the fabrication shop and stored in the designated area. Once all the material required for an isometric is available, that isometric is released to the shop for fabrication. Pipes, the main component of spools, must first be cut into pieces of the size required by the drawings. After pipes are cut, the cutting operators use disk grinders to smooth the end surface of the pipes and bevel them if required. Then pipes are moved to fitting stations to be joined together. Once the pipes and other components of the spool, such as reducers, valves, and flanges, are fit, overhead cranes are used to move the assemblies to the welding stations. Fit-

ters usually move assemblies that weigh less than 50 pounds by hand.

Welding is performed via two methods: roll welding and position welding. In roll welding, the welder fixes one end of the pipe into a pipe turner and rotates the assemblies while welding them. Position welding is used when the pipes cannot be rotated by a turner (the assembly has a branch longer than 5 feet), or when components are not round in shape. Position welding is a difficult procedure, and takes longer to perform than roll welding. Assemblies may move between fitting and

![Figure 1. Pipe spool fabrication process](image-url)
welding stations several times before roll welding is finished or the final spool is ready to be position welded. When spools are complete, they go through quality control. Then, based on the drawing requirements, they may be hydrotested or undergo other processes such as surface treatment and painting.

The typical processes in pipe spool fabrication are illustrated in Figure 1.

3 PRODUCTIVITY OF PIPE SPOOL FABRICATION PROCESS

Spool fabrication jobs are usually unit-based projects, where contractors bid on the unit cost of the project. One of the most common standards used for measuring spool fabrication unit cost, production, and productivity is called a diameter inch ($\phi''$). Factoring, based on diameter inches, is used to determine the quantity of manhours required to complete a specific task. Items with thicker material and/or higher material grades require more time to complete and therefore receive more factored diameter inches. The $\phi''$ is a reliable factor for cost estimation and scheduling that considers the physical attributes of a spool and its required fabrication processes. The $\phi''$ includes almost every physical feature of the spool and welds: type of material, wall thickness, diameter, and type of welding procedures. It is important to note that all the work performed on a spool, like cutting the pipes, fitting, welding, handling, and hydrotesting, is factored into the $\phi''$ of a spool. There is no unique definition for $\phi''$. As an example, a 6" diameter carbon steel pipe with standard wall thickness (0.281") requires 6 $\phi''$ worth of work to butt weld, whereas a 6" extra strong (0.431" wall thickness) stainless steel pipe requires 14.4$\phi''$ to butt weld. Thus, the latter weld takes 2.4 times longer to complete.

Currently, the most common productivity factor in the fabrication process is diameter inches of welded spool per manhour. The diameter inch standard only incorporates the physical attributes of the spool and the processes. There are many other factors that affect the process of fabrication and are not factored in the $\phi''$ of spools. Therefore, usually this productivity factor is not a reliable benchmark of the productivity of the fabrication shop. If these additional factors are recognized and incorporated in the productivity factor, a better estimation of the productivity will be possible.

Fabrication shop facilities are very different from each other in terms of size, layout, product, capacity, and equipment. In this research, one of the fabrication shops of a major industrial construction contractor in Alberta, Canada was studied for factors that affect the productivity of the fabrication process and are not or are only partially factored in $\phi''$ of spools. According to shop foremen and superintendents, the most important factor affecting productivity is the shop’s workflow: there is often a limited laydown area in the shop, and if the spools and assemblies are not in constant flow, bottlenecks will slow the process in all stations. Productivity can only be maximized when spools and assemblies constantly move from one station to another, with no delay in their completion.

The objective of this paper is to identify the factors that are not accounted for in $\phi''$ of spools. Nearly all of these productivity factors affect workflow in some way. These factors were identified using historical data, experts’ opinions, and observation of the fabrication process. A summary of the factors not included in the standard diameter inch measure is presented in Table 1.

