Integrated Project Management Framework for a Pipe Spool Fabrication Shop

by

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Abstract

Modularization of heavy industrial construction is generally employed in Canada's oil and gas projects. The concept of modularization is becoming increasingly popular, but this type of work demands accuracy and quality to ensure overall productivity improvement and avoid re-work on site. Construction of industrial modules involves a considerable amount of pre-fabrication of piping spools. The availability of actual labour cost and productivity data is important to accurate pricing and profitable billing but also provides a valid basis for cost estimating on similar projects and for shop production scheduling. Yet of date, the current practice is still largely to utilize industry benchmark data and personal experiences to estimate new jobs, price products and prepare invoices. Visibility into actual labour costs in a timely fashion lends a competitive edge to project planning and control throughout engineering, pricing, estimating and billing activities.

The objective of this research study is to automate the collection of actual labour costs which ensures the accuracy of the cost data and improves productivity by eliminating manual paper-and-pen based procedures. A radio frequency-based indoor positioning system was developed and employed for real-time localizing and tracking pipe spool fabrication processes inside a pipe spool fabrication shop. With the enabling technology available, we propose a research framework intended to integrate fabrication process planning and tracking with the drawing and document control system, the materials management system, the labour

costing system and the production progress control system. Experiments were conducted inside the fabrication shop of a partner company in order to evaluate the potential and limitations of the proposed research framework.

The proposed system is not only able to automatically track actual labour-hours and thus actual labour cost in real-time, it can also provide estimators with precise and accountable labour productivity norms for project cost estimation , if used over a long enough period of time. Moreover, the availability of real-time actual labour-hour information enables us to assess and improve the construction company's competitiveness through labour productivity benchmarking and production progress measurement.

The results from this study will help owners and contractors to understand the variability in process piping estimates and the importance of calibrating existing methods before applying them on real-world projects. This information can also be useful in analyzing the risk associated with the project's capital costs and resolving estimating issues.

Preface

This thesis is the original work by Meimanat Soleimanifar. It is organized in a combination of monograph and journal-article format. Chapter 2 of this thesis is written on the basis of the below research paper.

1. Soleimanifar, M., Shen, X., Lu, M., and Nikolaidis, I. (2014). Applying received signal strength based methods for indoor positioning and tracking in construction applications. Canadian Journal of Civil Engineering. 41: 703-716

Dedicated to my beloved parents,

My lovely husband

And

My adorable daughter Tina

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CHAPTER 1

1 Introduction

1.1 Background and problem statement

Modular construction - the process of completing different sections of a building or a plant offsite before bringing the components together to form a finished structure - is a relatively new industry approach that brings about many benefits. Modular construction is the common practice for building industrial plants in the Alberta oil sands region (Taghaddos et al. 2012). Modularization refers to the pre-fabrication and pre-assembly of a complete system away from the job site which is then transported to the site (Wu and Lu, 2013). This is a practical and economical construction technique for process systems in the chemical, petrochemical, gas processing and oil refinery industry. Building such facilities and structures is classified as a special type of construction, which is called "industrial construction". Industrial construction encompasses the design, installation, and maintenance of all the structural and mechanical components in oil refineries, power plants, petrochemical facilities, etc.

One of the primary advantages is fast delivery of construction projects on site in northern Alberta, as separate components can be made simultaneously at different sites before being brought together. This reduces the risk of being hampered by factors such as inclement weather or delays that could bring a project to a halt if all work is taking place in a single location (Maru and Kawahata 2002). This is invaluable for any industry, particularly one with massive potential for rapid growth, such as Canada's oil and gas sector. Canada's oil and gas industry has experienced strong growth in recent years and is on course for further expansion in the foreseeable future. Therefore, modularization of heavy industrial construction is employed in Oil and Gas projects in hope of reducing costs and increasing schedule certainty, and allowing the project team to push ahead with engineering work while other activities proceed concurrently at the construction site.

Improved site access, reduced congestion and trade stacking, and less need for scaffolding are other factors which all enhance productivity and safety. Modularization allows workers to perform a constant scope of work closer to the ground and in accordance with consistent standards, procedures, and policies. Because so much construction is performed off-site, modularization greatly reduces workforce requirements including camp and transportation costs. Therefore, requirements for highly skilled labour onsite are minimal, an advantage in areas where such as in Northern Alberta skilled labour is costly and insufficient. Engineering, module assembly, and site work can usually proceed concurrently when modular construction techniques are employed, so to reduce the overall cycle time.

1.2 Conventional “stick build” construction

“Stick build” is the conventional or traditional way of construction whereby the various components are transported to a site and then put together into a final product. Conventional "stick built" construction strategies are time-honored: the engineering, procurement and construction are done in a logical, consecutive fashion, with some parts completed in parallel and some consecutively. The goal is to carry out the project as expediently and cost-effectively as possible.

Equipment and materials are procured from worldwide suppliers and are delivered to the site. At the site, roads are paved, foundations are poured, equipment is set, piping is erected and electrical wiring is completed. All of this is according to the drawings, specifications and standards developed during the detailed engineering phase of the project (Tatum, 1987).

1.3 Modularization

Modularization can be done in components as site-specific needs dictate. For example; prefabrication, preassemblies or packaged/skidded components all fall under the umbrella of modularization. All of these can help a project owner overcome factors which may present technical or economic obstacles to traditional construction approaches. Hence, module fabrication and assembly companies supporting the oil sands sector has modular construction facilities where thousands of tradespeople assemble pipe rack add-ons to oil sands plants. They often operate technologically advanced pipe and steel fabrication facilities as well. There are generally various levels of modular construction. They can vary from stick build (no modularization) to very large modules. The following table provides a continuum of construction possibilities in Alberta:

Table 1-1 Dimensional Load Categories in Alberta, Canada (Wu and Lu, 2013)

Category	Width	Height	Weight
I	8’6” – 14’	17’	<62,000 lbs
II	8’6” – 14’	17’	62,000 lbs to 130,000 lbs
III	14’-24’	29’6”	130,000 lbs to 200,000 lbs
IV	<24’	<29’6”	200,000 lbs to 346,000 lbs
V	>24’	>29’6”	>346,000 lbs

1.3.1 Module

A module is a unit mounted on structural frame. This frame is often without full upper structural frame and can contain equipment, piping system, heat tracing, electrical and instrumentation systems, tubing, specialized coating, insulation, fire protection, ladders, or stairs and platforms etc. Modules can be horizontal, vertical, single level or multi-level. Figure 1-1 depicts a typical pipe-rack module composed of structural steel frames and pipe spool components.

Figure 1-1 a typical pipe-rack module

1.3.2 Pre-Fabrication

Prefabrication is generally a manufacturing process taking place at a specialized facility in which various materials are joined to form a component part of a larger item. Any component that is manufactured off site and is not a complete system can be considered to be pre-fabricated. A module assembly yard is usually located near the spool fabrication and structural steel fabrication facilities, where pipe spools and structural steels are fabricated indoors. Figure 1-2 displays the pipe spool and structural steel fabrication shops.

(a)

(b)

Figure 1-2 a: Pipe spool fabrication shop b: Steel fabrication shop

1.3.3 Pre-Assembly

Pre-assembly is a process where various materials, pre-fabricated components and equipment (such as pre-insulated devices, control stations, junction boxes, control panels, pipe spools, structural steels etc.) are joined together at a remote location for subsequent installation as a unit. Pre-assembly is generally completed at the job site which is in a location other than the final place of installation. Pre assembly can be a combination of pre fabrication and modularization. Figure 1-3 displays the layout of the module assembly yard located in Nisku, Alberta.

Figure 1-3 The layout of the module assembly yard of the partnering company

1.4 Research Problem

Manufacturing components of industrial plant projects off-site provides for more controlled work conditions and allows for improved quality and precision in the fabrication of the component. The bulk of the fabrication and assembly are performed in off-site facilities and then transported or shipped to a final destination where the modules are installed on-site to form a finished building (Wu and Lu, 2013). The concept of modularization is becoming increasingly popular. However, industrial modular construction is a complex production system involving multiple supply chains. Thus, this type of work demands accuracy and quality to avoid re-work on site. It also requires a higher level of initial planning, project administration, and control and proper management of material procurement and logistics in order to realize cost efficiency of modularization.

Project cost estimation is the most important preliminary process in any construction project and is a critical factor for the competitiveness and profitability of an engineering and contracting company. Therefore, estimators are required to prepare an estimate in the bidding process, in an attempt to approach the actual cost of the project while only limited information is available in the tender documents. As for the refinery and petrochemical plant projects, the typical contract is the lump-sum in which the contractor agrees to supply at a pre-determined price. Since the starting point for this price is the estimate prepared during the bidding, it is evident that a sound estimate is essential not only to the competitiveness and profitability but also as a basis for effective project cost and schedule control on process plant projects.

Many oil sands projects executed during the oil boom are defined as 'mega projects' since they are categorized as large industrial construction projects. Cost overrun in mega industrial construction projects is a common problem. In cost management, labour costs are typically the largest variable in many industrial construction projects, and as such present the largest single area of project cost overrun (Allmon et al. 2000).

In compiling the unit rates in a tender the contractor's estimator usually utilize a set of 'norms' or standard productivity outputs, to assess the unit costs for labour (Davison 2008). These norms will most often be sets of data compiled by the contractor's staff from their own experience, or from data recorded on similar projects undertaken by the contractor or from the published books of norms or pricing information. The difference between productivity norm and a unit-rate is that there are no costs involved in productivity norm, only hours.

For industrial works, there are industry recognized books of norms such as the *Estimator's Piping Man Hour Manual* (Page and Nation 1999) and the *Cost Estimating Manual for Pipelines and Marine Structures* (Page 1999), both considered by many to be reflective of gulf coast labour productivity. Therefore, the estimator will need to measure and apply different location and other adjustment factors to the labour productivity norms. Adjustment factors are generally applied based on experience alongside rule of thumb guidelines in practice (Lu 2001). On the other hands, collecting data manually is time consuming and labour intensive. Hence, there is a definite need to introduce a new labour productivity norm standard for each specific industrial company.

Of the macro-items contributing to the overall cost of a plant project, those linked to piping activities often constitute a significant portion of the overall cost and have thus become the object of considerable interest (Song et al. 2006; Tommelein 1998). Piping is always the major and most complicated part of an industrial construction project and is usually located on the critical path of the project schedule (Wang and Abourizk 2009). The assembly process begins once the required components are fabricated by the spool fabrication shop and other supply links. These fabrication activities are part of the assembly process of a module, although they take place outside of the yard. Construction of industrial projects involves a considerable amount of pre-fabricated pipe spools. Therefore, on any process plant project the pipe fabrication shop is recognized as a key player and a partner in the success of that project (Hu 2013). Thus, pipe spool fabrication constitutes a large portion of the total cost of a constructed industrial facility. These types of projects involve tens or thousands of spools with unique properties such as material, configuration, type of joints, etc.

Unlike manufacturing, the spool fabrication process is labour intensive, less automated and interrupted by frequent change orders issued by clients in the midst of the fabrication. These characteristics make tracking the daily utilization of the workforce and thus labour cost and productivity difficult. Likewise, estimating pipe work and shop fabrication is a time-consuming and complicated process that involves extensive data manipulation (Al-Hussein et al. 2005). It requires a search and evaluation of a large number of tabulated configurations in the procedure manual which can lead to costly mistakes. Moreover, since these work items are difficult to standardize, estimation is particularly challenging. A methodology that is capable of producing reliable labour productivity norms and thus estimates for these activities can certainly be usefully transferred for application in other project stages.

1.5 Scope of research

The availability of actual piping labour cost and productivity data is not only important to accurate pricing and profitable billing but also provides a valid basis for cost estimating on similar projects and for shop production scheduling. Moreover, in a highly competitive marketplace, controlling labour costs is one important opportunity for construction businesses to maintain their competitive edge. However, tracking tasks and the associated actual labour costs can be a very complex, time-consuming and costly effort. The uniqueness of the construction sector poses several challenges for the direct adaptation of technologies that are used in many other industries, for example, those that support mass production. Therefore, there is a definite need for developing an efficient system that can collect and process data associated with pipe configurations, the type of work involved in their preparation, and the labour productivity norms required to perform this task. Thus, a framework that integrates the dynamic flow of fabrication process and labourers needs to be designed and applied to achieve effective results. Such a system must guarantee efficient and sufficient labour-hours information collection and sharing, requiring minimal overhead cost while not negatively interfering with shop floor activities which are always performed under time and budget constraints.

Since Information and communications technology (ICT) plays a crucial role in dealing with challenges in construction, “Internet of things (IoT)”, thus, can be regarded as a new generation of the ICT industry which is able to achieve comprehensive sensing and intelligent processing by combining a variety of smart “things” such as identification and tracking technologies, wired and wireless sensors, motion detectors and mobile phones etc. (Ding et al. 2013).

The Internet of Things is about collecting and managing this data from a rapidly growing network of devices and sensors, processing the data and then sharing it with other connected “things” (Atzori and Morabito 2010). The ultimate goal is to find uses for the data and analyze it to make better decisions. Therefore, IoT represents a huge opportunity for the construction industry, which is constantly processing data and strives for efficiency. However, IoT technology is less developed and employed for large scale construction projects due to the complexity and dynamic nature of construction environments and activities.

1.6 Research objectives

The primary objective of this research is to develop a real-time monitoring framework for piping fabrication shops based on IoT technology. To reach this goal, three supplementary objectives have been identified:

I. To develop a practicable location tracking solution that is sufficiently accurate and cost-effective and can be designed and deployed in the challenging environment of fabrication shop with ease and in real-time

II. To develop a shop floor level project management framework and software system , with the enabling location tracking technology, intended to integrate various construction engineering and management functions such as fabrication process planning and tracking with the drawings and document control system, the materials management system, the labour costing system and the production progress control system

III. To develop a new solution to provide high-level labour-hour data using the developed framework to form labour costing reports for a large collection of spools. The cost report data can then be spread over pieces and connections in particular spools to deliver practical labour productivity norms, providing the basis for future estimation or productivity benchmarking.

1.7 Research methodology

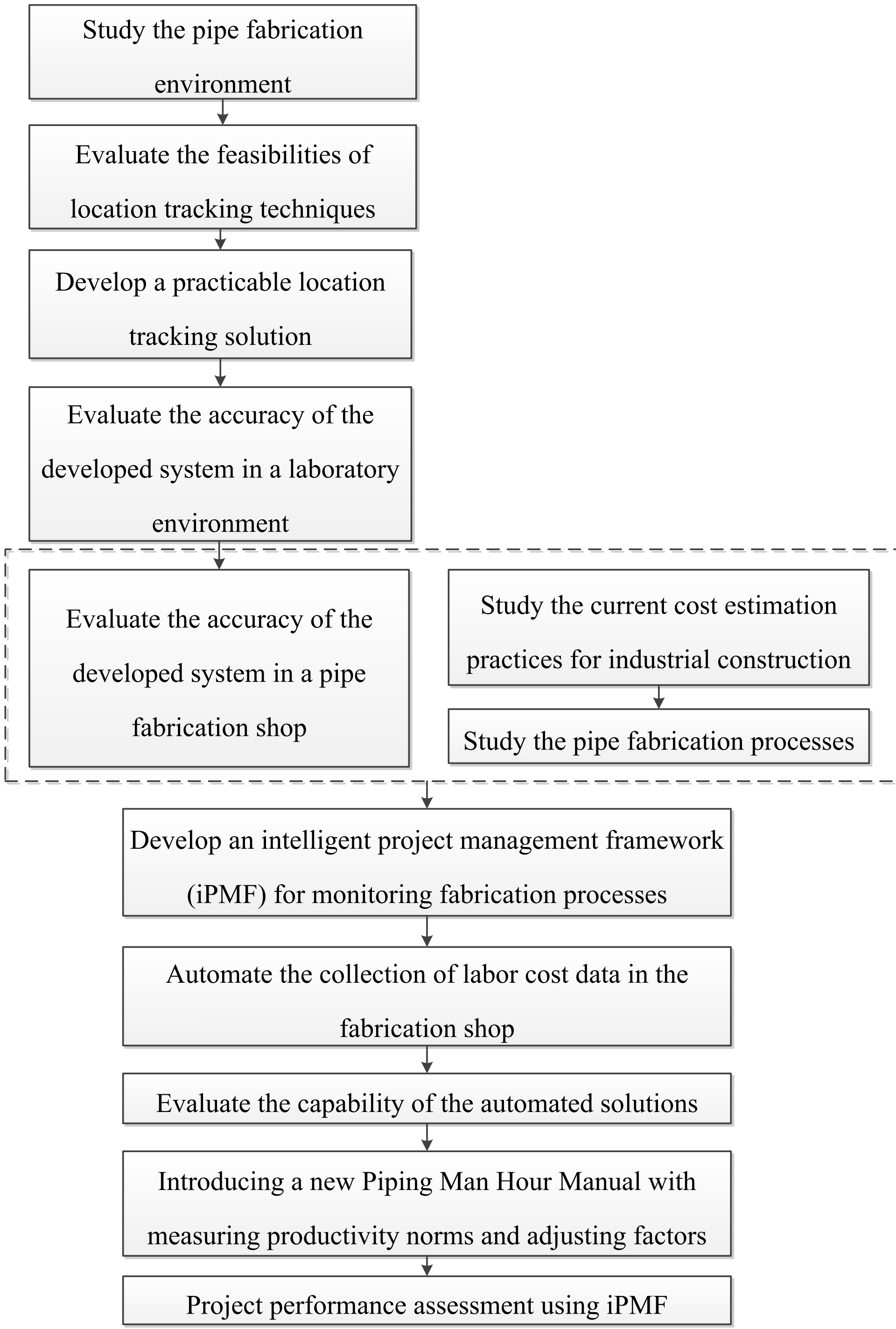

Figure 1-4 Research methodology

The research objectives are achieved through the methodology shown in Figure 1-4. In the first part of the research, the feasibility of applying Received Signal Strength (RSS) based methods in an indoor application setting is evaluated. The objective of this study is to identify the effective method for positioning and tracking resources with sufficient localization accuracy and reliability as needed in tracking pipe spools inside a fabrication shop. Tackling cost and automation will be our ensuing research based on establishing an effective indoor positioning method. First, we classify commonly applied RSS-based localization architectures for indoor positioning, which essentially represent the fundamental methods used to determine the location of mobile sensor nodes (referred to as "tags") by processing the RSS from multiple stationary sensor nodes (referred to as "pegs").

Next, illustrated with experiments in an indoor carpark, in an effort to achieve the sufficient localization accuracy and reliability, we contrast computing procedures for (i) the most-commonly applied RSS ranging method and the underlying geometric trilateration localization algorithm; and (ii) a recently developed RSS profiling method which is intended to overcome the limitations of RSS ranging method by not requiring the direct determination of inter-sensor distances. Based on experiments conducted in the carpark, it is confirmed that the positioning performance achievable by the RSS ranging method is far poorer than the RSS profiling method. With insight gained from the carpark experiments, a noise filter algorithm (Kalman filtering) is added to preprocess the RSS data prior to applying the RSS profiling method in an attempt to enhance the reliability of the positioning method when employed in a dynamic, noise-rich indoor setting in the real world. This has been validated based on further experiments conducted in a pipe spool fabrication shop. The methodology was found to potentially serve the needs of tracking components and labour-hours in connection with handling and connecting spool components within a typical work zone inside the fabrication shop. However, it was found that in a dynamic indoor application setting such as the spool fabrication, the RSS-based localization performance is susceptible to frequent reconfiguration of the work zone for handling different jobs. The positioning performances of this method would deteriorate accordingly, so there is a need to conduct re-profiling task frequently which is time-consuming and labour-intensive.

In our long search for a practicable localization method that eliminates the need of taking RSS measurements for decoding the location of a node, we encountered an innovative collision-based localization method that is more resistant to external interfering sources. This unique investigation allowed the introduction of a fundamentally new approach for indoor localization that overlaps the transmissions of signals and employs the zoning context to calculate the location of the construction resources and identify the fabrication work stations in which the tag is located inside the fabrication shop. While indoor localization is a very active research area in construction management, to the best of our knowledge, this research is the first attempt to investigate and evaluate a collision-based approach in construction industry.

The accuracy and reliability of the proposed localization methodology and its capability to monitor the fabrication work progress was confirmed with a dynamic error test in the fabrication shop for tracking and localizing pipe sections and fittings that frequently travel from one location to another. Since, it is also very important to develop a plan for the tagging, de-tagging and re-tagging events in conjunction with fabrication or construction process planning, the tagging plan for tracking the spool components is developed for the possible fabrication sequences, which can be presented to the fabrication shop workers along with the design drawings and cut sheets.

The second part of this research study explains the use of proposed indoor positioning system for real-time localizing and tracking pipe spool fabrication and to support the pipe spool production progress control. An integrated project management framework (iPMF) is developed that integrates fabrication process planning and tracking with the drawings and document control system and the materials management system and allows its users to obtain information about the labour cost and production process. Experiments were conducted at the same pipe fabrication shop to verify the feasibility of the pipe spool monitoring system and identify the real-time work progress and labour-hours for each task of fitting, handling and welding in fabrication of pipe spools. In order to value proposition of the developed framework, actual data on the labour-hours was collected manually to simulate the capability of the system and validate the hypothesis.

In the third part of this research study, first different common practices for estimating the cost of industry pipe work are studied and as a result the *Estimator's Piping Man Hour Manual* (Page 1999) was considered as the current best practice since it is a commercially available labour productivity norms standard and is used by majority of the industrial companies. In order to provide a valid basis for future project cost estimation, labour productivity norms were calculated for each cost element based on the actual fabrication cost data. In addition, adjustment factors for labour productivity norm were measured since the *Estimator's Piping Man Hour Manual* is considered by many to be representative of "Gulf Coast" labour productivity only.

Ultimately, the developed project performance assessment component of iPMF is illustrated which employs earned value management (EVM) to calculate the productivity factor and provide an effective progress measurement. The results from this study will help owners and contractors to understand the variability in process piping estimates and the importance of calibrating existing methods before applying them on real-world projects. This information also can be useful in analyzing the risk associated with the project's capital costs and resolving estimating issues.

1.8 Organization of the Thesis

This document is organized into six chapters and this section provides an overview of the thesis content. Chapter 1 consists of the introduction to the background, the objective and the scope of the research study.

An overview of indoor positioning technologies and methodologies is provided in first part of Chapter 2. A review of the indoor positioning applications in construction and classification of localization methodologies are also presented in this chapter. In the second part of Chapter 2, the RSS ranging method plus trilateration-based localization algorithms and a RSS profiling method are contrasted and illustrated with calculation examples. The feasibilities of applying both methods in a building site environment and the piping spool fabrication shop are specifically evaluated and compared in this chapter.

Chapter 3 reports on the development of the integrated Project Management Framework (iPMF) and explains the use of radio frequency-based indoor positioning system for real-time localizing and tracking pipe spool fabrication and to support the pipe spool production progress control. The system integration and structure which is based on a multi-tiered architecture is elaborated in this chapter. The detail of the localization methods and the relevant data collection implemented in iPMF is further described in the remainder of Chapter 3.

Chapter 4 presents the system validation and provides details of a series of experiments that are conducted in the fabrication shop of the partner company. The chapter is started with a brief introduction and review of the concept of the industrial pipe spool fabrication and operation and highlights the typical processes that are generally employed. It is then followed by a detailed discussion of a dynamic error test which was conducted in the fabrication shop for tracking and localizing pipe and fittings to evaluate the accuracy and reliability of the proposed localization methodology. The results of the experiments are then analyzed and discussed. After validation of the positioning system, the proposed tagging strategy is presented. The applicability of the iPMF framework to the industrial labour data collection is investigated through a number of experiments conducted in the same fabrication shop. In the end, the experiment measurements are analyzed using the actual data which were collected manually to simulate the capability of iPMF.

Chapter 5 includes the results and discussion of a case study, the fabrication of eight pipe spools that form the experiment work-package, which was carried out to demonstrate the feasibility of the implemented iPMF in providing the actual labour productivity norms for the partner company. An overview of common practices for estimating the cost of industrial piping work is presented in the first part of this chapter. Subsequently, a parametric study is conducted to calculate the labour productivity norms and related adjusting factors.

Chapter 6 summarizes the conclusions drawn from the experimental and numerical studies in the thesis research. Based on the findings in this research program, a series of recommendations for future work are given.

CHAPTER 2[1]

2 Applying received signal strength based methods for indoor positioning and tracking in construction applications

2.1 Introduction

In the past decade, the construction industry has been improving project performance and overall productivity by embracing innovative technologies that improve transparency and communication while significantly saving time and cost. Positioning and tracking critical resources including materials, equipment, and labourers with sufficient accuracy and reliability is crucial to measuring, controlling, and further enhancing productivity performances on projects with ever-growing size and complexity. Determining the locations of construction resources on a real-time basis presents distinct challenges to technological innovations in consideration of the size, complexity, and dynamic nature of different projects (Jang and Skibniewski 2007).

State-of-the-art sensors and automated data acquisition technologies hold promises to improve construction productivity and safety management (Song et al. 2006a, 2006b, 2007; Akinci and Anumba 2008; Grau and Caldas 2009; Grau et al. 2009). Automated positioning and tracking systems provide construction managers with timely and accurate access to updated status information of crews and materials.

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Increasing interest in location awareness systems and services (Kim et al. 2011; Cho et al. 2010) in the construction industry have led to widespread applications of radio frequency (RF) technologies, including the global positioning system (GPS), and the radio frequency identification (RFID).

Previous studies and industrial applications of the RF technologies for positioning and tracking in construction have been mostly limited to open outdoor areas. Nonetheless, crucial functions of construction project management (such as safety inspection, progress monitoring, and job costing) also require access to location-based resource information in indoor or partially covered environments (e.g., industrial fabrication shops, building jobsites, and underground tunnels). Applications of the traditional RF technologies and positioning methods have been impeded by a set of hurdles, including severe multipath effect of signal propagation, lack of line-of-sight, and environmental interference (Zhang et al. 2010). For instance, the communication distance between RFID tags and readers decreased significantly when metal structures, concrete, and water were in their vicinity (Ergen et al. 2007); the performance of a GPS-based localization system was substantially compromised on the dynamic construction jobsite due to the blockage of satellite signals and multipath effects (Lu et al. 2007). Lu et al. (2007) concluded that multipath error is associated with the deflection and distortion of satellite signals in the presence of both permanent structures and temporary facilities on a building site.

Indoor localization research has been rapidly gaining momentum in construction engineering and management (Khoury and Kamat 2009). Luo et al. (2010) investigated the possibility of developing cost-effective positioning solutions by analyzing the received signal strength (RSS) data from RF communications. RSS-based positioning methods can be designed and deployed in the field with ease and low cost (Haque et al. 2009). On the downside, such methods can hardly achieve sufficient localization accuracy and reliability as needed by particular construction applications (Shen and Lu 2012). For example, tracking the location of workers inside a tunnel site can prevent fatal accidents. In this case, high latency and unreliable localization in connection with RSS-based methods would compromise values and benefits from applying the RF-related technologies.

Despite the advances in new technology and applied research, current practices of tracking resources in partially enclosed or indoor environments in construction applications still largely rely on manual approaches, which are generally error-prone and time-consuming in data processing and analysis. Inefficiency and untimeliness resulting from current practice in recording, reporting, and transferring productivity data do not make much difference to productivity improvement but only add to overhead costs while degrading project delivery performances. Development of cost effective methods for positioning and tracking based on received signal strengths of radio frequencies is desired to harness the full potential of applying new technologies in construction.

The objective of this study is to confirm the feasibility of applying RSS-based methods in an indoor application setting: whether the positioning accuracy of 1-2 m with high reliability (95% of the time) is achievable or not. This is generally accepted as the sufficient positioning performance for material and labour tracking and field productivity determination in construction (Sacks et al 2005; Lu et al 2007). In the remainder of this paper, first, we classify commonly applied RSS-based localization architectures for indoor positioning, which essentially represent the fundamental methods used to determine the location of mobile sensor nodes (referred to as "tags") by processing of the RSS received from multiple stationary sensor nodes (referred to as "pegs"). Tags and pegs are interconnected wirelessly and communicate RSS data via certain radio frequencies, essentially forming a wireless sensor network (WSN). This provides advantages for construction applications under relatively dynamic and harsh environments, such as easy deployment and flexible expandability, low cost, and operational reliability (Shen et al. 2008). Next, illustrated with experiments in an indoor carpark, we contrast computing procedures for (i) the most-commonly applied RSS ranging method and the underlying geometric trilateration localization algorithm; and (ii) a recently developed RSS profiling method which is intended to overcome the limitations of RSS ranging method by not entailing direct determination of inter-sensor distances. Based on experiments conducted in the carpark, it is confirmed that the positioning performance achievable by the RSS ranging method is far poorer than the RSS profiling method. With 95% likelihood, the positioning error from RSS profiling method is less than 2.14 m.

With insight gained from the carpark experiments, a noise filter algorithm (Kalman filtering) is added to preprocess the RSS data prior to applying the RSS profiling method in an attempt to enhance the reliability of the positioning method when employed in a dynamic, noise-rich indoor setting in the real world. This has been validated based on further experiments conducted in a pipe spool fabrication shop: consistent positioning accuracy of 1-2 m away from the actual position of a tracked tag could be obtained, with 95% probability. Last, we discuss the importance of (i) updating the RSS profiling data in a dynamic setting to maintain the accuracy and (ii) streamlining profiling point grid and peg sensor deployment to ensure simplicity and cost-effectiveness of implementing the proposed RSS profiling method for indoor positioning and tracking in construction applications. This indeed sheds light on opportunities of follow up research with regards to automation and optimization of the proposed RSS profiling method.

2.2 Overview of indoor positioning technologies and methodologies

2.2.1 Indoor positioning applications in construction

Ekahau is a proprietary technology relying on a wireless local area network (WLAN) infrastructure such as WiFi, achieving a positioning accuracy of 2 m in the laboratory testing environment (Khoury and Kamat 2009). The ultra-wide band (UWB) technology boasts high immunity to interference and multipath, thus leading to higher accuracy in localizing objects. Teizer et al. (2008) presented algorithms and experiments utilizing UWB technology for positioning and tracking construction resources. As part of robot performance evaluation, Khoury and Kamat (2009) performed indoor experiments using a UWB-based positioning system, which could obtain an accuracy of 10 to 50 cm in the labouratory environment. On the downside, the UWB technology is still expensive while requiring line of sight in communication and a dense network of fixed receivers, making it difficult to deploy in a crowded and dynamic construction environment (Torrent and Caldas 2009).

Positioning and tracking methodologies were also implemented by combining radio frequency signals received from wireless sensor modules (ZigBee) and ultrasound, aimed to deliver acceptable measurement accuracy for construction applications (Jang and Skibniewski 2009; Skibniewski and Jang 2009; Shin and Jang 2009). However, ultrasound positioning has inherent disadvantages including line-of-sight requirement, multipath, high cost and power consumption; these factors prevent the proposed methodology from being applied in complicated construction environments (Purushothaman and Abraham 2007; Wu et al. 2010). Hybrid methodologies by integrating RFID and Zigbee-based sensor networks were also applied for material tracking and supply chain management (Cho et al. 2010; Cho et al. 2011). RFID tags were used to identify various kinds of materials, while the Zigbee communication technology was used to wirelessly transfer the identified information. These studies have confirmed that wireless sensor networks (ZigBee being the most popular commercial solution) provide the effective infrastructure that enables inexpensive wireless communication networks while rendering straightforward networking capability in construction applications.

Li et al. (2012) and Motamedi et al. (2013) used k-Nearest Neighbor (kNN) based localization algorithms for localization of RFID-equipped assets during the operation phase of facilities and HVAC. This method utilizes a selected set of the closest neighboring points to the tracked tag (whose locations are known) to estimate the location of the target tag. This method has better adaptability in dynamic environments like construction sites compared to other positioning method. LANDMARK (Ni et al. 2004) has been one of the popular localization techniques using K-Nearest Neighbor (KNN). Soltani et al. (2015) investigated the use of RFID technology for tracking construction assets by extending cluster-based movable tag localization (CTMl) technique which uses a kNN algorithm. However, the varying accuracy of the RFID localization systems had been reported by researchers from 5 to 9 m in real environments of construction sites depending on the density of tag deployment (Pradhan et al. 2009) which does not meet the positioning requirements for construction applications.

2.2.2 Classification of localization methodologies

In general, RF-based localization algorithms can be classified into three categories: (i) ranging-based, (ii) ranging-free, and (iii) profiling-based. Regardless of the algorithm applied, the localization process can be divided into two phases: signal measurement and position calculation. In the first phase, RF signals are transmitted between two communication devices. During this process, the properties of these signals are captured, such as arrival time, signal strength, or travel direction. In the second phase, the position of the target is determined based on processing signal parameters obtained in the first phase.

The most commonly used indoor positioning technique is based on ranging, whereby distance or angle approximations are obtained (Zhang et al. 2010). With ranging measurements, complementary geometric approaches, such as the classic trilateration method, can be employed to calculate the position of the target. In the first phase of localization, various measurement methods are utilized to estimate the Euclidean distance between different sensor nodes, e.g., angle of arrival (AOA), time of arrival (TOA), time difference of arrival (TDOA), and received signal strength (RSS) (Almuzaini and Gulliver 2010). However, AOA, TOA, and TDOA methods largely depend on line-of-sight communication and require expensive and custom built infrastructure (Almuzaini and Gulliver 2010). In previous studies, the majority of positioning systems relied on the RSS-based technique, due to simplicity and low cost of the required hardware (Lymberopoulos et al. 2006; Haque et al. 2009). It is noteworthy that the correlation of RSS data with distance measurements can be weak, which is more commonly encountered in an indoor application setting than in an open area.

Ranging-free localization methods provide a simplified version of the ranging-based approach in the context of large-scale sensor networks (He et al. 2003). The ranging-free algorithms rely on proximity sensing or connectivity information to estimate node locations. The basic principle assumes a sensor falling in the transmission range of another sensor, which defines a proximity constraint between the two sensors. This constraint can be utilized for localization (Mao et al. 2007). With the deployment of a large scale, relatively dense sensor network in the setting, the localization problem can be easily solved by the ranging-free approach, resulting in a location estimate.

The RSS profiling-based localization technique directly correlates locations with the RSS data (Haque et al. 2009), so as to mitigate the effect of a changing environment on the reliability of estimated ranges. The RSS profiling method first develops a map of the radio signal strength behavior in the localization area. The map is constructed either offline by pre-collected measurements or online using sniffing devices (Krishnan et al. 2004), which are tag sensor nodes placed at profiling points with known locations. The map stands for an "ad hoc" spatial distribution model of RSS in the local area being investigated. The RSS mapping model is stored in a database residing on a central server. By referencing the RSS mapping model, the location of a mobile node (tag) can be estimated by comparing RSS measurements acquired by the mobile node against measurements taken at the profiled points with known coordinates.

Although the RSS-based localization methods have been widely tested in indoor environments, to the best of our knowledge, characterizing radio propagation behavior and applying RSS mapping model in construction application settings have yet to be reported. In the next two sections, the RSS ranging method plus trilateration-based localization algorithms and a RSS profiling method recently proposed in the computer science area are contrasted and illustrated with calculation examples. The feasibilities of applying both methods in a building site environment are specifically evaluated and compared. Further, the piping spool fabrication shop serves as a real-world indoor application setting in construction. The objective of this study is to identify the effective method for positioning and tracking resources with sufficient localization accuracy and reliability as needed in tracking pipe spools inside a fabrication shop. Tackling cost and automation will be our ensuing research based on establishing an effective indoor positioning method.

2.3 RSS ranging and trilateration localization method

Radio frequency transmission is attenuated with the distance between emitter and receiver, which can be quantified by the RSS values provided by a wireless device. This attenuation (Shen et al. 2008), also known as path loss, can be modeled to estimate the distance between the emitter and the receiver.

The indoor propagation model, commonly referred to as the ITU model (ITU is short for International Telecommunication Union, which is the United Nations specialized agency for information and communication technologies), estimates the path loss in complicated and "hostile" indoor environments and is given in the following equation (Seybold 2005; Shen and Lu 2012)

(1) $$L = 20log_{10}(f) + Nlog_{10}(d) + Lf(n) - 147.56$$

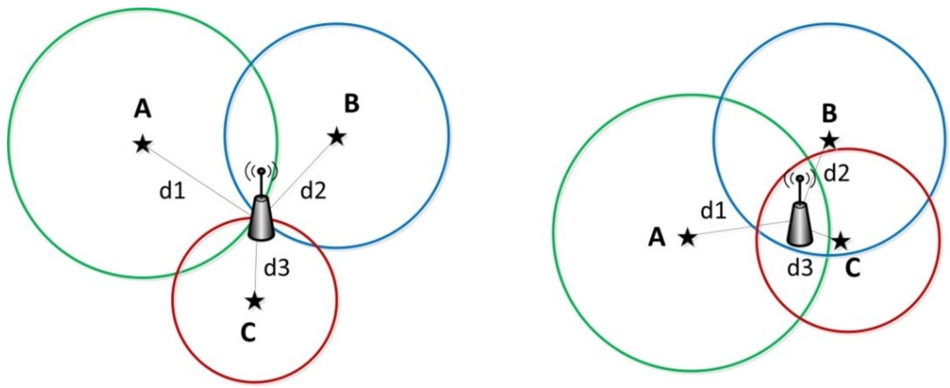
where f is the frequency of radio signal, d is the distance to be determined between the two devices, N is the distance power loss coefficient, and Lf(n) denotes the floor penetration loss factor which can be omitted when the line-of-sight transmission is available. It is noteworthy that N is unknown for a construction environment, and can only be determined based on the real data collected at a specific jobsite. Then, the received signal strength index (RSSI) at distance d can be calculated as

(2) $$RSSI = \mathrm{RSSI}_0 - L$$

where RSSI_0 is the RSS value measured at a reference distance d_0. Generally, d_0 is fixed as a constant of 1 m. Therefore, the distance is calculated as

(3) $$d = 10^{\left(\frac{RSSI_0 - RSSI - 20log_{10}(f) + 147.56}{N}\right)}$$

Based on distances measured in the first phase and known coordinates of multiple pegs, the second phase focuses on position calculation. The multilateration (Holger and Andreas 2005) algorithm is commonly applied. Multilateration fixes the position of the device of interest using the estimated distances from several non-collocated, non-collinear transmitters (Stüber and Caffrey 1999). It is called trilateration when three transmitters are utilized, as shown in Figure 2-1. The distance is used to draw a circle around each transmitter in the area (Figure 2-1). The mobile node is therefore located at the intersection point of the three circles. Under ideal situations (i.e., there is no fading and no shadowing), this method gives rise to an exact, unique solution, i.e., the single point at the intersection of the three circles shown in Figure 2-1a. In reality, the three circles may not intersect at a single point, nor overlap at all due to errors resulting from RSS ranging correlation modeling. Therefore, as shown in Figure 2-1b, an optimal localization result is generally determined by means of the mathematical technique of least square estimation (LSE) (Stüber and Caffrey 1999).