<table>
<thead>
<tr>
<th>No.</th>
<th>Productivity factor</th>
<th>Accounted for in $\phi''$</th>
<th>The process it affects</th>
<th>Impact on productivity</th>
<th>Method of measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Position welding</td>
<td>No</td>
<td>Welding</td>
<td>Up to 100%</td>
<td>Position welds take twice as long as roll welds</td>
</tr>
<tr>
<td>2</td>
<td>Complexity</td>
<td>No</td>
<td>Fitting, welding</td>
<td>Up to 50%</td>
<td>Scale of 1 to 5</td>
</tr>
<tr>
<td>3</td>
<td>Physical attributes</td>
<td>Partially</td>
<td>Fitting, welding</td>
<td>Up to 20%</td>
<td>Length of spool</td>
</tr>
<tr>
<td>4</td>
<td>Handling</td>
<td>Partially</td>
<td>Handling</td>
<td>Up to 10%</td>
<td>Shape of spool</td>
</tr>
<tr>
<td>5</td>
<td>Skill of workers</td>
<td>No</td>
<td>Cutting, fitting, welding</td>
<td>Up to 50%</td>
<td>Scale of 1 to 5</td>
</tr>
<tr>
<td>6</td>
<td>Rework</td>
<td>Partially</td>
<td>Cutting, fitting, welding, hydrotesting</td>
<td>Up to 20%</td>
<td>$\phi''$ of spool that require rework</td>
</tr>
<tr>
<td>7</td>
<td>Change in spool priorities</td>
<td>No</td>
<td>Entire process</td>
<td>Up to 20%</td>
<td>Percentage of $\phi''$ of spools that are changed</td>
</tr>
<tr>
<td>8</td>
<td>Configuration</td>
<td>No</td>
<td>Entire process</td>
<td>Up to 50%</td>
<td>Percentage of $\phi''$ of spools that are configured</td>
</tr>
<tr>
<td>9</td>
<td>Shop layout</td>
<td>No</td>
<td>Entire process</td>
<td>Variable</td>
<td>Simulation modeling</td>
</tr>
<tr>
<td>10</td>
<td>Tools and equipment</td>
<td>No</td>
<td>Cutting, fitting, welding</td>
<td>Variable</td>
<td>Simulation modeling</td>
</tr>
<tr>
<td>11</td>
<td>Weather</td>
<td>No</td>
<td>Shipping</td>
<td>Variable</td>
<td>Wind chill factor</td>
</tr>
</tbody>
</table>
In the remainder of this paper, the identified factors, methods to model and measure the effect of each on the fabrication processes, and the factors' impact on the shop’s productivity are discussed.

3.1 Roll Welding and Position Welding

Position welding is a difficult procedure that takes longer to perform than roll welding. In order to reduce the amount of position welding as much as possible (if needed), before starting a new drawing, fitters seek ways to break the spool into smaller assemblies. Moreover, various fixtures are available to fit spools with different angles into the rotator. Some components of a spool (such as shoes) that should always be position welded are factored into the $\phi''$ during the drafting of the isometrics. However, there are other welds that can not be roll welded, due to the physical attributes of the spool (for example, a spool with a branch more than 5 feet). These position welds are not factored in the $\phi''$, but can take twice as long to complete, affecting productivity of welding procedure by up to 100%. The best way to model this factor is to measure the $\phi''$ of welds that are position welded and to calculate the extra manhours required for these welds.

3.2 Complexity of the Spool

Spools come in all forms. Usually the easiest spools to build are straight, with no angles and holes. On the other hand, complex spools may have many components and various branches with different angles. They usually traverse between fitting and welding more than normal spools, and require position welds more often. A complex spool may require up to 50% more time to fit and weld in comparison to a regular spool with the same $\phi''$. The complexity of a spool may also increase fabrication errors, which result in rework or, in rare cases, rebuilding of the spool. To model the complexity of spools, a scale of 1 to 5 can be used to adjust the extra manhours required, where level 1 is a regular spool, and level 5 is a spool that takes 50% more manhours to complete.

3.3 Physical Attributes of the Spool

Nearly all physical attributes of spools are factored in $\phi''$; however, the length of a spool is not factored in $\phi''$, but it may affect the productivity of the fabrication process. Usually spools are assigned to stations based on their size and length. Some medium spools may not fit in regular fitting and welding stations, making them difficult to position. In addition, long spools are difficult to handle and require larger work stations. These spools increase the time required for positioning them in fitting and welding stations. To model the effect of the length on the fabrication process, spools can be classified into three categories: short spools, less than 40 feet, that have no effect on productivity; medium spools, 40-70 feet, that affect the productivity by 10%; and long spools, more than 70 feet, that affect the productivity by 20%.

Other attributes that can reduce productivity are the weight and diameter of the spool. On the one hand, larger spools are usually heavier, more difficult to manoeuvre, and require the correct size of rigging equipment. On the other hand, small diameter spools (smaller than 2”) require specific attention, and can be difficult to weld. These two attributes can be modeled under handling of spools and complexity of spools.