(a) (b)

Figure 2-1 Trilateration-based positioning into (a) one unique point (b) a possible zone

Suppose the coordinates of the three reference nodes are $A(x_1, y_1), B(x_2, y_2)$, and $C(x_3, y_3)$, and the corresponding distances from the target node to each reference node are d_1, d_2 , and d_3; we can obtain the following equations

$$(4) \quad \begin{cases} (x_1 - x)^2 + (y_1 - y)^2 = {d_1}^2 \\ (x_2 - x)^2 + (y_2 - y)^2 = {d_2}^2 \\ (x_3 - x)^2 + (y_3 - y)^2 = {d_3}^2 \end{cases}$$

where (x, y) denotes the unknown coordinates of the target. The coordinates of the target node can be determined by LSE method as shown as per the following equations (Srbinovska et al. 2008)

$$\begin{bmatrix} x \\ y \end{bmatrix} = (A^T A)^{-1} A^T b \tag{5}$$

where

$$A = 2 \cdot \begin{bmatrix} x_3 - x_1 & y_3 - y_1 \\ x_3 - x_2 & y_3 - y_2 \end{bmatrix} \tag{6}$$

and

$$b = \begin{bmatrix} \left({d_1}^2 - {d_3}^2\right) - ({x_1}^2 - {x_3}^2) - ({y_1}^2 - {y_3}^2) \\ \left({d_2}^2 - {d_3}^2\right) - ({x_2}^2 - {x_3}^2) - ({y_2}^2 - {y_3}^2) \end{bmatrix} \tag{7}$$

Application of the RSS ranging method combined with the trilateration localization method is demonstrated with a lab testing example. Figure 2-2 shows the test layout of 12 m × 9 m in which the solid squares on the corners represent pegs, and the circle in the middle denotes a tag placed at the location (3, 1) m. We assume that the location of the tag is unknown and needs to be determined. According to eq. (1), the calibrated empirical ITU model for the testing can be rewritten as in eq. (8).

$$\mathrm{L} = 20 \log_{10}(\mathrm{f}) + \mathrm{N} \log_{10}(\mathrm{d}) - 147.56 = 30 \log_{10}(\mathrm{d}) + 31.67 \tag{8}$$

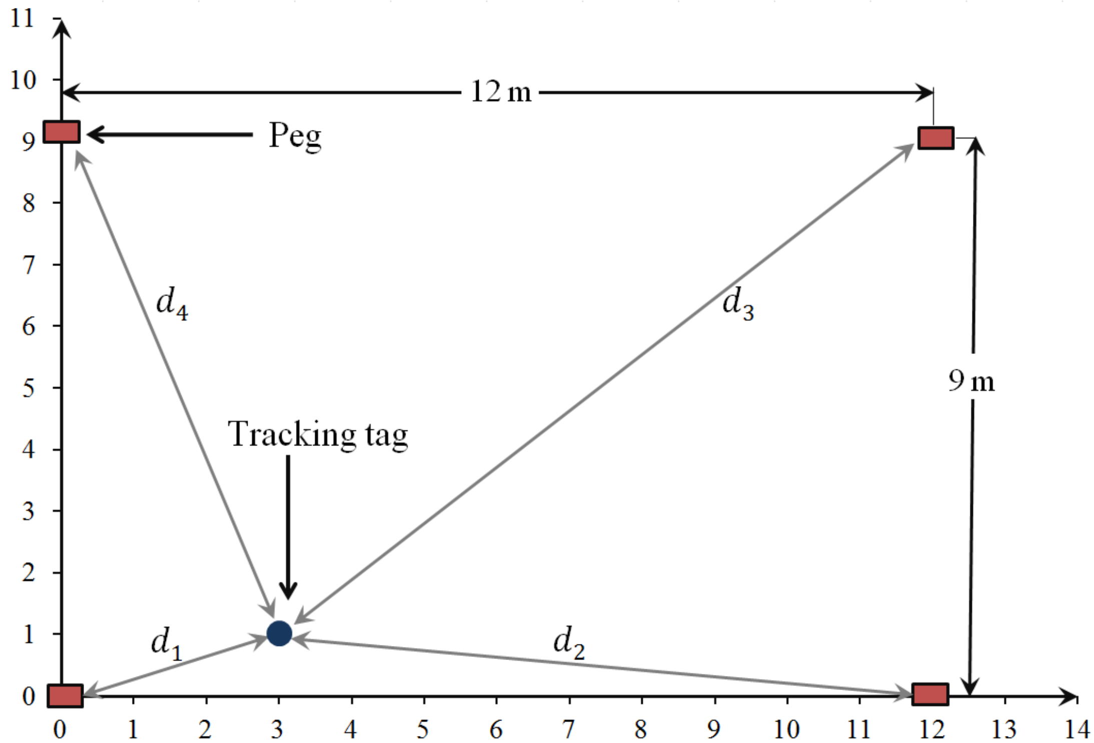


Figure 2-2 Experiment layout and nodes' distributions for RSS ranging method

where, for this specific case, we assume $f = 915 \times 10^6$ Hz, and $N = 30$. Given $RSSI_0 = -50$ dBm, the received signal strength at distance d is expressed as:

$$(9) \qquad RSSI = RSSI_0 - L = -30\log_{10}(d) - 81.67$$

Note dBm is the unit of measure for RSSI, which stands for the power ratio in decibels (dB) of the measured power referenced to one milliwatt (mW). Therefore the distance is calculated as:

$$(10) \qquad d = 10^{-(\frac{RSSI + 81.67}{30})}$$

Table 2-1 shows the coordinates of the pegs, the true distances between the tag's location and the locations of four pegs, the tag's RSSI in relation to each peg, the estimated distance from the tag to each peg using Eq. 10, and the resulting ranging errors.

Table 2-1 Ranging measurements in the lab testing

Ranging measurements	Pegs			
	P_1	P_2	P_3	P_4
Pegs' Coordinate (x,y) (m)	(0,0)	(12,0)	(12,9)	(0,9)
True distance of the tag from pegs (m)	3.16	9.06	12.04	8.54
Tag's RSSI (dBm)	-73.23	-88.14	-107.75	-99.50
Estimated distance d (m)	0.52	1.64	7.40	3.93
Distance error (m)	2.64	7.41	4.64	4.61

According to Eq. 4, the geometric model for the testing can be rewritten as in Eq. 11.

(11) $$\begin{cases} (0-x)^2+(0-y)^2=0.52^2 \\ (12-x)^2+(0-y)^2=1.64^2 \\ (12-x)^2+(9-y)^2=7.40^2 \\ (0-x)^2+(9-y)^2=3.93^2 \end{cases}$$

where:

(12) $$A=2.\begin{bmatrix} 0 & 9 \\ -12 & 9 \\ -12 & 0 \end{bmatrix}$$

(13) $$b=\begin{bmatrix} 65.83 \\ -75.76 \\ -104.68 \end{bmatrix}$$

The estimated coordinate of the target node can be determined:

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 4.87 \\ 2.97 \end{bmatrix}$$

Comparing the estimated coordinates of the tag to the true coordinates of the tag (3, 1) m, the localization error is 2.72 m, which denotes the Euclidean distance between the estimated and true coordinates.

2.4 RSS profiling-based positioning technique

A positioning technique combining a range-free method and the RSS profiling method was proposed by Haque et al. (2009). The localization process consists of two phases: RSS profiling and position computing. A tracked tag periodically emits radio frequency packets. In the profiling stage, the tag is located at predetermined known locations called profiling points. All the pegs can "hear" the radio frequency packets transmitted by the tag and then forward a report to the central server, consisting of its peg ID, the tag ID, and RSS measured. The server maintains a database of RSS readings in the format of $< C;\Omega >$, where C represents the known coordinates of the sampled point, Ω stands for the set of RSS values corresponding to all of the pegs at this sampled point.

In the localization stage, the location of the tracked tag is estimated based on the information of profiling points. The server compares the tag's RSS measured by all the pegs against the RSS registered at each profiling point. Assume Ψ is the set of RSS values obtained from the tracked tag, the distance between the tracking point and a specific profiling point is determined by Eq. 14.

(14) $$D(\Omega, \Psi) = \sqrt{\sum_{i=1}^{n} \left(\Omega(i) - \Psi(i)\right)^2}$$

where n is the total number of pegs in the network. The next step is to select an arbitrary number, *k*, of profiling samples having small distance values away from the tracked tag, which represents a best matched set of profiling points. Subsequently, the coordinates of the selected samples are averaged to produce the estimated coordinates of the tag. The averaging formula biases the selected samples in such a way that the one with a smaller distance is weighed with a proportionally larger weight. Suppose $D_{\max}$ is the maximum distance among the best k selected samples and $S_d = \sum_{i=1}^{K} D_i$ is the sum of all those distances, then the tag coordinates are estimated as:

(15) $$x_{est} = \frac{\sum_{i=1}^{k} x_i \times (D_{\max} - D_i)}{K \times D_{\max} - S_d}$$

(16) $$y_{est} = \frac{\sum_{i=1}^{k} y_i \times (D_{\max} - D_i)}{K \times D_{\max} - S_d}$$

where (x_i, y_i) are the coordinates of the profiling point i.

In contrast with RSS ranging-based methods, the proposed profiling-based method compares the RSS differences between the tracking point against the profiling points, rather than using the Euclidean distance between a tag and a peg, . It is also worth mentioning that the current profiling system design is most suitable to problems concerning positioning on a 2-D domain. However, it can be readily extended into 3-D applications by deploying the pegs and profiling points throughout the physical space, while all the pegs and profiling points are located not necessarily on a single plane. For instance, once pegs have been established and reference points profiled at different floors, the system could determine the exact floor in which the tracked tag is located. As such, a particular area on a specific floor can be identified with a unique set of measured signal strengths of relevant pegs.

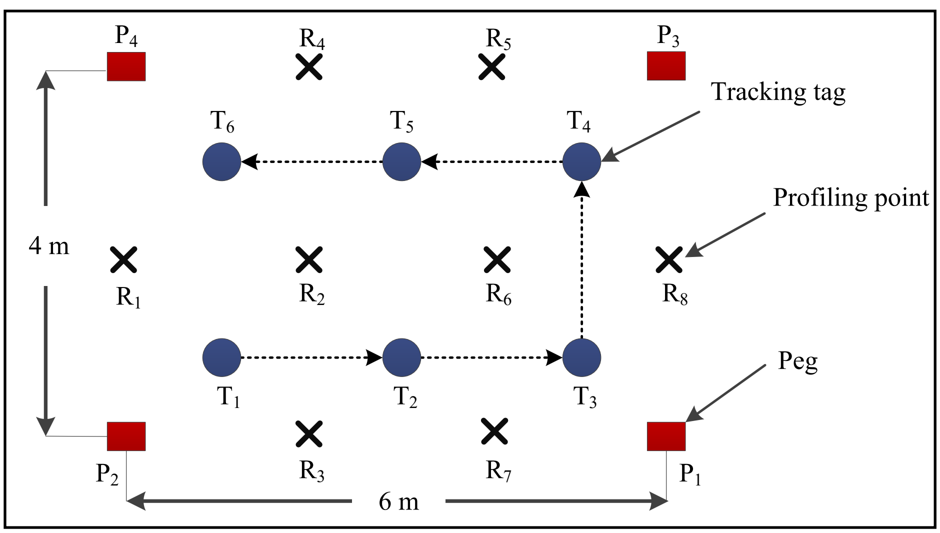


Figure 2-3 Experiment layout and nodes' distributions for RSS profiling method

The RSS profiling based positioning method is further illustrated with a lab testing example. Figure 2-3 shows a sensor node distribution layout in the demonstration test. The testing area was 6 m × 4 m, in which all the markers represent the locations of sensor nodes. The four solid squares (on the corners) are the pegs with known coordinates, while the six solid circles stand for the locations of a tag which are determined by the proposed positioning method. RSS samples were taken at the eight predefined profiling locations each being marked as a cross (“×”).

Table 2-2 RSS perceived by pegs collected from profiling points in the lab testing

Profiling Point ID	Profiling Point Coordinate		Peg ID / RSS (dBm)			
	X(m)	Y(m)	P_1	P_2	P_3	P_4
R_1	0	2	-77.09	-64.83	-80.82	-66.48
R_2	2	2	-84.41	-70.50	□76.04	-73.20
R_3	2	0	-77.38	-67.56	-93.44	-77.69
R_4	2	4	-89.74	-74.67	-78.56	-70.45
R_5	4	4	-73.43	-82.92	-68.70	-85.14
R_6	4	2	-77.29	-84.40	-70.82	-79.71
R_7	4	0	-69.18	-74.24	-76.84	-89.92
R_8	6	2	-67.61	-78.71	-68.05	-83.02

Table 2-2 shows the profiling data stored in the RSS database, indicating RSS values measured at the eight profiling points in relation to the four pegs during the profiling stage. The local coordinates of the profiling points were also registered. In the localization stage, the RSS data of the tracking target in relation to each peg were collected. Table 2-3 shows the RSS testing results for six tag locations.

Table 2-3 RSS of different tag locations by pegs in the lab testing

Tag ID	Peg ID / RSS (dBm)			
	P_1	P_2	P_3	P_4
T_1	-78.37	-64.15	-90.09	-72.48
T_2	-80.01	-76.05	-78.05	-83.36
T_3	-63.66	-75.52	-71.88	-89.□8
T_4	-68.18	-83.83	-59.12	-86.64
T_5	-83.81	-79.27	-75.76	-76.70
T_6	-83.44	-69.88	-79.31	-62.39

The tag locations were then calculated for a given number of *k*. First, the RSS-based distance between a tag and each profiling point are calculated in order to find the closest profiling point to the tag. For instance, the RSS-based distance between Tag T_1 and the profiling point R_1 at (0, 2) m is calculated as follows:

$$\sqrt{\left((-78.73-(-77.09))^2+((-64.15-(-64.83))^2+((-90.09-(-80.82))^2+((-72.48-(-66.48))^2\right)}=9.06$$

In the same way, the RSS-based distances between all of the tag locations and the profiling points are calculated as given in Table 2-4.

Table 2-4 Distances between Profiling Points' RSSI and Tags' RSSI

Profiling Point ID	Tag location ID RSS distances					
	T_1	T_2	T_3	T_4	T_5	T_6
R_1	9.06	11.19	18.75	29.85	16.40	8.49
R_2	16.58	6.63	21.37	26.7	8.59	4.78
R_3	5.39	17.61	26.54	38.97	22.18	16.03
R_4	19.26	9.16	26.58	30.18	7.61	8.45
R_5	29.10	13.41	12.50	10.90	13.39	20.14
R_6	28.10	11.21	16.00	14.61	9.81	18.38
R_7	19.47	11.34	7.56	20.26	15.93	15.99
R_8	28.70	16.15	5.84	10.14	18.13	21.82

The determination of k is by trial and error such that the selected best value would produce the smallest average localization error. Previous research has found that the proper value of k ranges from 5 to 7 (Soleimanifar et al. 2011). In the current research, k is selected as 5, meaning the best five profiled samples with shorter RSS-based distances to the tracked tag are relevant to fix the tag's position. Subsequently, the coordinates of the selected five samples are averaged to derive the estimated coordinates of the tag according to Eqs. 15 and 16. Here, $D_{\max} = 19.47$

is the maximum distance among the best selected samples and $S_d = 69.76$ is the sum of all those distances.

Table 2-5 shows the testing results, including the actual location, the estimated location, and the localization error for the six tag locations.

Table 2-5 Estimated local position of the tags for K=5

Tag ID	Tag Location (m)		Error (m)
	Actual (x,y)	Estimated (x,y)	
T_1	(1,1)	(1.25,1.00)	0.25
T_2	(3,1)	(3.39,1.99)	1.07
T_3	(5,1)	(4.68,1.60)	0.□8
T_4	(5,3)	(4.65,2.37)	0.72
T_5	(3,3)	(2.81,2.71)	0.34
T_6	(1,3)	(1.15,2.57)	0.45

2.5 Field Testing and Evaluation

To evaluate the performances of both localization methods in an indoor environment, a field test using WSN was conducted in an underground parking lot on the University of Alberta campus. The basement and the first floor of the multi-level carpark were specifically chosen to mimic a completely enclosed or partially covered construction site (Figure 2-4). The absence of interior finish features in the underground parking lot makes the setting resemble a reinforced concrete structure being built. The building has steel access doors, metallic cages, concrete columns and power cables located near the test area. In addition to the metallic obstacles, the pedestrian and vehicle traffic in this area was analogous to a practical building site. The experiment was designed to trace the travel path of a labourer tagged with a sensor node in a building construction site. The dynamic positioning error was determined by evaluating the difference between the actual travel path and the estimated travel path in the building.

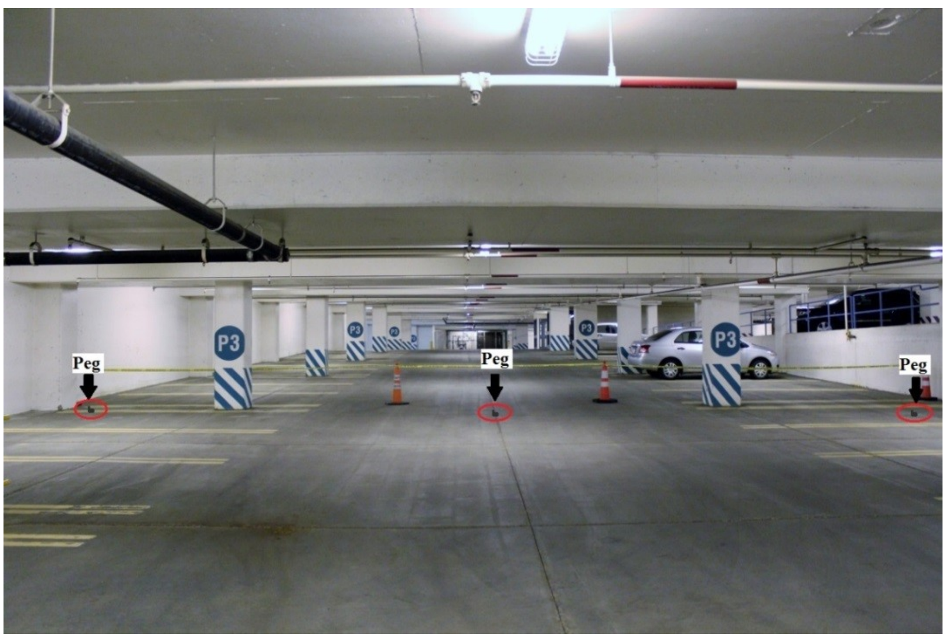


Figure 2-4 Testing set up at the carpark

The experiments were conducted by deploying a number of sensor nodes within the 12 m × 9 m monitored area. Fixed sensor nodes were distributed on the borders and a tracking node inside the test area. The WSN nodes used in the test incorporate the Texas Instruments (TI) CC1100 RF module and operate in the 915

MHz RF band. As mentioned earlier, the WSN nodes can be classified into pegs and tags, where the fixed pegs capture the RSS of RF communication from the mobile tags.

2.5.1 Evaluation of the ranging-based localization method

Error! Reference source not found. shows the distribution of nodes for the RSS anging experiment. Ten pegs were fixed at known locations (marked as solid squares). A tracking node (marked as solid circle) moved along a square-shaped path (8 m × 6 m).

The first phase was to measure the signal parameters in the monitored area. Line-of-sight wireless communication was available between the pegs and the tag. The RSS data collection consisted of 700 readings from 30 locations in order to develop the ITU propagation-loss model and to populate the profile-point database.

Figure 2.6 shows the relationship between the RSSI values and distances from the tag node to a peg node. It is evident from Figure 2-6 that RSSI broadly fluctuates at a certain distance range. For instance, given the signal strength at -88 dBm (see Fig. 6), the corresponding distance varies from 4 m to 16 m. The following points in connection with the data analysis are noteworthy: (1) the ranging error resulting from this step is propagated to the final positioning error; (2) In order to fairly evaluate the two RSS-based positioning methods, no "outlier" data was removed (such as extremely low RSSI values); (3) Environmental changes can also affect the signals, such as temperature, humidity, so can the presence of people or vehicles in the testing area. According to Eq. 1, the calibrated empirical ITU model for the testing can be rewritten as in Eq. 17.

$$L = 20log_{10}(f) + 33.46log_{10}(d) - 147.56 = 33.46log_{10}(d) + 31.67 \quad (17)$$

The received signal strength at distance d is calculated as:

$$RSSI = RSSI_0 - L = -33.46log_{10}(d) - 86.17 \quad (18)$$

where the measured $RSSI_0$ is -54.5 dBm. Therefore, the ranging distance will be as follows:

$$d = 10^{-\left(\frac{RSSI+86.17}{33.46}\right)} \quad (19)$$

Table 2-6 shows the average and standard deviation of distance measurement errors between a tag and the ten pegs. These results indicate that the distance measurement technique is inherently inaccurate and resulting range measurements are prone to errors caused by environmental noise. Large standard deviations are indicative of highly fluctuating signal strengths.

Table 2-6 Average error and standard deviation of distance measurement from pegs

Distance error (m)	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Average	1.24	1.50	1.79	4.31	2.73	2.25	3.74	3.72	3.74	2.65
Standard Deviation(m)	0.95	1.58	1.39	3.52	1.71	2.97	1.99	4.08	2.37	2.11

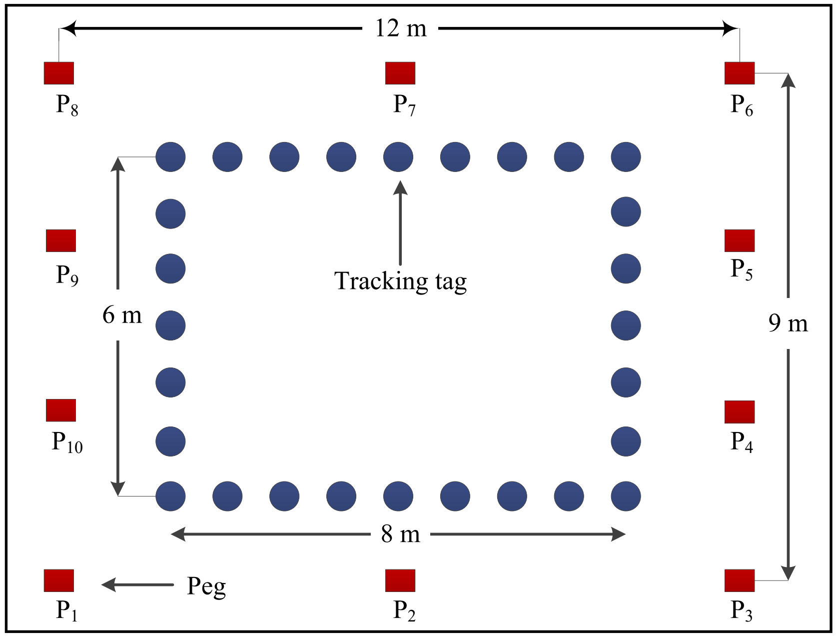


Figure 2-5 Experiment layout in the parking lot for RSS-ranging localization method

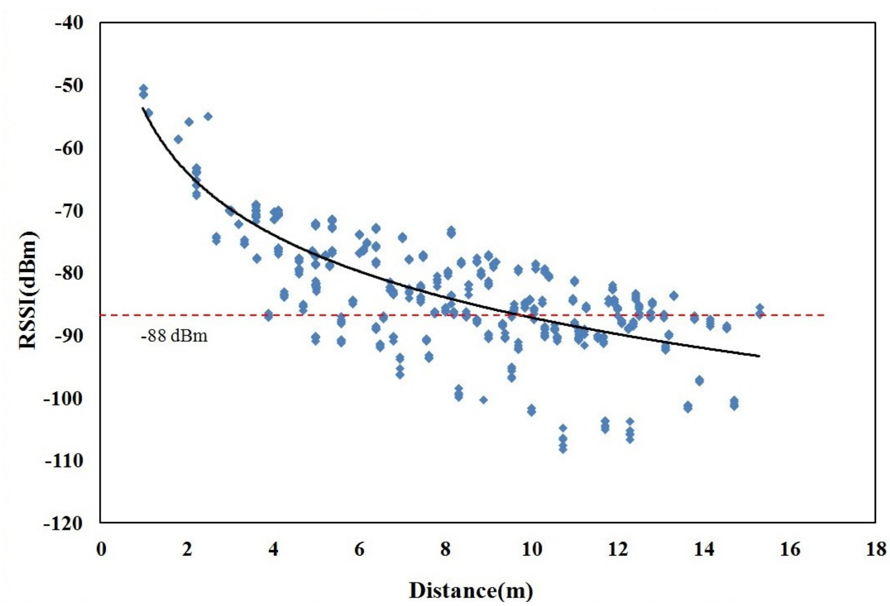


Figure 2-6 The relationship between RSSI and distance

The multilateration method is then used to determine the position of the mobile tag based on the calculated distances to the ten pegs. Figure 2-7 presents the frequency histogram of the resulting localization errors for the tracked tag. The experimental results show that the average positioning error is 4.56 m and the standard deviation is 2.40 m. The minimum and maximum location errors are 0.58 m and 9.45 m, respectively.

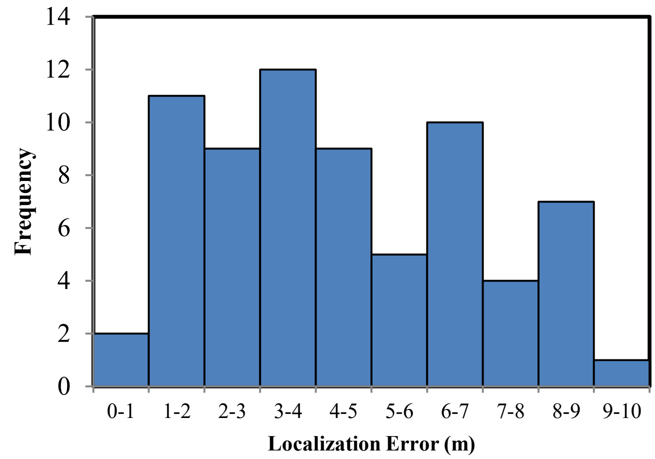


Figure 2-7 Frequency histogram of the RSS-ranging localization error data in the carpark experiment

Figure 2-8 contrasts the actual path versus the estimated path, indicating significant positioning errors. This experiment has corroborated that the position method of multilateration positioning based on RSS ranging only performs effectively for the ideal setting in which precise range estimates can be reliably obtained from RSS readings. In short, development of more accurate and reliable positioning methodologies especially for dynamic and practical indoor settings in construction applications is desirable. In the next section, the performance of the RSS profiling method is examined in the carpark field testing.

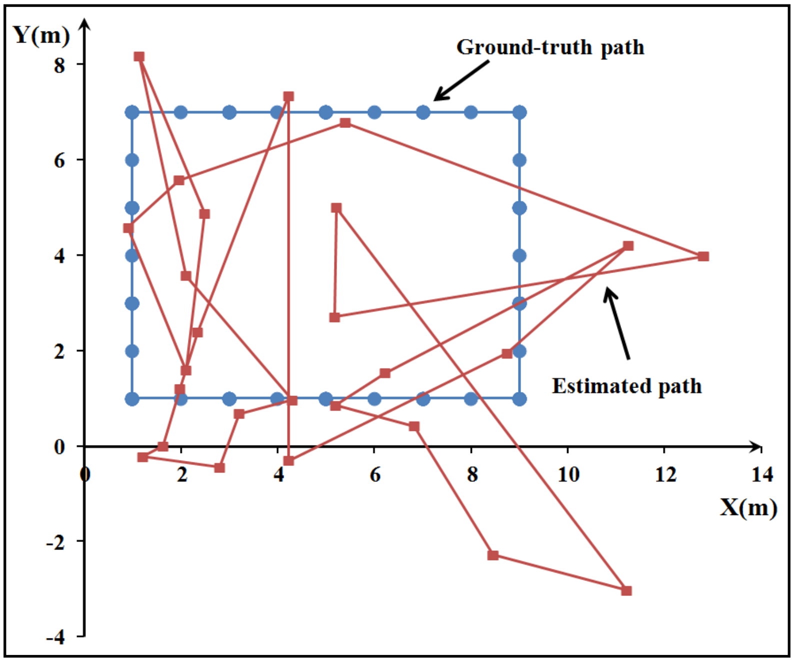


Figure 2-8 True path vs. estimated path by RSS-ranging method

2.5.2 Validation of the RSS profiling-based positioning technique

The identical experiment layout for the trilateration method was utilized for evaluating the profiling-based technique. Figure 2-9 shows the distribution of the sensor nodes for the experiment, in which ten pegs were deployed at fixed locations (marked as solid squares) and a tracking tag (marked as solid circle) moved along the same path. Profiling samples at predefined locations are marked as a cross ("×") with a spacing of 2 m between them.

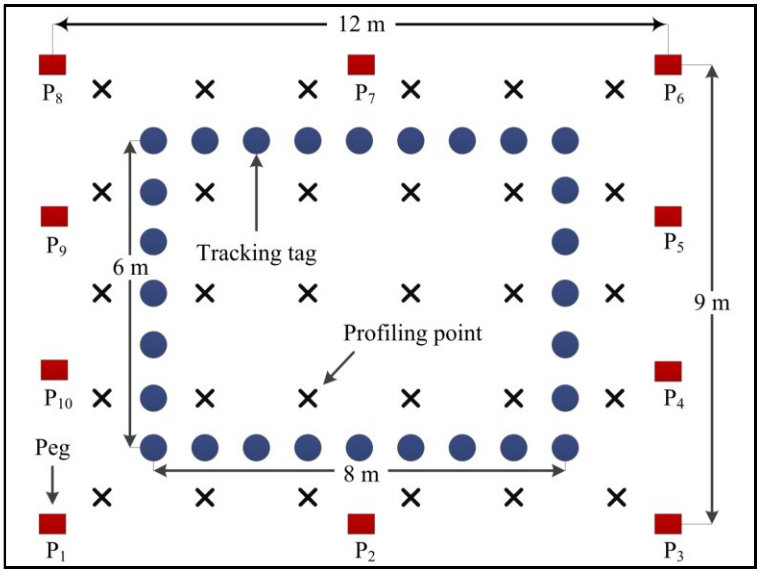


Figure 2-9 Experiment layout in the parking lot for RSS-profiling localization method

During the localization testing, a person carried the tag and walked along the planned path. The position of the tag was measured every 1 m by the prototyped profiling-based positioning system. Figure 2-10 demonstrates the frequency histogram of the localization error. It indicates that the system is able to locate the tracking tag with an average error being 1.44 m and the standard deviation of the errors being 0.61 m. The minimum location error was 0.52 m and the maximum was 2.85 m.

Figure 2-11 compares the true path and the estimated path resulting from the profiling-based positioning system. It can be observed that the path derived analytically from the RSS profiling method agrees closely with the actual path, producing more accurate position results than the ranging-based method as shown in Figure 2-9.

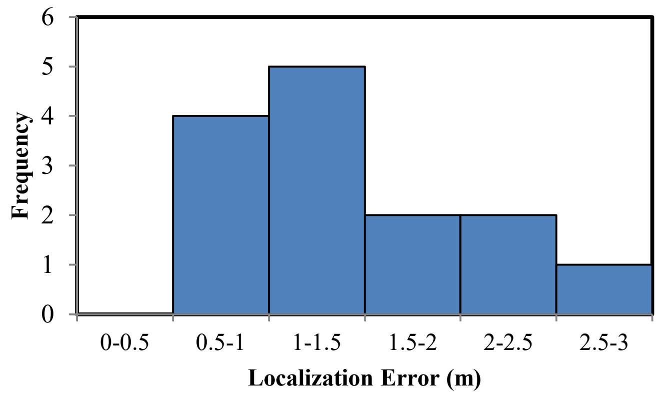


Figure 2-10 Frequency histogram of the RSS-profiling localization error data in the carpark experiment

2.5.3 Comparison of the two methods

Table 2-7 summarizes the experimental results from the two methods. Based on the indoor lab testing, with about 95% likelihood, the profiling-based method is able to fix the tag position within 2 meters of the tag's actual position. In contrast, the ranging-based method can only achieve 8 meters tracking accuracy for most of the time. If the RSS profiling based method is able to achieve the accuracy and reliability (under 2 meters accuracy with 95% confidence) in a practical construction setting, such as a piping spool fabrication shop, the methodology can potentially serve the needs of tracking components within a typical work zone inside the fabrication shop and the labour-hours in connection with handling and connecting those components into the final spool.

Table 2-7 Accuracy comparison on the ranging-based and the profiling-based positioning techniques for indoor environments

Positioning Techniques	Localization accuracy (m)				
	Min	Max	Average	Standard Deviation	95th Percentile
Ranging-based	0.58	9.45	4.56	2.40	8.7
Profiling-based	0.52	2.85	1.44	0.61	2.14

It must be pointed out that the RSS-based localization performance is susceptible to environmental changes. In extreme situations, the wireless RF signals can be drastically attenuated. Therefore, this RSS profiling approach alone would not provide sufficient accuracy and robustness as needed by construction applications due to high fluctuations of RSS over time. To address these challenges, noises must be detected, modeled, and filtered out during the process of data collection and analysis. To ensure accuracy and reliability of the proposed RSS profiling method, the Kalman filter, which is a commonly applied error-correction technique in signal processing and navigation, is recommended to preprocess the collected RSS data prior to employing the proposed profiling-based approach. The RSS profiling method coupled with the Kalman filtering process are described in the following sections, together with fabrication shop experiments and results.

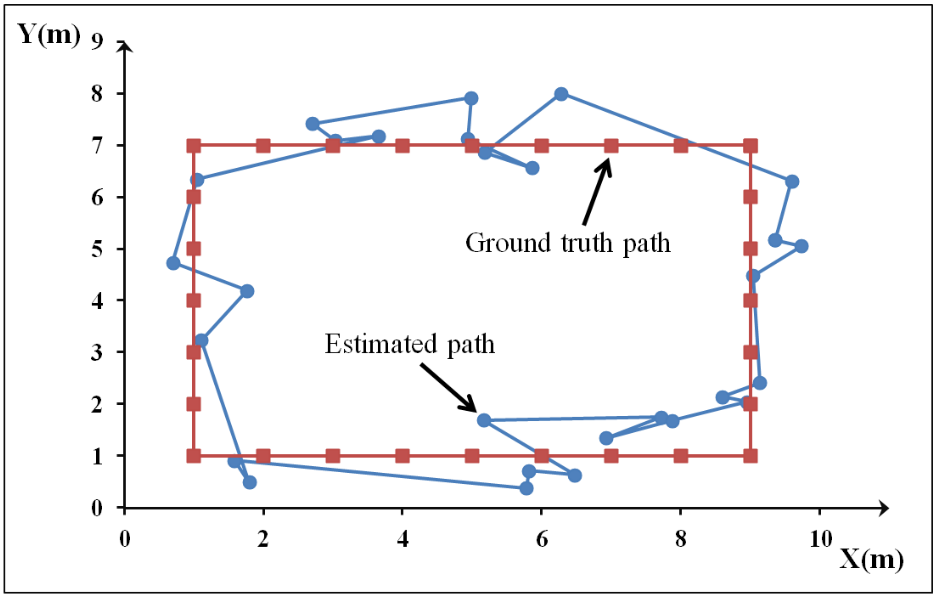


Figure 2-11 True path vs. estimated path by RSS-profiling method

2.6 System validation in a piping spool fabrication shop

Experiments were conducted at a pipe fabrication shop near Edmonton, Alberta. The environmental conditions of the fabrication shop were generally more challenging to apply RSS-based positioning methods with the presence of welding and cutting machines, metallic and many obstacles to signal processing. The shop configuration is frequently changed for handling different jobs. Figure 2-12 shows the test area selected for conducting the experiment. The objective of the study is to evaluate the feasibility and assess the performance of the proposed profiling-based positioning method inside the spool fabrication shop.

Figure 2-12 Experiment area in the fabrication shop and its dynamic nature

Eighteen pegs were fixed at known locations along the perimeter of a 20 m × 20 m test area, of which fourteen were placed on tripods at the height of 1.30 m while other four were either placed on top of the tool boxes or secured to walls or beams at the approximate height of 2 m (Figure 2-13). A tag was attached to a small piece of pipe and moved along a square-shaped path (14 m × 14 m) within a defined work zone of the shop. Figure 2-14 demonstrates the experiment layout.

According to the inputs from the floor personnel, the proposed methodology would be cost effective if the accuracy and reliability achieved in the previous lab testing (carpark) could be delivered in such a practical shop setting, namely:

under 2 meters with 95% probability. As such, the layout and quantities of pegs and the grid of profiling points were designed to be sufficient in order to evaluate the best achievable performances of the proposed method and assess whether the proposed indoor positioning methodology can potentially serve the application needs of tracking spool components and labourers within a typical work zone in the shop. How to streamline and optimize the layout design of profiling points and the pegs while retaining the achievable performances of the methodology can be the ensuing research to pursue.

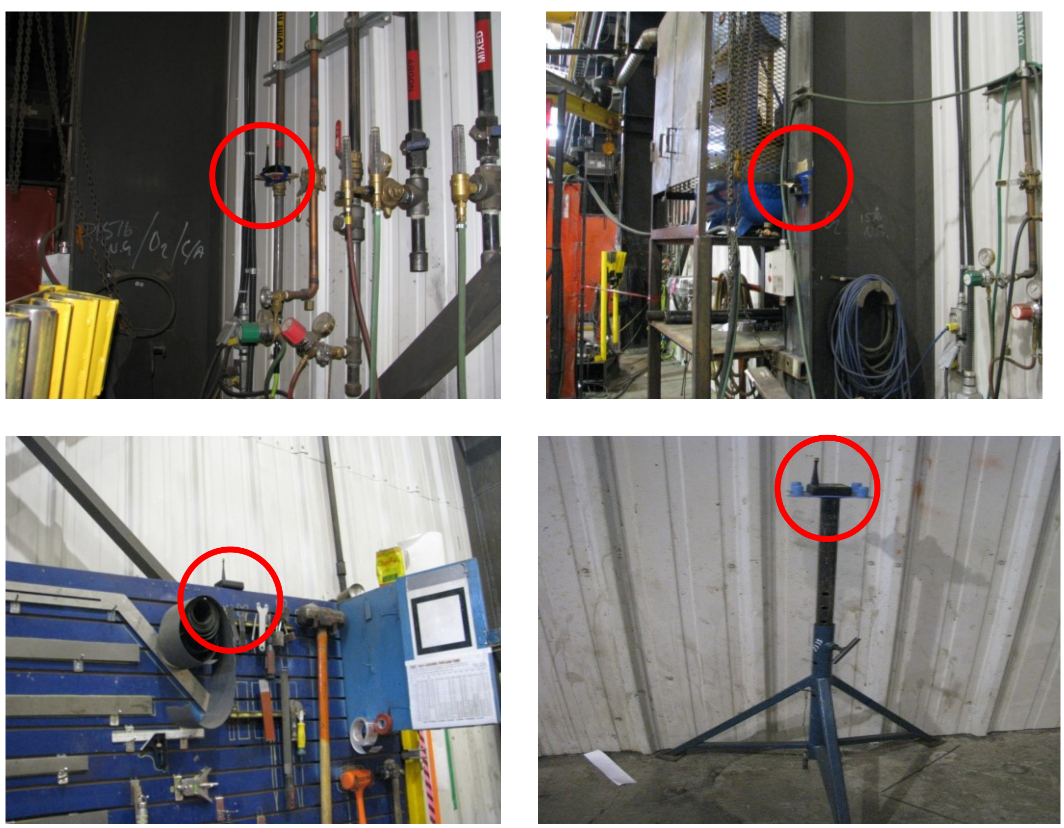


Figure 2-13 Peg nodes placement in the fabrication shop

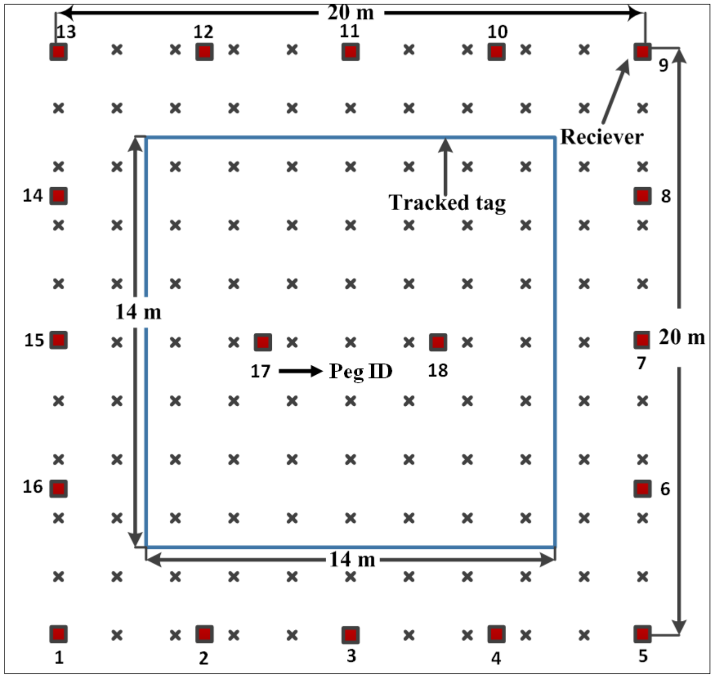


Figure 2-14 Experiment layout in the fabrication shop for RSS-profiling localization method

Figure 2-15 compares the true path of the moving tag in the fabrication shop with the estimated path resulting from the profiling-based positioning system. It can be observed that the path derived analytically from the RSS profiling method still agrees closely with the actual path. The results indicate that the system is able to locate the tracking tag with an average accuracy of 1.52 m, the standard deviation of the errors being 0.73 m. The minimum location error was 0.13 m and the maximum was 3.47 m. The 95th percentile is 2.72 meters, which implies with 95% likelihood, the tag's position can be fixed within 2.72 m of its actual position in the shop.