3.4 Handling of Spools

Improper handling of the assemblies and spools during the fabrication process can cause bottlenecks. Spools come in different sizes and shapes. The best way to categorize them is by diameter, as follows:

1. Small: diameter less than or equal to 2”;
2. Medium: diameter greater than 2” and less than or equal to 12”;
3. Medium large: diameter greater than 12” and less than or equal to 24”;
4. Large: diameter greater than 24”.

Small diameter pipes in light assemblies can be handled manually. However, sometimes over-handling may occur. This means the amount of $\phi''$ produced is very small in comparison to the amount of time spent handling the pipes and assemblies. Medium and medium-large spools usually require only one crane to handle them, making the process relatively productive, whereas large spools can affect productivity to a great extent. Positioning large spools in rotators and other fixtures requires attention and time. While the cranes are moving these pipes and assemblies between stations, other stations cannot use the cranes. Large spools that are longer than 60 feet require two cranes to pick them up and move them from one station to another. Therefore welders and fitters may lose several manhours waiting for cranes to move the pipes out of their stations and bring new ones in.

Modeling the effect of different spool attributes on the handling process is difficult, and various methods can be employed for this purpose. If the project is an average general fabrication project and has a good combination of all sizes of spools, handling large spools (larger than 24” diameter) and long spools (longer than 60 feet) can each increase the required manhours by 4%, and small spools (less than 3” diameter) can increase the required manhours by 2%.

3.5 Skill of the Workers

Workers in the shop have different experience levels. For example, some welders can set up and weld spools faster than others. Also some workers have more certifications than others and can perform more welding techniques. The skill level and experience of workers
significantly affects the productivity of activities in the fabrication shop, but they are not factored in the $\varphi''$. The most experienced fitters and welders can finish the same $\varphi''$ of spool approximately 25% faster than a standard crew. The skill of workers can be modeled by a scale of 1 to 5, where a worker with a level 5 experience can do a job twice as fast as a worker with a level 1 experience.

### 3.6 Rework

Rework is not common in fabrication processes, but when it happens, it reduces the productivity. Rework may be caused by various errors. Some may be fabrication errors, such as wrong orientation, wrong dimension of pipes or fittings, and incorrect material. Spools that do not pass quality control or hydrotest also fall under this category. Another type of error that results in rework is engineering error. Engineering errors are made during the drafting of original isometrics. The owner is responsible for these errors, and will pay the cost of fixing them. Spools with engineering errors are usually rebuilt, since most spools with engineering errors are not repairable. For repairing spools, many manhours are spent to locate the spools and bring them back for changes. The effect of rework on productivity can be modeled by using the $\varphi''$ of spools that require rework and the manhours spent on handling and repairing them. In a given week up to 10% of $\varphi''$ of spools may require rework.

### 3.7 Change in Spool Priorities

Sometimes the owner of a project makes changes to the project schedule that may affect the process of fabrication. For example, the owner may change the priority of the spools and the sequence in which they should be delivered, or they may send new drawings which have a higher priority and are needed immediately on site. These changes to the spool priorities can reduce the productivity if the fabrication shop is working at maximum capacity and does not have enough available resources to fabricate the new spools. In such situations, in order to start fabricating the new spools, some of the current spools and assemblies may be moved outside the shop, and then brought back in again when the high priority job is completed. These sudden changes to a schedule can result in extra handling of the spools, which can reduce the productivity of the shop.

As mentioned before, flow of the process is the most important factor in the shop. When sudden changes are made to the schedule, the current flow of spools, which has been established as the most productive for the fabrication shop, will be interrupted. Therefore the fabrication shop can no longer perform at its peak productivity for a period of time. Schedule changes are rare in fabrication shops, but if they happen they affect the entire process and can reduce overall productivity of the fabrication shop by up to 20%. The best way to model the effect of this factor on the productivity is to reduce the productivity by the percentage of $\varphi''$ of spools that are changed in a given week, which usually does not exceed 20%.

### 3.8 Configuration of the Spool

A “configured” spool is 120 feet long, with more than two directional changes, each greater than 12 feet in length. Configured spools can drastically reduce productivity of the fabrication shop under certain circumstances. Nearly all have branches long enough to prevent roll welding. Therefore, most welds are done in position. In addition, configured spools are unwieldy, since two overhead cranes are needed to move them into the fixtures. While they are moving in the shop, other adjacent stations have to stop their work for safety reasons. Sometimes overhead cranes are required to hold the branches during welding. Stations required for these large spools also occupy a floor space equal to three or four smaller stations. Shipping these configured spools is also difficult and takes more effort than smaller spools.