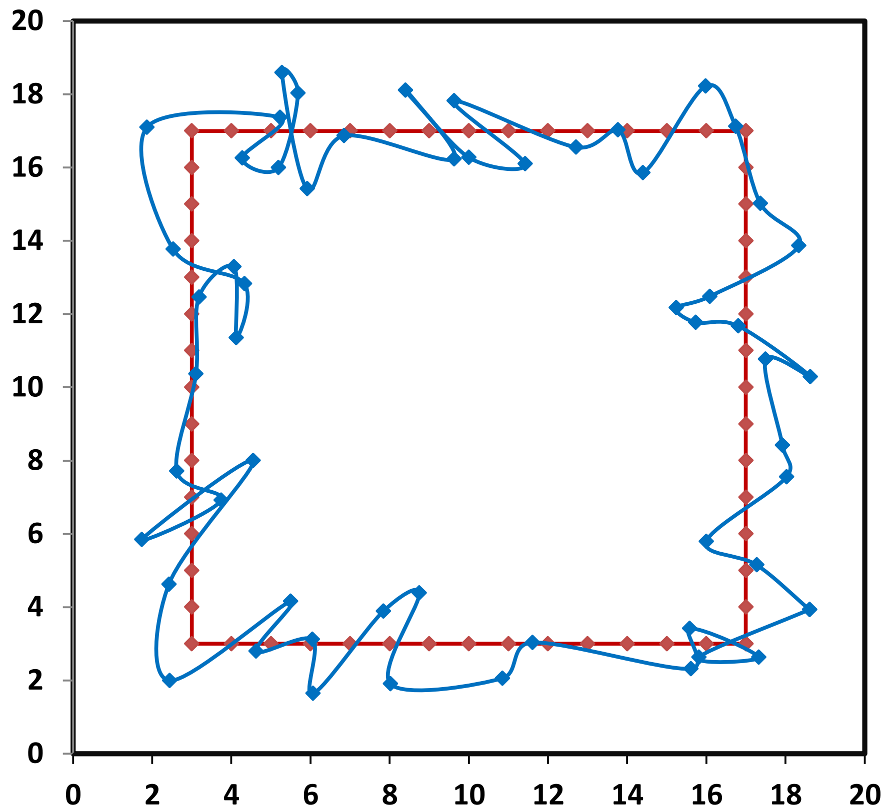


Figure 2-15 True path vs. estimated path by RSS-profiling method in the fabrication shop

In this present study, Kalman filter is further applied in an attempt to reduce the signal noise and compensate for any signal loss for the RSS profiling method. As the noise measurement is application specific and can hardly be predicted specially in a construction environment, a real- time adaptive Kalman filtering algorithm is utilized (Hu et al. 2003) to make up for signal loss and level out sudden, considerable signal changes in both profiling and tracking phases. The effect of the filtering algorithm on the RSS-profiling based model is explicitly illustrated in Figure 2-16, which shows how the RSS data, which was collected at one sample location from four peg nodes, is processed through an adaptive Kalman filtering algorithm so as to eliminate noise.

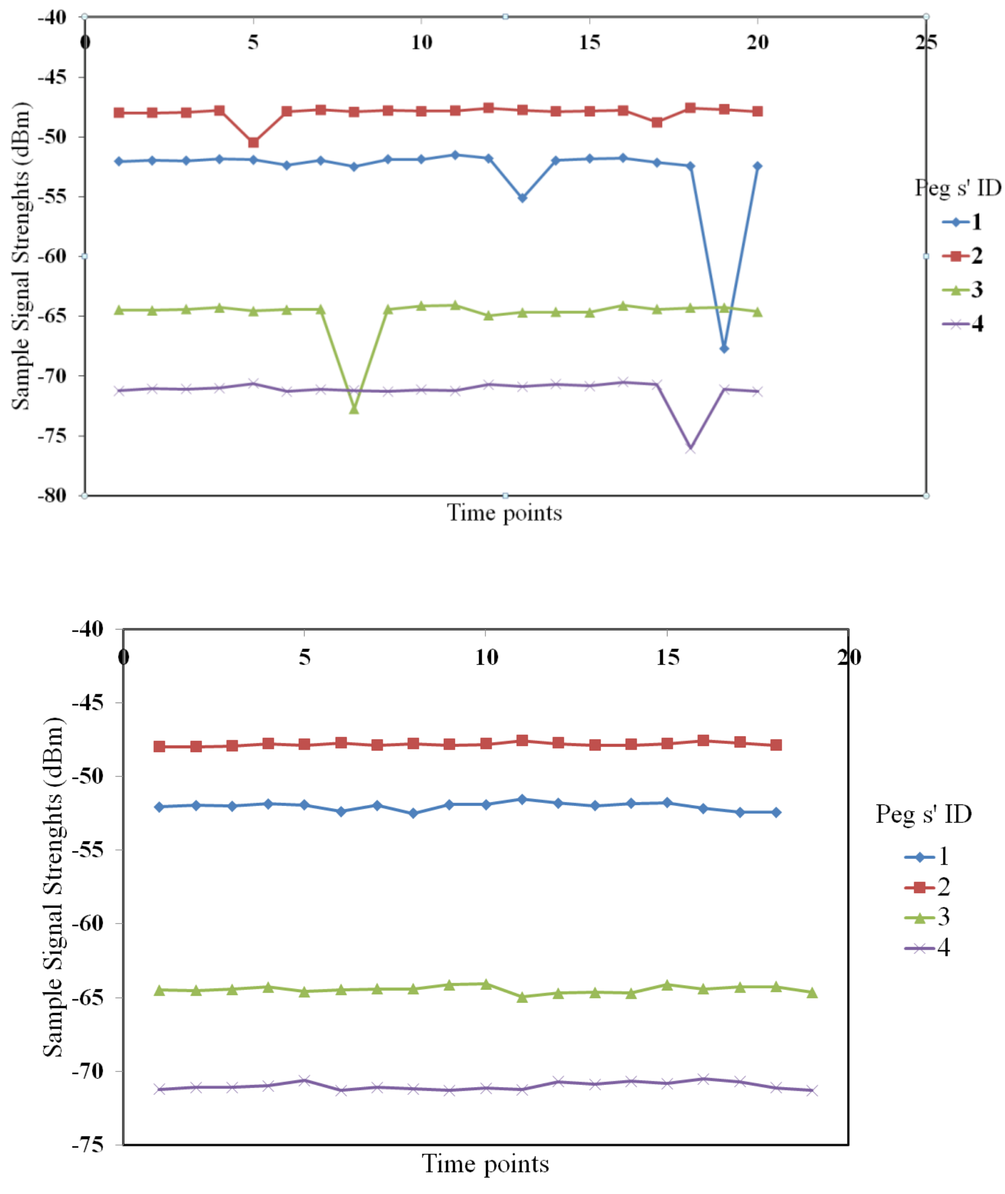


Figure 2-16 Effect of filtering process on signal strength

The final positing results from applying the RSS profiling based method coupled with the Kalman filtering algorithm demonstrate that the average localization error and the standard deviation can be reduced from 1.52 meters and 0.73 meters to 1.17 meters and 0.50 meters, respectively (See Figure 2-17).

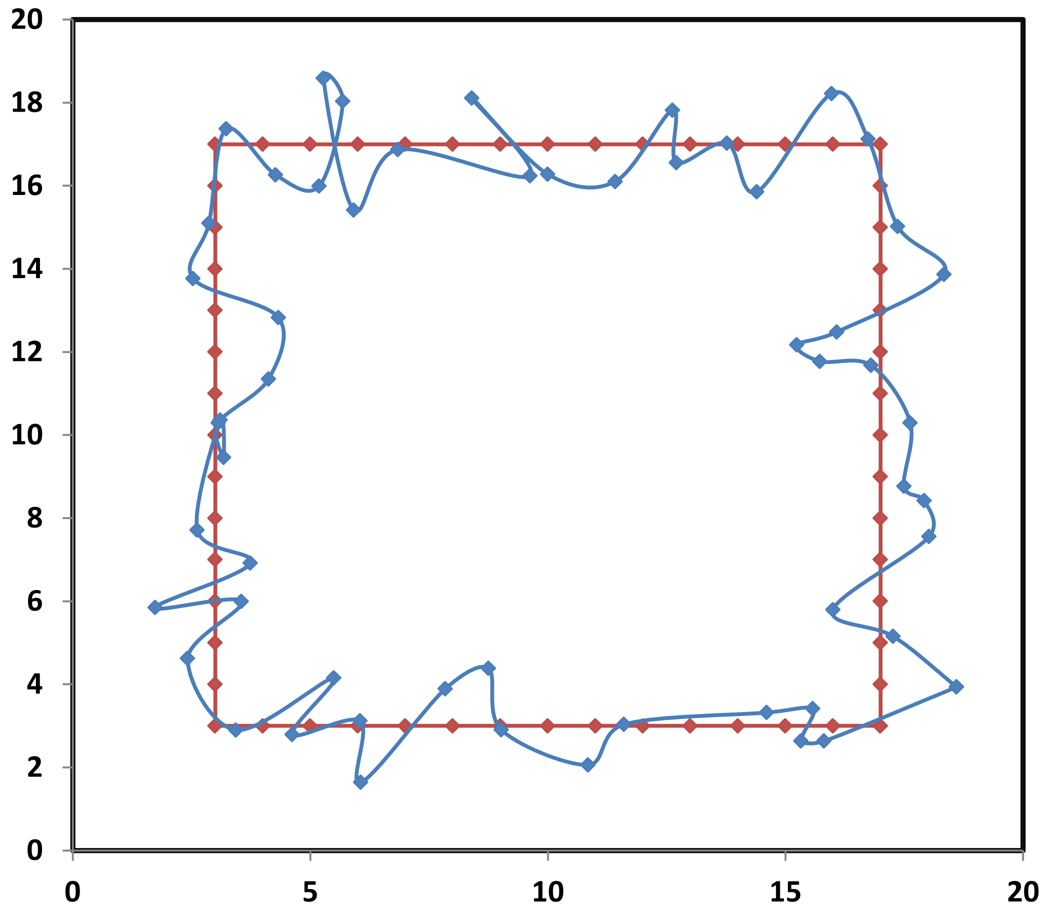


Figure 2-17 Error enhancement after employing Kalman filter

The position error statistics based on shop testing given in Table 2-8 contrast the effect of preprocessing RSS data by Kalman filtering. It can be observed that with Kalman filtering, satisfactory accuracy and reliability of tag positioning results can be obtained, with the average and the standard deviation being 1.17 m and 0.50 m, respectively. The 95th percentile is 1.90 meters, which implies with 95% likelihood, the tag's position can be fixed within 2 m of its actual position in the shop.

Table 2-8 Accuracy comparison on the profiling-based positioning technique with and without Kalman filter

Positioning Techniques	Localization accuracy (m)				
	Min	Max	Average	Standard Deviation	95th Percentile
Profiling-based	0.13	3.47	1.52	0.73	2.72
With Kalman Filter	0.13	1.97	1.17	0.50	1.90

2.7 Stability of localization in a unmodified application setting

Stable and reliable localization in unmodified environments belongs to the basic features of a practical positioning system. By "stable" we mean that the localization error does not grow without bound over time and remains bounded by time-invariant values at all times when the zone is not reconfigured entirely for a different job. In order to evaluate the stability of the proposed profiling-based positioning method, fixing the tag position was repeated in the same location a

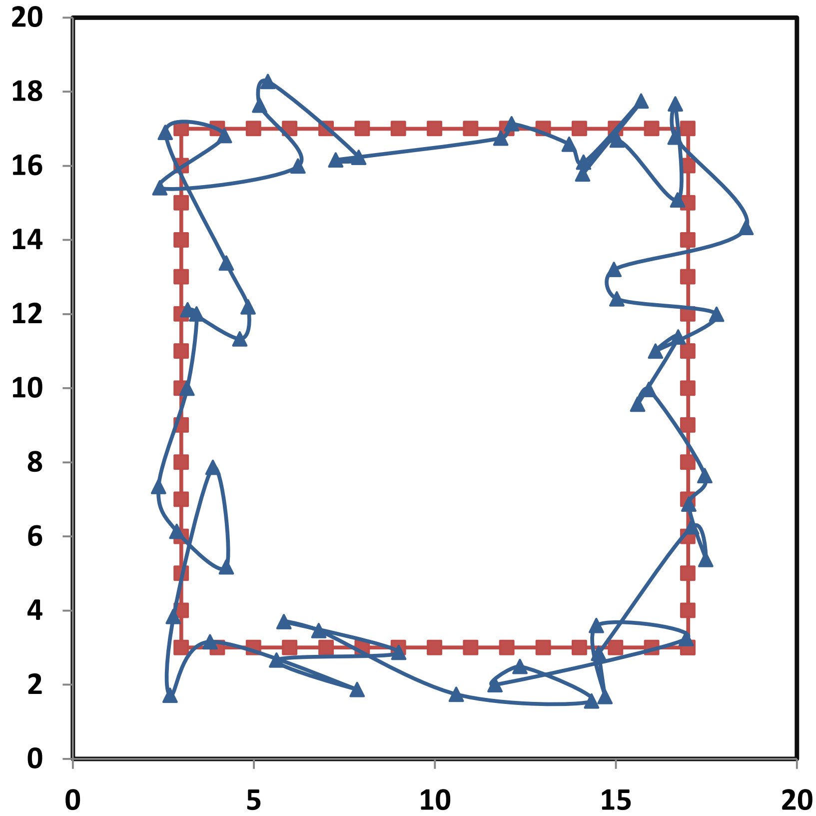


Figure 2-18 True path vs. estimated path by RSS-profiling method in the unmodified environment using previous profiling data

day after using the same RSS profiles in the fabrication shop. The setting of the zone remained much unchanged. Figure 2-18 contrasts the true path of the moving tag with the estimated path resulting from the profiling-based positioning method. It can be observed that the estimated path still agrees closely with the actual path. The results indicate that localization is able to locate the tracking tag with average localization error of 1.61 m with the standard deviation of 0.81 m. The minimum location error was 0.25 m and the maximum was 3.63 m (with the 95^{th} percentile being 2.97 m). Employing Kalman filter (Figure 2-19) further reduces the localization error statistics (with the 95th percentile being 1.97 m) implying that the system is constantly able to lock the tag's position within 2 m of its actual position in the shop with 95% likelihood. The position error statistics given in Table 2-9 contrast the two shop tests. The proposed method provides relatively stable positioning performances consistent with the results obtained the day before (1-2 m). In short, when the application setting inside the test zone of the fabrication shop is not modified, there is no need to update the RSS profiling data.

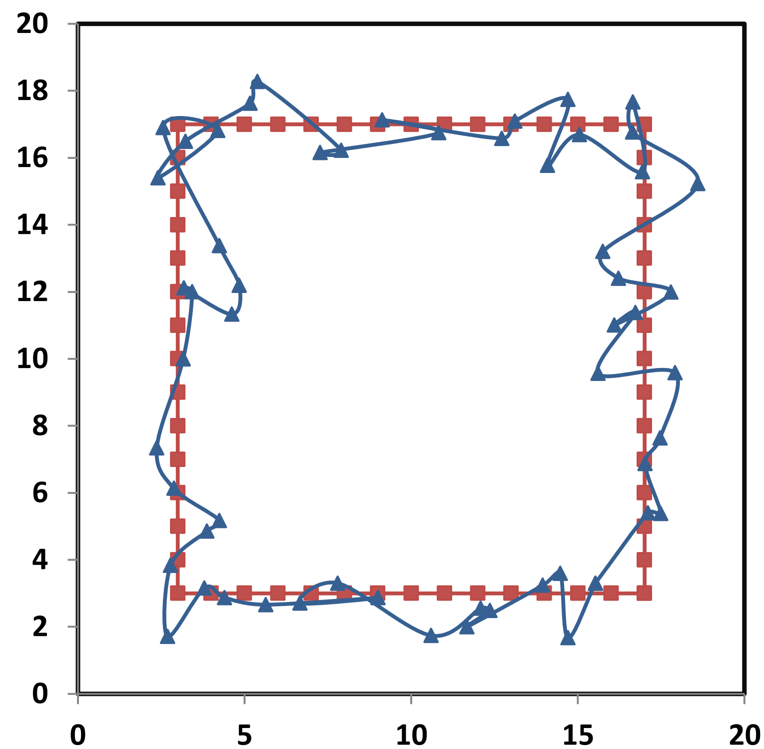


Figure 2-19 Error enhancement after employing Kalman filter in the unmodified environment

Table 2-9 Accuracy comparison on the profiling-based positioning technique over time

Positioning Techniques	Localization accuracy (m)				
	Min	Max	Average	Standard Deviation	95^{th} Percentile
Profiling-based coupled with Kalman filter (First day)	0.13	1.97	1.17	0.50	1.90
Profiling-based coupled with Kalman filter (Second day)	0.24	2.04	1.20	0.49	1.97

2.8 Discussion on stability of RSS signals in a dynamic environment

In a dynamic indoor application setting such as the spool fabrication shop, the RSS profiles can significantly change over the time mainly because arrangement of the work zone is frequently reconfigured for handling different jobs. Accordingly, the positioning performances of the proposed RSS profiling method deteriorate over the time.

Figure 2-20 Different configuration of pipe spool fabrication in the test area

For instance, the same work zone setup had been reconfigured a few days after the first experiment (shown in Figure 2-20), with pipe sections being set up for fitting and welding. Based on the RSS profiles established in the first experiment, fixing the tag's positions was repeated but resulted in larger position errors particularly near the lower left corner of the work zone (shown in Figure 2-21). The position error statistics are also contrasted in Table 2-10 in terms of applying the profiling-based method in the original setting and in the reconfigured setting. The 95th percentile increases from 1.90 meters to 5.33 meters, which implies downgraded performances and insufficient accuracy for meeting the application objective.

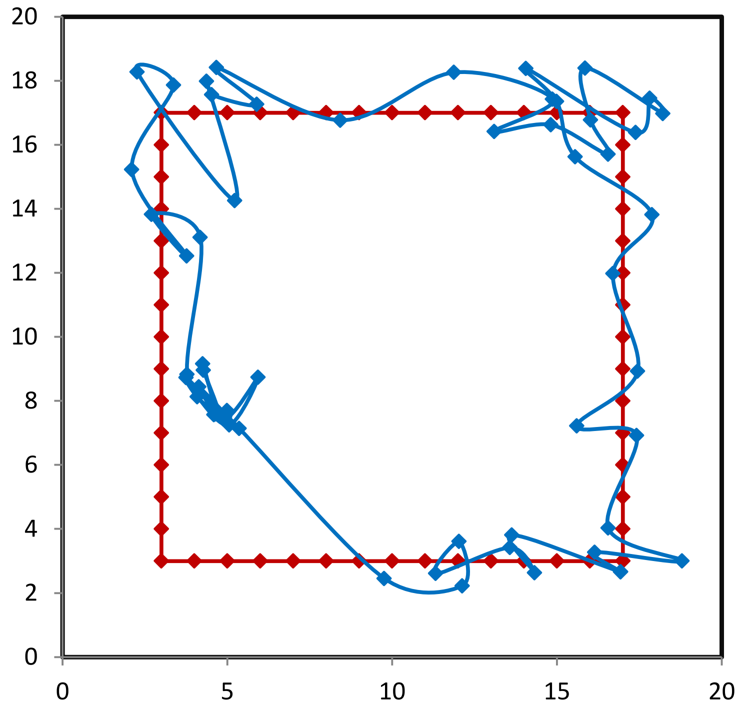


Figure 2-21 True path vs. estimated path by RSS-profiling method in the interfering environment using previous profiling data

Table 2-10 Accuracy comparison for applying the profiling-based method in the original setting and in the reconfigured setting

Positioning Techniques	Localization accuracy (m)				
	Min	Max	Average	Standard Deviation	95th Percentile
Experiment in the reconfigured setting	0.35	6.67	2.37	1.61	5.33
First Experiment in the original setting	0.13	1.97	1.17	0.50	1.90

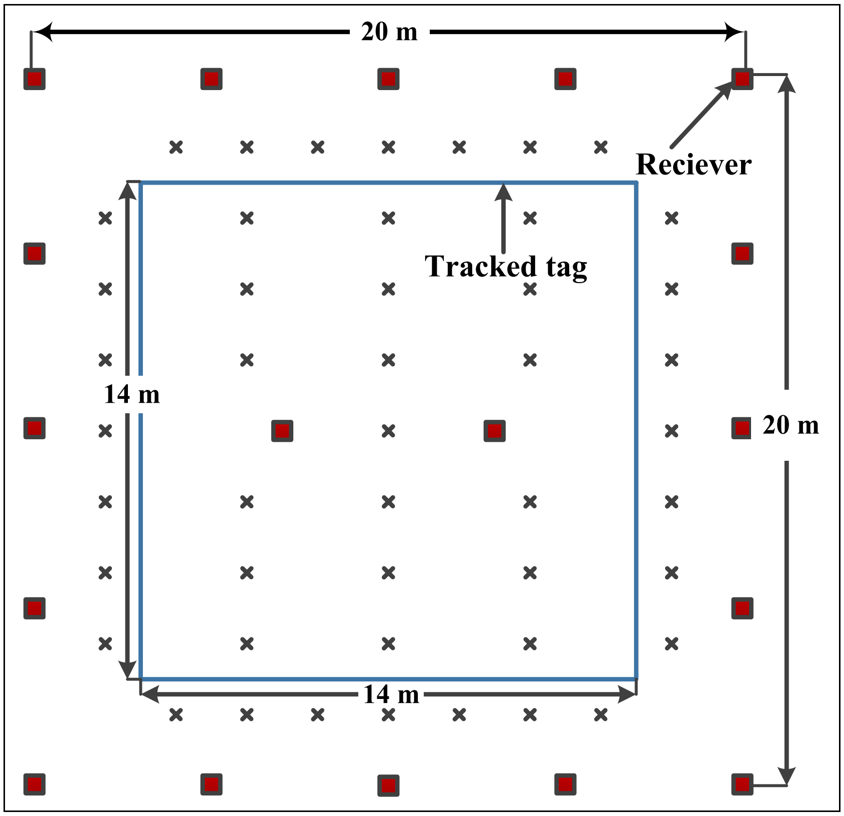


Figure 2-22 Streamlining the reference points' layout: 49 profiled points

Re-profiling all the landmark points in relation to all the pegs would be required in order to restore the desired positioning accuracy by applying the proposed profiling-based method. However, it should be pointed out that re-profiling can be a tedious and time-consuming process if it is performed manually. To streamline the re-profiling procedure in the fabrication shop, we identified that the use of 49 points for RSS re-profiling could result in positioning accuracy comparable to the scenario when the original 169 points were used in the fabrication shop (as shown in Figure 2-22). Nonetheless, in the follow up research, an automatic re-profiling approach will be attempted, as well as optimizing and streamlining the layout and quantities of profiling points and pegs which will be needed to obtain the desired performances.

2.9 Conclusions

Over the past few decades, sensor technologies, mobile computing, and tracking methods have advanced while field data collection and communication technologies becoming cost-effective. Nevertheless, indoor localization remains a technical challenge. It is not straightforward to model the radio signal propagation patterns inside a building under construction or a fabrication shop. Besides, three crucial factors must be considered and balanced in developing a positioning system for construction applications in indoor or partially covered sites; these include implementation cost, localization accuracy, and operational reliability.

This study evaluated the feasibility of applying two RSS-based methods in indoor construction application settings so as to achieve the positioning accuracy of 1-2 meters with high reliability. This accuracy is generally accepted as the sufficient positioning performance for resource tracking and field productivity measurement in construction. In order to assess the performance of these methodologies, an indoor experiment was conducted in a carpark, identifying two limitations for the RSS ranging-based method: (1) the performance of the geometric trilateration algorithm depends on the accuracy of distance measurements from RSS; therefore, any error in the estimated ranges is directly propagated in the error of the positioning system; (2) it is impractical to produce sufficient positioning results due to large ranging errors. It was also found that localization performances in indoor environments can be improved by utilizing the RSS profiling-based method with achieving less than 2.14 meters position error with 95% likelihood.

The profiling-based method was then coupled with commonly used noise filtering algorithms in order to conduct field testing in a pipe fabrication shop and evaluate the accuracy of this method in a practical indoor environment. With 95% likelihood, consistent positioning accuracy of 1-2 meters away from the actual position of a tracked tag was obtained in the fabrication shop. We also evaluated the stability of localization in the same location but at a different time by repeating the experiment when the shop setting is much unchanged. It is found that positioning performances based on the profiling data recorded on a different day remain relatively stable and comparable to the degree of accuracy obtained the day before (1-2 meters).The proposed methodology would potentially serve the needs of tracking components and labour-hours in connection with handling and connecting those components within a typical work zone inside the fabrication shop.

The objective of this study was to identify the effective method for positioning and tracking resources with sufficient localization accuracy and reliability as needed in tracking pipe spools inside a fabrication shop. However, it must be pointed out that in a dynamic indoor application setting such as the spool fabrication, the RSS-based localization performance is susceptible to frequent reconfiguration of the work zone for handling different jobs. The positioning performances of the proposed method would deteriorate accordingly.

CHAPTER 3

3 Integrated project management framework (iPMF)

3.1 Introduction

This section explains the use of radio frequency-based indoor positioning system for real-time localizing and tracking pipe spool fabrication and to support the pipe spool production progress control. The development of the integrated Project Management Framework (iPMF) is also described. This framework integrates fabrication process planning and tracking with the drawings and document control system and the materials management system and allows its users to obtain information about the labour cost and production process.

3.2 Integrated Project Management Framework (iPMF)

Figure 3-1 illustrates the structure and concept of iPMF and the relationships between different layers of iPMF such as the database servers, tracking and localizing technologies, interfaces, drawings and document control system, the materials management system and labour costing system.

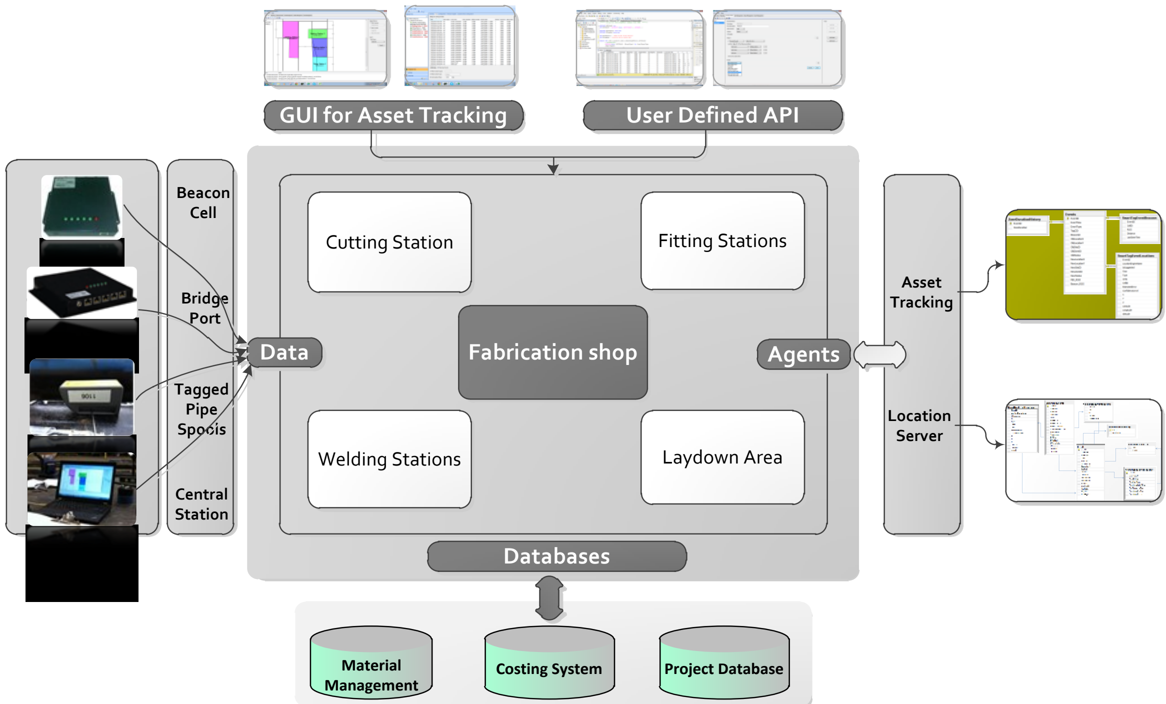


Figure 3-1 System Architecture of iPMF

The system structure is based on a multi-tiered architecture, designed to support scalability, and to allow easy integration of only those components needed to deliver the performance levels and features required by the nature of the customer's working environment. iPMF consists of four key layout layers:

The Smart Agents layer (Appendix 1) - Including 2.4 GHz tags. All tags include an embedded motion-sensor. Each tag has a receiver, transmitter and onboard processor, executing embedded software.

The infrastructure layer (Appendix 1) - Incorporating the location and communication devices (Beacons and RF base station with a bridge port are the infrastructure building blocks). The infrastructure layer provides two-way, long-range wireless data communication - up to 1000 feet. The Bridge Port (BP) is an independent RF communication and synchronization unit, which allows for bi-directional wireless communication with smart agent tags and beacon cells, supporting multi-frequency mode for RF interference protection.

The central-sever middleware layer – Responsible for the management of the air-to-air protocols, location calculation and the system's resources management.

The API layer - bridges between the server middleware, the centralized database and the existing customer's management software. It also provides API for user application allowing querying tags in real time for obtaining the current tag status and querying database offline for obtaining either the most updated tag status or history of the tag activity.

The pipe spool monitoring system relies on three SQL server databases including Location server, Asset Tracking server and project database.

Location server offers a real time monitoring and configuration management console that helps improve the efficiency of managing the localization system network services and its real time asset visibility infrastructure. Location Server allows users to manage the software and hardware elements of the network, such as Base Stations, Beacon Cells and even Smart Agents through its user friendly client console. This server utilizes an indoor positioning architecture based on a location method using colliding signals combined with a zone detection method which will be discussed in detail in the subsequent section.

The Location Server interface includes the following functionality:

1. Real time monitoring of system elements

2. Element configuration (Smart Agent, Base Station, Beacon Cell, Location server)

3. Reporting

The Asset Tracking server and client allow users to implement real time asset visibility tools coupled with business process automation features, through a single user interface that offers a robust graphical interface, reports, real-time alerts and the utilization of business rules.

The Asset management components of the Asset Tracking server is used to introduce assets into the database, associating an asset with the unique ID of the agent attached to it. Assets can be added either one at a time, or in bulk, using formatted data in an input file. Assets can be divided into groups to aggregate and track several assets together.

The project database includes information about existing projects, fabrication schedule and modules each having a number of activities, corresponding pipe spools and definitive quantity takeoffs for particular module component parameters like pipe spools. The information will be identified from the project drawings specifically isometrics, bill of quantities and specifications. When the pipe spool components are tagged, relevant coding information such as ID, name, technical features, specifications, design drawing numbers and the delivery date of the pipe spools will be input into the tags which will be automatically reported to asset tracking database. The database is also able to track the isometrics that are broken down into smaller subassemblies in order to account for all the pieces of a pipe spool.

When a pipe spool is cut to the required size according to the cut sheets information, a tag representing the spool is attached to the pipe, which also contains descriptive information such as size (Length and Diameter Inch), job number, and work package number in addition to the ID code of the spool. The ID of the tag is mapped to the object identifier of the spool on the drawing. This allows the users, who have access to the system, to understand the context of the spool and to update the pipe spool status on the system database in real-time. As mentioned earlier, the pipe spool passes several work stations including cutting, fitting, handling, welding and inspection.

The spool information is gathered using tags in wireless sensor network, while status information is stored in the databases, which records the information generated from each task in the process, as well as the tracking information from the sensors operations in the process chain. On the work process management system, the collected information is interrelated to aid relevant management decisions. While setting up the iPMF, the bridge port functionality is tested from the Location administrator interface to make sure that the server and the base station are interconnected over the network and that the bridge port functions properly.

3.3 Localization Methods and Data Collection in iPMF

Accurate and robust indoor localization is a key enabler for context-aware future internet applications, whereby robust means that the localization solutions should perform well in diverse physical indoor environments under realistic RF interference conditions. The main limitations of indoor localization research are (1) the difficulty to reproduce research results in real life scenarios suffering from uncontrolled RF interference and (2) the weakness of numerous published solutions being evaluated under one-of-a-kind, not comparable and not repeatable conditions.

The localization process of the proposed positioning technique can be viewed as a combination of a location method using colliding signals and zone detection to overcome error induced in RF based localization due to RSS variation. When the pipe spool components enter the shop, the colliding localization algorithms provide the Location server and Asset Tracking server with the exact location of the spool components within the shop or a specific zone. Both the colliding method and zone detection are explained in next section. As the components move into or out of a zone, the zone beacon reports the movement (i.e. Enter and

Exit time) and the duration a component stayed in a zone to the asset tracking database.

Dynamic Kalman filtering is also used to further increase localization reliability and to effectively reduce uncertainty. Such algorithms take into account the localization of the previous tag signals, in case of complex situation. To effectively reduce uncertainty and improve accuracy, the adaptive Kalman (Hu et al. 2003) filter is then used to correct for signal loss and exorbitant signal changes in both signal colliding and zone detection phases. Generally, a Kalman filtering algorithm works in a two-step process: a prediction stage and a measurement updating stage. The Kalman filter operates recursively on a set of noisy, uncertain and inaccurate input observations which herein are the RSS samples, producing an optimal estimate of the system state.

Other than status of the process progress, the iPMF automatically collects data about labour-hours and process itself and allows managers to track costs and output productivity to improve bottom line by viewing and managing real-time information related to all fabrication tasks and labour activities inside the fabrications shop. Access to activities and costs in real-time allows manager to manage productivity and make better decisions.

The beacon devices collects data using sensor tags on pipe spool components. iPMF sensing technology can assist in detecting the spool components in the specific working zones.

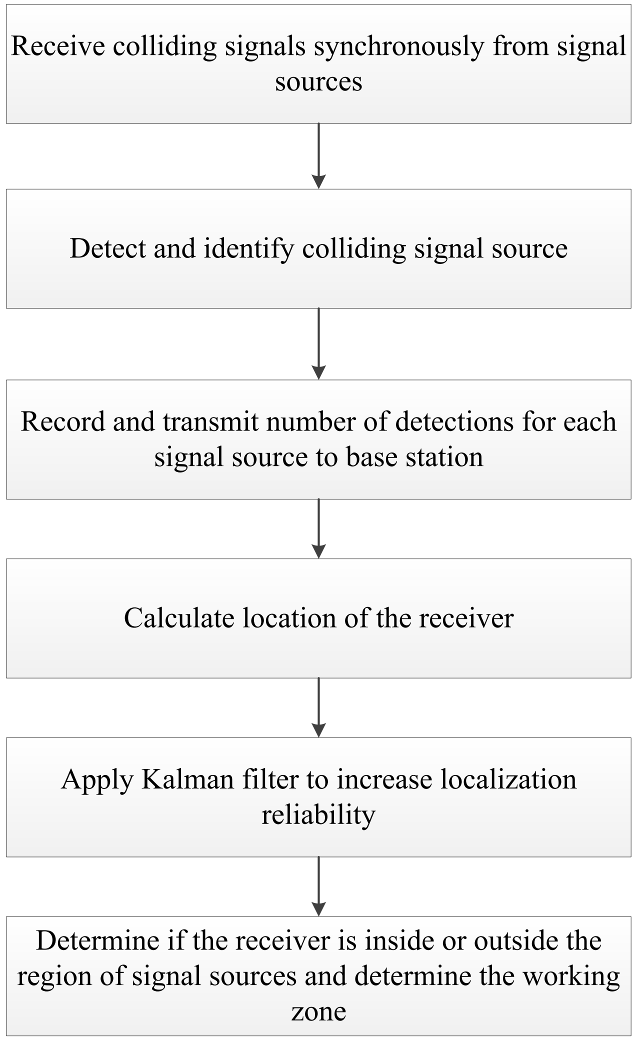


Figure 3-2 flow chart of the proposed localization method

iPMF is able to report the component ID along with the start and stop times of the fabrication activity in precise entries of date and time (recorded in seconds, minutes, hours, day, month, year, and time zone). The recorded time represents the amount of work the labour has been doing on the specific component in the specific work station. This information is sent to the databases and the costing system as the labour-hours. Figure 3-2 demonstrates the flow chart of the proposed localization method.

3.3.1 Colliding localization method

Indoor localization research has been rapidly gaining interest in construction engineering and management (Khoury and Kamat 2009). There have been several different technologies available to collect location information, including GPS, Radio Frequency (RF) sensors, Ultrasonic, Ultra Wideband (UWB), laser scanner, LADAR, Infrared, and video/image-based tracking. Typical positioning methods and technologies that are widely used for locating objects in three dimensional space are mostly based on triangulation utilizing various received signal parameters. For example, typical radio frequency identification (RFID) tags periodically transmit RF signals that are then received by geographically distributed RF readers. The final tag location is calculated using one of the following parameters or their combinations: received signal strength (RSS), phase delay, angle of arrival (AOA), time of arrival (TOA), time difference of arrival (TDOA) and etc. RSS based positioning methods can be designed and deployed in the field with ease and low cost (Haque et al. 2009). On the downside, such methods can hardly achieve sufficient localization accuracy and reliability as needed by particular construction applications (Shen and Lu 2012). The other methods usually require a complicated digital signal processing to be involved in the calculation, increasing the cost of the devices and the system (Khalid and Gulliver 2010).

Deploying a cost-effective and scalable materials location identifying system in real world construction sites has recently become feasible. However, there are still much research opportunity to improve accuracy, precision and robustness. A limited number of research studies have been conducted to explore potential approaches to deal with imperfect data for improving the positioning and tracking system performance in a realistic world of construction sites.

For instance, Razavi and Haas (2010) identified that the obtained data from automated data collecting (ADC) technologies were imperfect and proposed five major frameworks to deal with imperfect data: probabilistic, evidential belief reasoning, soft computing, optimization-based, and hybrid methods. They developed a data fusion model with the integration of the five major frameworks for tracking onsite materials. The Dempster-Shafer theory or the "Belief Function Theory" (Razavi and Haas 2012) and weighted averaging were the main two algorithms that they examined for representing and enhancing data imperfection. RFID technology equipped with GPS was used for generating location observations.

The result of their study indicated that adaptive weighted averaging has the highest impact on improving the precision, while adaptive Dempster-Shafer, simple averaging, and Dempster-Shafer methods stand next in an ordered fashion. Their study was, however, focused on outdoor sites only.

In another study by Luo et al. (2014), basic approaches were used to improve accuracy, from simple averaging of multiple readings to the use of supplemental velocity and acceleration data. Those approaches showed some improvement over use of raw data generated by Cricket Development Kit for autonomous crane safety monitoring system. The results indicated that system performance could be improved if at least ten position readings from sensors were collected at small intervals at any location along the moving path. However, including additional data such as velocity and acceleration data of the workers has the potential of reducing localization error. Though, the research was implemented on a scaled-down testbed with LEGO model tower crane and bricks in a 0.5m × 0.5m area, which might not achieve the same performance as in a full-scale and real-world environment.

In an effort to achieve sufficient localization accuracy and reliability as needed for resource tracking and field productivity measurement in construction, authors have previously conducted a research study to evaluate the feasibility of applying an RSS-based profiling method in indoor construction application settings (Soleimanifar et. Al 2014). In this method, the RSS of the tag was compared against a pre-collected set of samples from known (profiled) reference points (Haque et al. 2009). The profiling-based method was coupled with commonly used noise filtering algorithms to conduct field testing in a pipe fabrication shop and evaluate the accuracy of this method in a practical indoor environment. With 95% likelihood, consistent positioning accuracy of 1-2 m away from the actual position of a tracked tag was obtained in the fabrication shop. The details of the system development and experimental studies are provided in Chapter 2 of this dissertation.

The methodology was found to potentially serve the needs of tracking components and labour-hours in connection with handling and connecting those components within a typical work zone inside the fabrication shop. However, in a dynamic indoor application setting such as the spool fabrication, the RSS-based localization performance is susceptible to frequent reconfiguration of the work zone for handling different jobs. The positioning performances of this method would deteriorate accordingly, so there was a need to conduct re-profiling task frequently which was time-consuming and labour-intensive. The colliding localization method, on the other hand, is an automated localization method which does not need human intervention for data collection.

Typically, indoor localization methods rely on beacons that periodically transmit their data such as coordinates using radio signals. Mobile nodes then use the received information to decode that information and estimate their own locations based on that information. The primary assumption for all these methods is that beacons should send their signals at different times, i.e. the signals should not collide. A collision is the situation that occurs when two or more devices attempt to send a signal along the same transmission channel at the same time. The colliding of the signals can result in distorted and useless data messages. All computer networks require some sort of mechanism to either prevent collisions entirely or to recover from them when they occur. For that reason, in traditional methods, beacon nodes transmit signals asynchronously. The mobile node listens to receive a signal from all beacon nodes within range. The mobile node then estimates its position based on the received information. To make sure that beacon nodes do not interfere with each other's signal transmission, extra waiting intervals is added between each timeslot for signal reception. The simple change of perspective from non-colliding to colliding signals makes the positioning method more resistant to external interfering sources, such as WiFi signals.