When the spools change from general spools to module spools, the percentage of configured spools increases as well. Based on the job, type of modules, and ratio of configured spools to general spools in a project, the productivity of the fabrication shop can decrease by 20% to 50%. The best approach to model this factor is to measure the ratio of $\varphi''$ of configured spools to general spools in the project.

### 3.9 Shop Layout

The shop layout is another factor that affects the productivity of the fabrication shop. The shop is most productive when spools are in constant flow and are not laying on the ground, waiting for the next process. The flow of the job is very important in the fabrication process because of the limited space in the shop to lay down spools. In addition, different stations need to be carefully positioned to minimize the handling of spools and to provide the best layout for the job. Layout should be changed based on the properties of each job to provide the best flow of spools and assemblies in the shop. Jobs can be categorized as general fabrication, module piping, and large bore piping.

Measuring and modeling the effect of the shop layout on the productivity of the fabrication process is extremely difficult and requires advanced modeling methods. Wang et al. (2009) used simulation modeling to study the effect of different shop layouts on spool cycle time and illustrated that changing the shop layout can effectively reduce the cycle time.
3.10 Tools and Equipment

Every product of the fabrication shop is unique, and the attributes of each spool vary greatly from one another. The appropriate tools and equipment should be available in each station, so that fitters and workers do not spend extra time looking for the right size of tools. Equipment and tools occupy a large portion of the shop’s floor. In certain jobs, some large pieces of equipment are not used in the shop and, if possible, removing them will provide enough floor space for laydown areas or even new stations. The effect of removing the unnecessary equipment from the shop on productivity can be modeled in the same way as shop layout by developing an appropriate simulation model.

3.11 Extreme Weather Conditions

Extreme weather conditions, usually cold, can also reduce productivity. The fabrication shop is a closed, heated environment, and weather conditions have no effect on the performance of workers. However, based on the design of the facility, some processes like unloading the pipes and shipping the spools may be performed outside the controlled environment of the shop. Therefore, extreme weather conditions may slow down these processes. The effect of weather conditions can be modeled by wind chill factor which varies from “no effect” to “complete shutdown”.

Among the investigated factors in this study, the configuration of spools was found to be the factor with the greatest impact on the productivity of the fabrication shop. Configured spools interrupt the flow more frequently, since these spools occupy a large portion of the shop. Moreover, when configured spools are completed, they also need to be hydrotested and undergo quality control procedures. During these activities, the spools are laid on the floor of the fabrication shop, which reduces the flow of other processes.

4 CONCLUSIONS AND FUTURE RESEARCH

There are many factors that affect the process of pipe spool fabrication. Different features of spools and processes affect the production of a fabrication shop, and some are factored into the ϕ” of a spool, while others are not. Most productivity factors affect the flow of the fabrication process, which is the most important factor to keep the fabrication shop at its best production rate. One important productivity factor, not accounted for in the ϕ” is the configuration of spools, since it has the greatest effect on the workflow.

In this paper, the steps that pipe spools undergo during fabrication were explained. The diameter inch standard for measuring unit cost, production, and productivity of pipe spool fabrication and the factors accounted for in this standard were introduced. Other important factors that affect the productivity of the fabrication shop that are not accounted for in ϕ” of spools were presented, and their effect on the productivity of different processes was discussed. A method to model the effect of each productivity factor on fabrication processes was suggested.

This paper attempts to introduce additional productivity factors and their approximate effect on the fabrication process, based on a case study. The estimates of the effect of these factors on the productivity (and therefore the duration) of activities were based on observations from previous projects and the opinion of shop foremen and superintendents. To further investigate and truly evaluate the impact of these factors on the processes and assess ways to improve productivity, a discrete event simulation model of the fabrication shop that is capable of modeling the fabrication process and the productivity factors that affect this process should be developed. Based on the results of the simulation model, various methods can be used to incorporate each productivity factor in the diameter inch measure of a spool. Alternatively, a new measure can be developed that includes the combined effect of these factors, which can be applied separately for better estimation of the productivity. The simulation model can also be used to measure the effect of these factors on the productivity of the fabrication process under different scenarios, and to model the impact of different approaches used for mitigating the effect of these factors on the productivity. Future research should investigate the proposed factors and their effect on productivity in other fabrication shops, to compare the results of different models and to propose more accurate measures for each of these factors.

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