Since all signals are sent at the same time, only two outcomes are possible. If the interference signal is lower than the strongest beaconing signal, colliding method is unaffected because the capture effect “filters out” this type of interference. If the interference signal is similar or higher than the strongest beaconing signal, no location can be decoded. Notice that in the latter case no system would be able to decode the signal either. To increase the resilience of the positioning method, the beaconing frequency could be increased (at the cost of shorter duty cycles, and hence, higher energy consumption).

While indoor localization is a very active research area in construction management, to the best of our knowledge, there was no previous attempt to evaluate and apply a collision-based approach in construction industry. We propose a fundamentally new approach for indoor localization that overlaps the transmissions of signals. The collision-based method employs the capture effect, which means that when several radio signals collide, only the strongest (nearest) signal is detected. Under normal circumstances overlapping transmissions cause all packets to be destroyed, or to be damaged to the extent that contents can't be recovered. However because of a phenomenon called the capture effect the mobile node does in fact receive the packet which has the strongest signal, which is from the closest beacon node.

The capture effect has been used in recent flooding protocols to improve their reliability and throughput (Drif 2015). These protocols are mostly used in the field of wireless sensor networks (WSNs). The goal of flooding protocols is for all the nodes in the WSN to move data they have collected to the sink node which collects all the data. One of the methods that were proven to maximize the throughput is to flood the network, i.e. by making all the nodes actively send their data towards all nodes in the direction of the sink. Collisions, however, lowers the throughput when two or more nodes try to send data at the same time to another node in the network. This occurs frequently in flooding protocols, as all nodes are willingly transmitting data. The capture effect can give a significant boost to the throughput of such a system, since it ensures at least one packet to be received.

The colliding localization method was first proposed by Braiman (2011) based on the beacon-based location architecture. The patented technology by PrecyseTech (2016) provides the interface to build new applications, however, only a limited access was provided into the core localization algorithms.

The proposed localization method comprises receiving colliding signals by a receiver from a number of signal sources, such that the receiver has a respective non-zero probability of detecting and identifying the colliding signals from each of the signal sources at a given time. In our method, the term "colliding signals" refers to two or more signals, transmitted purposefully at the same time in the same area, having the following characteristics:

- Signals are specially configured to interfere with each other.
- The basic transmitting signal parameters are drifting randomly, causing variation in the maximum likelihood of the receiving signal during detection. The colliding signals from at least two signal sources are the same with respect to at least one of the following transmitting parameters such as carrier frequency, occupied frequency band, modulation type, etc. In our method, signals are transmitted on the same frequency.
- At least one transmission parameter of the colliding signals from each of the signal sources varies with a predetermined probability distribution. For instance, in our method the colliding signals have different transmitting amplitude. The random drifting function of the transmitting signal parameters is known (for instance Gaussian with the mean=0 and variance σ^2).
- Each signal has 100% probability to be detected and read by the receiver if transmitted alone and non-Zero probability to be detected and read when colliding with the other signals transmitted by the colliding sources due to the capture effect which will be explained later in detail. As used herein, "Detecting" the signals includes determining the existence of signal emissions (e.g., RF emissions) and "Reading" the signals includes extracting one or more payload data from the signals. "Identifying signals" includes extracting information unique to signals from one signal source.

As explained earlier, the colliding signals are configured with at least one common transmission parameter value so as to interfere with each other, so that the receiver only detects and identifies one of the received colliding signals (the one having a larger probability to be detected and read) if multiple signals are received at any given time. For instance, the transmitted signal pattern is known, so we know what we expect to receive at the mobile node. At receiver, the received packet is decoded and compared with the expected message from the beacon node. A probabilistic model is then used to calculate the location of the receiver using the coordinates of the decoded beacon node. The model correlates with a respective number of times the receiver detects and identifies one of the colliding signals given the location of the receiver.

The philosophy behind and the algorithm for performing tag location in a colliding signal environment is further illustrated by the following example. Figure 3-3 shows two signal sources S_1 and S_2, with a receiver placed between the two signal sources with equal distances from the transmitters. Assume two colliding signals transmitted by the independent sources S_1 and S_2, and R_1 and R_2 are the received signals corresponding to S_1 and S_2. The probability of the signal detection, p(S), can be easily calculated empirically for all identified signal sources within the period of time t using the following equations (Braiman 2011):

(1) $$p(S_1) = \frac{n\,(R_1)}{n\,(R_1) + n\,(R_2)}$$ for the received signal R_1

and

(2) $$p(S_2) = \frac{n\ (R_2)}{n\ (R_1) + n\ (R_2)}$$ for the received signal R_2

Or

(3) $$p(S_m) = \frac{n\ (R_m)}{n\ (R_1) + n\ (R_2) + \cdots + n\ (R_k)}$$ for multiple signal sources

Where n is the number of detections for signal m within k signal sources.

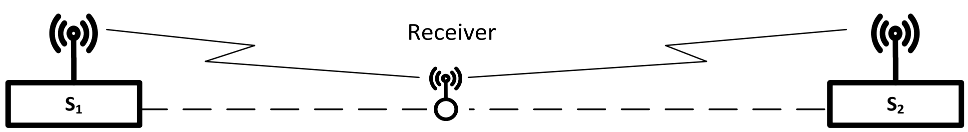


Figure 3-3 a diagram of a system having a receiver between signal sources

Now, assume the receiver is located closer to the signal source S_2 than to signal source S_1. Because the signal strength is reduced when the distance from the signal source increases, the amplitude of the received signal from source S_2 has a greater mean than the mean amplitude of the received signal from source S_2. So, the $p(S_2)$ probability of the signal detection, will be greater than $\mathrm{p(S_1)}$. Thus, there is a direct correlation between the overall probability of the colliding signal to be detected and its actual position between colliding sources.

As mentioned earlier, the amplitude of the transmitting signal is drifted with normal Gaussian distribution with the mean = 0 and variance σ^2 . Therefore, because of the random variation in received signal, in any given individual transmission cycle, there is a probability that signal R_1 will be received, so R_1 will be detected although its average amplitude is lower than average amplitude of R_2 because the receiver closer to S_2. Thus, the probability of this event however will be lower than the probability of R_1 detection according to equation 1 and 2. Since colliding sources (beacons) transmit on different power levels, hence amplitudes of the transmitting signals will not be equal. In this case, the amplitude value of each beacon has to be included in the final position calculation.

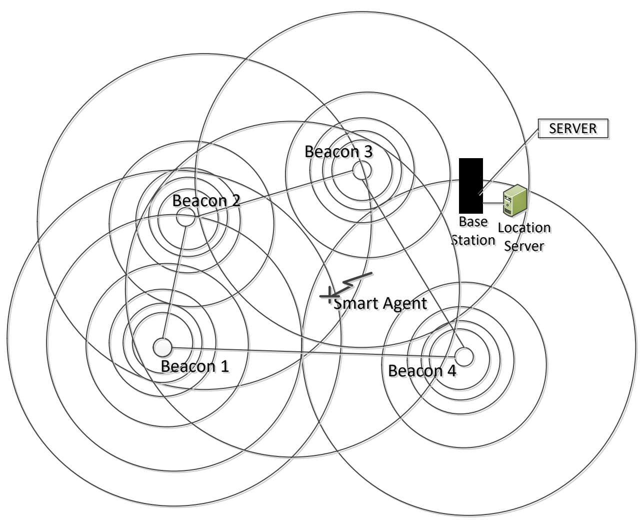


Figure 3-4 a location system having a plurality of colliding signal sources

Figure 3-4 is a schematic diagram of a system having a number of colliding signal sources, such as RF beacons 1-4, which produce colliding signals at the location of a receiver. The three dimensional geographical position of the receiver is in the “center of mass” of the three dimensional shape formed by the lines between the transmitting nodes, where the “mass” of each node will be defined as a total number of times the receiver has detected the signal transmitted by the specific node.

Assume that the number of colliding sources is n. The X, Y, Z coordinates of the receiver location can be calculated as described below (Braiman 2011):

$$X = \frac{\sum_{i=0}^{n}\left[\frac{Q_i^2 x_i}{r_i}\right]}{\sum_{i=0}^{n}\left[\frac{Q_i^2}{r_i}\right]},$$

$$(4) \quad Y = \frac{\sum_{i=0}^{n}\left[\frac{Q_i^2 y_i}{r_i}\right]}{\sum_{i=0}^{n}\left[\frac{Q_i^2}{r_i}\right]},$$

$$Z = \frac{\sum_{i=0}^{n}\left[\frac{Q_i^2 z_i}{r_i}\right]}{\sum_{i=0}^{n}\left[\frac{Q_i^2}{r_i}\right]},$$

where x_i , y_i , z_i are coordinates of the n^{th} colliding source ,or in other words, beacons (in meters). Q_n is the number of times a particular signal was successfully detected and r_n is maximum range of the an antenna coverage.

If the asset is constrained to move along a line segment, it is possible to determine the position of the asset using the method and system described herein with only two beacons. With three or more beacons, the location of the asset can be determined within a two or three dimensional region. In any given system, the stability of the location data increases when a larger number of measurements are collected. Generally, increasing the number of beacons and/or the number of frequencies for which each beacon broadcasts signals will increase the accuracy of the location determination. The number of measurements that are used to achieve a desired level of accuracy for any given system depends on the application, the level of accuracy desired, the number of beacons, and the number of frequencies for which signals are broadcast from each beacon. In some systems, three to five readings (for each frequency) is sufficient. If a large number of readings are collected, the distribution of the location data approaches a Gaussian distribution.

Application of the colliding localization method is further demonstrated with a lab testing example. Figure 3-5 shows the test layout of 14 m × 8m in which the squares on the corners represent beacons, and the circle in the middle denotes a tag receiver placed at the location (8, 4, 1) m. We assume that the location of the tag is unknown and needs to be determined. Table 3-1 shows the coordinates of the beacons, number of colliding signal successful detections at each beacon for the same r = 15 m for all beacons.

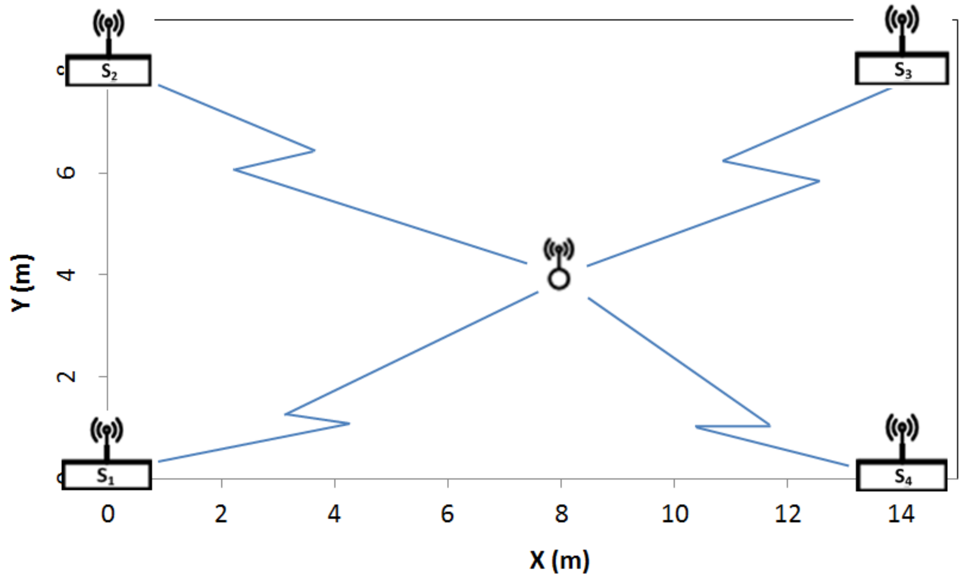


Figure 3-5 Experiment layout and nodes' distributions for colliding method

Table 3-1 Colliding measurements in the lab testing for r = 15m

Colliding measurements	Beacons			
	S_1	S_2	S_3	S_4
Beacons' coordinate (x,y,z) (m)	(0,0,1)	(0,8,1)	(14,8,1)	(14,0,1)
number of colliding signal successful detections (Q_i)	5	4	5	3

According to eq. (4), the geometric model of X coordinate for the testing can be rewritten as below

$$X = \frac{\frac{5^2 \times 0 + 4^2 \times 14 + 5^2 \times 14 + 3^2 \times 0}{15}}{\frac{5^2 + 4^2 + 5^2 + 3^2}{15}} = 7.65$$

In the same way, the Y and Z coordinate of the tag are calculated and so, the estimated coordinate of the target node can be determined.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 7.65 \\ 3.63 \\ 1 \end{bmatrix}$$

Comparing the estimated coordinates of the tag to the true coordinates of the tag (8, 4, 1) m, the localization error is 0.51 m, which denotes the Euclidean distance between the estimated and true coordinates.

3.3.2 Decay factor

As the pipe handling speed is much slower than foot speed and as the pipes stay in each workstation for a while, localization module operates by accumulating windows of events from the smart agent (tag), and choosing the best location statistically. The window count (in term of seconds) is specified in the iLocate server configuration, and can be different based on the smart agent motion status (in motion or static). When the first signal arrives, the beacon module creates a new window of events for the smart agent, and marks it's time as the time of the first event in it. Then, after inserting the newest event into a window, the beacon module checks if the window count is equal to the maximum window count. If it does reach the maximum window count, the beacon module proceeds to the next stage, and calculates the accumulative beacon count for each beacon cell in the windows of the current smart agent. The maximum window count is selected to be 10 for the experiment. Then, the Center of Mass is calculated, using the beacon cell locations and the calculated masses (Braiman 2011).

(5) $$Mass = f \,.\, e^{-r} .\frac{3\pi}{2} \,.\, c^2$$

where f is the decay factor (explained below), r is the cell radius and c is the event count from the specified cell, in all the windows.

The decay factor mechanism was added to the collider module (Braiman 2011) in order to weaken the mass of cells that are no longer relevant over time. Each cell has its own decay factor (mentioned above as f), which is the average of all the decays factors of all the windows that include an event from that cell.

The decay factor of a certain window is either 1, if decay has not started for the window, or $d^{t/i}$ otherwise, where:

d is the percentage that the decay factor is multiplied by, on every time unit (configurable).

i is the time interval that specifies the time unit mentioned above (configurable).

t is the time passed since the window time (the time the window began).

t / i specifies the number of time units passed since the window time.

Intuitively, the idea behind this formula is that the decay factor of a window is multiplied each time unit by d, allowing the user to configure how fast the decay happens. Additionally, there is a Minimum Decay Factor. If the decay factor for a window reaches the Minimum Decay Factor, the window is completely dropped.

3.3.3 Zone detection method

Since active RFID came to market, manufacturers have claimed that RFID would enable us to accurately localize objects with only three readers, using RF triangulation algorithms. After a number of years, however, it has become clear that this great promise is not so true and for indoor localization, a zoning-based approach provides far more reliable results than the respective triangulation-based methods, and at a cheaper cost.

Actual zoning entails allocating a reader to each zone, and tuning its gain in order to detect only those tags within that zone. The beacons periodically emit signals indicating the ID of the zone and the RSS values in which the tagged components are located. Tag searches a beacon once a second, thus, as soon as the tag receives any of the beacons, beacon's location is allocated to the tag and the tag is shown at the beacon's location on the asset tracking screen. Therefore, the tag location will be the last beacon position.

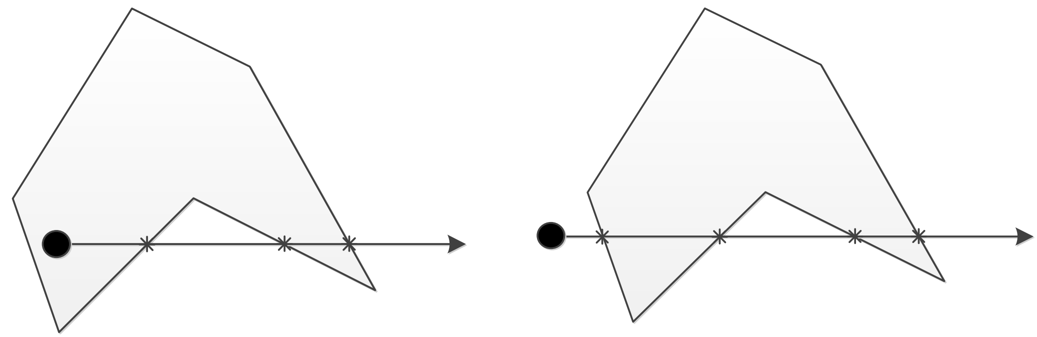
3.3.4 Combined localization method

In our proposed localization method in iPMF, zoning context is differently employed. In this method, beacon cell zones are real RF zones, which smart agents are able to read and report to the base station. For logical use and graphical representation of the smart agents in or out of zones on the user's screen, a beacon must be defined in the user application interface. In this way, a beacon is allocated to each working station and its actual location on the floor map is defined in the location server. According to the zoning method, the zone indicator (beacon power gain) can be tuned to reach only the tags in that particular zone. Though, in our method, its gain is tuned to cover the whole testing area instead of the particular zone. Rather, shop floor plan with its coordinates are loaded into the asset tracking interface and the topographical features of the zones (here working stations) are defined and delineated in the system. A single RF base station is installed and tuned to cover the large area of the fabrication shop, while the beacon devices are deployed within each individual station.

The beacons periodically emit signals indicating the ID of the zone and the RSS values received by the tags. Tag searches a beacon once a second under system coverage and once in every 5 seconds out of system coverage. The tag observes and measures RSSI (relative signal strength indicator) on all received RF links from surrounding beacons. If tag receives 2 beacons signals congruently, tag will report the first beacon it received. A location based application subscribes to zone-based updates by sending a respective request message to the location server. The request carries the zone definition, either in terms of geographical coordinates of the zone topography, e.g. as a circle or a polygon or symbolically, e.g. as a floor section.

Generally, in the majority of zone-based localization researches, a zone prediction method is combined with a positioning algorithm to calculate the location of the tag. In those studies, first the system identifies the zone in which the tag is located and then uses a positioning algorithm such as trilateration to determine the tag location inside the zone. Nonetheless, in the proposed localization method, first the colliding localization algorithms calculate the location of the tag. Since one beacon, whose location is known, is placed in and allocated to each working zone, the server then compares tag location to the location of beacons in the zones to find the closest beacon and thus the closest zone. Subsequently, point-in-polygon (PIP) (Haines 1994) is used to determine whether the tag is located inside or outside the zone. In computational geometry, the point-in-polygon (PIP) problem checks whether a given point in the plane lies inside, outside, or on the boundary of a polygon. It is a special case of point location problems and finds applications in areas that deal with processing geometrical data, such as computer graphics, computer vision, geographical information systems (GIS), motion planning, and CAD.

One definition of whether a point is inside a region is the Jordan Curve Theorem (Haines 1994). Essentially, it says that a point is inside a polygon if, for any ray from this point, there is an odd number of crossings of the ray with the polygon's edges (Figure 3-6.a). But if the point is on the outside of the polygon the ray will intersect its edge an even number of times (Figure 3-6.b). This test also works in three dimensions. Matlab toolbox is used to develop the PIP program for the working zones inside the pipe fabrication shop.



(a) (b)

Figure 3-6 a. Crossing test: Three crossings so point is inside; b. Crossing test: Four crossings so point is outside

At the location server, it is also checked whether the tag location correctly correspond to entering or leaving the zone. In that case, a position update is sent to the location server.

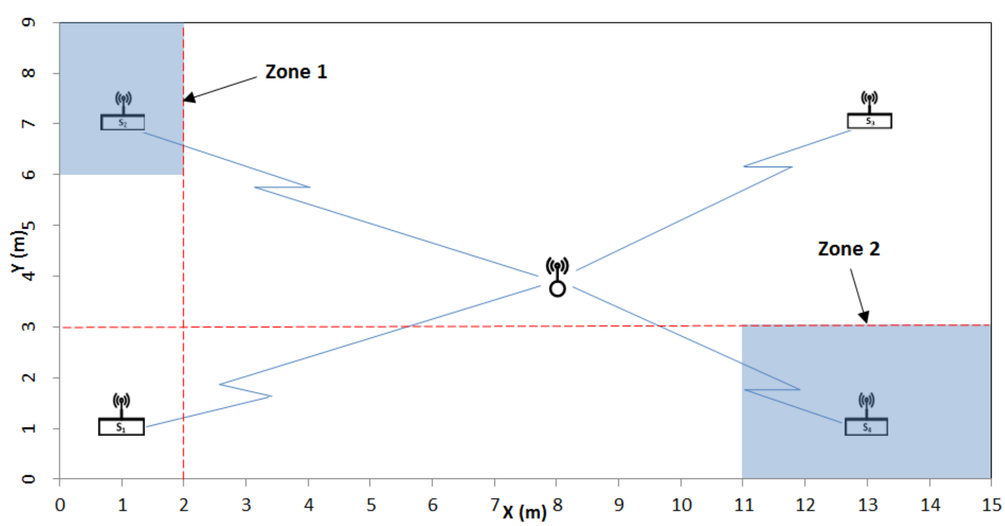


Figure 3-7 lab testing example

Application of the proposed method is further demonstrated with an example in Figure 3-7. Suppose that we have two zones of interest namely zone 1 and zone 2.

Beacon 2 is located in zone 1 and beacon 4 is located in zone 2. Geometrical parameters associated with floor plan and the zones are first fed to the system as prerequisite details. Table 3-2 shows the localization information. We assume that the tag is primarily placed at coordinate (8, 4, 1) (m). Number of colliding signal successful detections (Q_i) for this location are respectively Q_1=5; Q_2 =3; Q_3= 6, Q_4=4. Using equation 1, tag's location is estimated to be (8.26, 4.14, 1) (m). Thus, localization error is 0.29 m. Server then determines the distance of the tag's estimated location to beacon 2 and beacon 4. These distances are respectively 7.80m and 5.69m. Hence, the system concludes that beacon 4 is closer to the tag compared to beacon 2. PIP method is then employed which determines that the tag is located outside zone 2. Now suppose that the tag moved to the new location (12, 1.5, 1) m. With new numbers for signal successful detections (Q_1 = 3; Q_2 = 1; Q_4 = 6, Q_4 = 10), the new colliding estimated coordinate for the tag would be (12.05, 1.81, 1) m for which the localization error is 0.31m. The estimated distances of the tag to the beacons are now 12.21m and 1.25m. Hence, the system concludes that beacon 4 is still closer. PIP method then determines that the tag is now located inside zone 2. As soon as the tag passes zones' border, a position update is sent to the server. The proposed zone based processing will help us exclude deviated results due to condition changes in the environment.

Table 3-2 Localization information

Colliding measurements	**Beacons**			
	S_1	**S_2**	**S_3**	**S_4**
Beacons' coordinates (x,y,z) (m)	(1,1,1)	(1,7,1)	(13,7,1)	(13,1,1)
Zone 1 coordinates (x,y,z) (m)	(0,6)	(2,6)	(2,9)	(0,9)
Zone 2 coordinates (x,y,z) (m)	(11,0)	(15,0)	(15,3)	(11,3)
Number of successful detections (Q_i) at first location	5	3	6	4
Tag's estimated location(m)	(8.26, 4.14, 1)			
Distance to beacons(m)		7.80		5.69
Detected zone		NA		NA
Number of successful detections (Q_i) at second location	3	1	4	10
Distance to beacons (m)		12.21		1.25
Tag's estimated location(m)	(12.05, 1.81, 1)			
Detected zone		NA		Yes

3.4 Conclusions

This chapter explained the use of a collision-based indoor positioning system called collider for real-time localizing and tracking pipe spools and to support the integrated Project Management Framework (iPMF) developed for monitoring the pipe spool fabrication process. This framework integrates fabrication process planning and tracking with the drawings and document control system and the materials management system and allows its users to obtain information about the labour cost and production process.

The decay factor mechanism was added to the collider module in order to weaken the mass of cells that are no longer relevant over time. In the proposed combined localization method, first the colliding localization algorithms calculate the location of the tag. Since one beacon, whose location is known, is placed in and allocated to each working zone, the server then compares tag location to the location of beacons in the zones to find the closest beacon and thus the closest zone. Subsequently, point-in-polygon (PIP) is used to determine whether the tag is located inside or outside the zone. Application of the proposed localization method is further demonstrated with lab testing examples.

CHAPTER 4

4 System Evaluation: Test results and discussion

4.1 Introduction

This chapter presents the system validation and provides details of a series of experiments that were conducted in the fabrication shop of the partner company. The chapter starts with a brief introduction and review of the concept of the industrial pipe spool fabrication and operation and highlights the typical processes that are generally employed in the fabrication shops. It is then followed by a detailed discussion of a dynamic error test that was conducted in the fabrication shop for tracking and localizing pipe and fittings to evaluate the accuracy and reliability of the proposed localization methodology. The results of the experiments are then analyzed and discussed. After validation of the positioning system, the proposed spool component tagging strategy is presented, which depends on the fabrication method and sequence. The applicability of the iPMF framework to the industrial labour data collection is investigated through a number of experiments conducted in the same fabrication shop. In the end, the experiment measurements are analyzed to simulate the feasibility of the iPMF in tracking actual labour-hours.

4.2 Pipe Spool Fabrication

Pre-fabrication is generally a manufacturing process taking place at a specialized facility in which various materials are joined to form a component part of a larger item. Any component that is manufactured off site and is not a complete system can be considered to be pre-fabricated (Taghaddos et al. 2012). A module assembly yard is usually located near the spool fabrication facility, where pipe spools and structural steels are fabricated indoors. Figure 4-1 displays a typical pipe spool fabrication shop.

Figure 4-1 Pipe spool fabrication shop

The operation of pipe spool fabrication typically includes the following steps: cutting, fitting, welding, quality control, stress relief, hydro testing, painting and other finishing. Fabrication of pipe spools shall be in accordance with the piping isometric drawings. An isometric drawing for a piping system is a detailed orthographic drawing. The isometric drawing represents the details of the 3D structure of the pipe in the form of a 2D diagram. A pipe spool is a collection of pre-assembled pipe and fittings, usually prepared in a shop so that installation on the module yard or the construction site can be more efficient. When the shop drawing for the spool is issued to the shop, it will be either fabricated as is or split into smaller subassemblies, which will be then fabricated into the isometric pipe spool.

The design stage includes piping and instrumentation diagram, 3D modeling and isometric-drawing. The piping and instrumentation diagram lists pipe size, location, material, surface treatment, fluid types and pressure. Constructability and inference checks are made using 3D models and construction drawings are made based on the models. The bill of materials is produced from the design, which is passed to the material vendors. Spool components such as pipes, fittings, flanges, gaskets, valves and fasteners are then delivered to the fabricator and stored in a 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.

Welding is performed via two methods (Hu 2013): 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. Welding process can be divided into three major categories: Butt weld, socket weld and olet weld. A butt weld is where the diameter of the pipes welded together are the same, while a socket weld is where a larger diameter pipe is fitted into a smaller one. Olet is the type of fitting used to create a branch with the smaller size of main pipe.

Assemblies may move between fitting and 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 4-2.

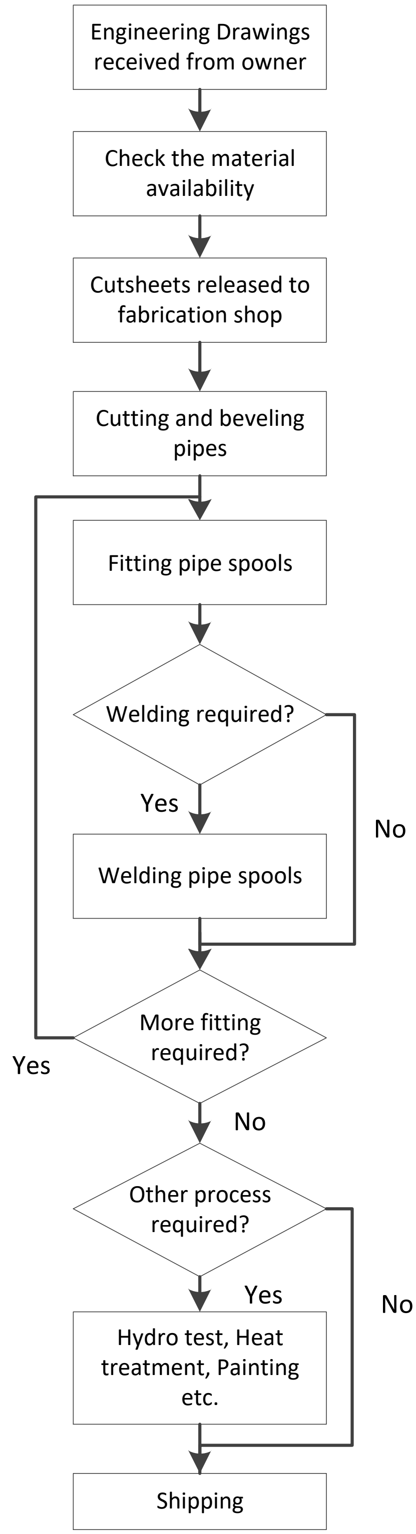


Figure 4-2 Pipe spool fabrication process

4.3 Localization System validation and progress monitoring

Figure 4-3 Experiment area in the fabrication shop; Cutting, Fitting, Welding and Handling

To evaluate the accuracy and reliability of the proposed localization methodology and its capability to monitor the fabrication work progress, a dynamic error test was conducted in the fabrication shop for tracking and localizing pipe and fittings that frequently travel from one location to another. Experiments were conducted at a pipe fabrication shop near Edmonton, Alberta. Figure 4-3 shows the test area selected for conducting the experiment. Four beacons were placed at one fitting and three welding stations (Figure 4-4). The configurations of these working stations with the actual coordinates of the beacons were defined in the server. This information was also loaded into the asset tracking interface in order to delineate the zones. Twelve pipes with their fittings were tagged outside the fabrication shop. Pipes were moved to fitting stations to be joined together. Once the pipes and other components of the spool were fitted, overhead cranes were used to move the assemblies to the welding stations. Depending on the job, assemblies moved between fitting and welding stations.

The beacon read range is usually limited by metallic and non-metallic obstacles placed in the environment. In the fabrication shop, beacons had the transmission power set to give a range about 40 meters to cover the entire working environment. This tag and beacon readability range was confirmed through a simple test inside the fabrication shop. RF base station (the RF transceiver) was used to synchronize both the beacons and the receiving tag to the system clock, as well as receive the final data sent by the tag for further processing by central processor. Each base station unit is connected to a data communication module comprising client and server units.

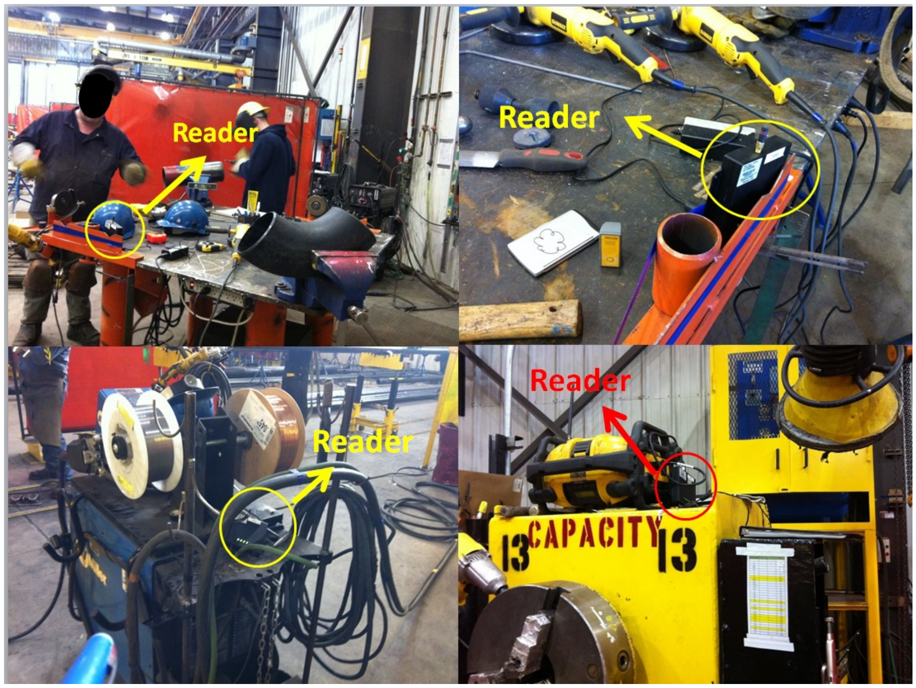


Figure 4-4 beacons placed at one fitting and three welding stations

As each tag emits an RF signal, location was calculated using the proposed integrated localization method (signal colliding, and zoning as described in the previous chapter).

Once position data was obtained, the raw data was analyzed and the location was corrected by the Kalman filter (Hu et al. 2003). Comparison between the system readings and the known locations of the pipes and fittings in the stations were analyzed to find the level of accuracy of the positioning system. Figure 4-5 demonstrates the shop layout and the workstations along with a graphical representation of a sample pipe spool located in the fitting station (green circle). Figure 4-6 presents the frequency histogram and cumulative frequency diagram of the resulting localization errors for the tracked tag.

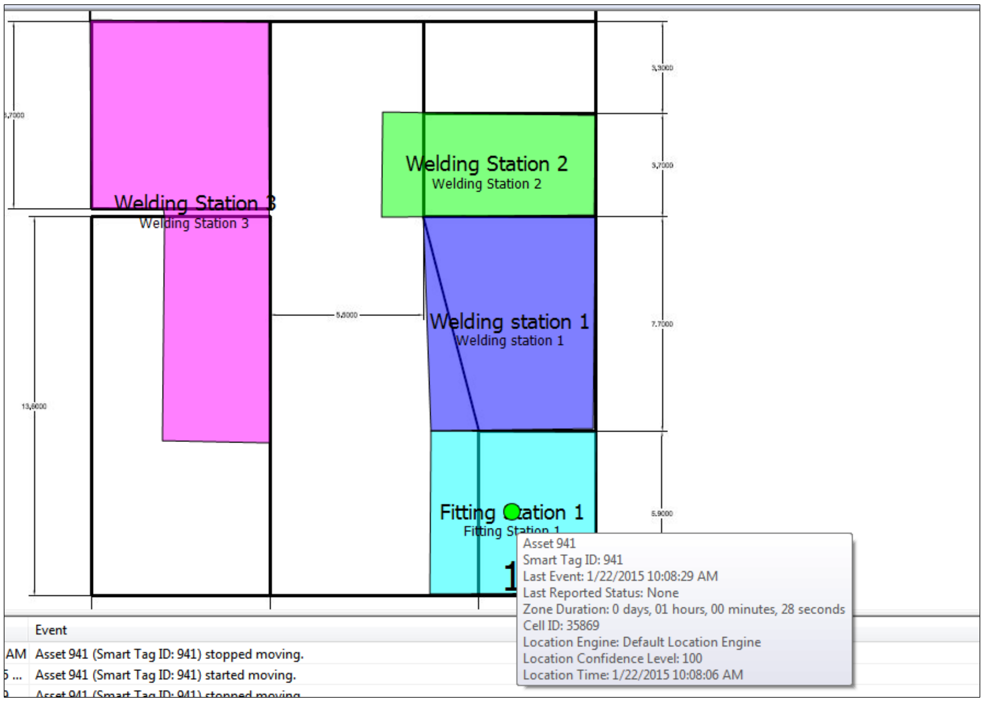


Figure 4-5 Experiment layout inside the fabrication shop with estimated location of sample pipes inside the station

Table 4-1 shows the summery of the test results for a sample size of 39204. Statistical analysis shows that normal distribution can be fitted to the data with μ=0.96 m and α = 0.55 m. To construct a 95% confidence interval estimate of the mean, α=0.05 was selected. Experiment results indicated that colliding method with employing decay factor is able to locate the components in the fabrication shop with average accuracy of 0.96 m, the standard deviation of the errors being 0.55 m. The 95th percentile is 1.69 m, which implies with 95% likelihood, the tag's position can be fixed within 1.69 m of its actual position in the shop. The common practice of all the location technologies, when operating in harsh environment, is that the location jumps due to bouncing of RF from all the metal, concrete and other non RF friendly materials. Therefore, the best way will be to show median, since average may be affected by some rare jumps that can be filter out. The median for the experiment results is 0.93 m and its proximity to the average indicates there was no jump in the positioning results.

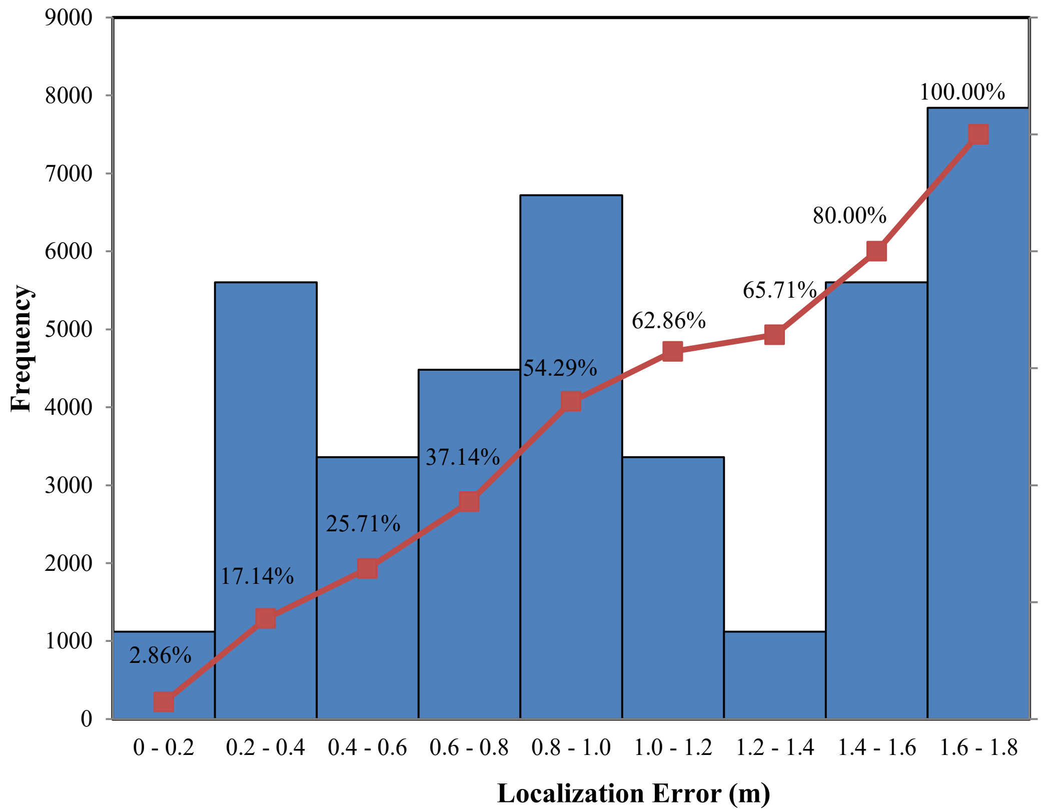


Figure 4-6 Frequency histogram and Cumulative frequency diagram of the resulting localization errors

The final positioning results from coupling the colliding method with the Kalman filtering algorithm demonstrate that the average localization error and the standard deviation can be reduced from to 0.55 m and 0.29 m, respectively. The 95th percentile is also reduced to 0.94 m, which implies with 95% likelihood, the tag's position can be fixed within 1 meter of its actual position in the shop.

Table 4-1 Summary of the evaluation test

Localization method	Sample standard deviation	Sample mean	Median	95 Percentile
Colliding method	0.55 m	0.96 m	0.93 m	1.69 m
With Kalman filter	0.29 m	0.57 m	0.61 m	0.94 m

Practically speaking, beacon readers deployed using the proposed zone-based system, along with colliding method and Kalman filter can warrant high percentage accuracy in tag localization. Their installation is very simple and requires no infrastructure, other than a network connection between them and power supply for each beacon. The RF based zone localization can provide an accuracy level as the application requires. The test results indicated that combining the zone localization with colliding method and Kalman filter can provide an average accuracy location down to half meter. These results show that the system is practically able to collect labour-hour data with sufficient accuracy by correlating location and timing of the spool pieces with fabrication activities.

Time	Smart Tag ID	Event Type	Smart Tag RSSI	Bridge Port RSSI	Beacon Name
1/22/2015 9:56:36 AM	941	Periodic Transmission	-72 dBm	-70 dBm	Fitting Station 1 - 35869
1/22/2015 9:57:06 AM	941	Periodic Transmission	-70 dBm	-74 dBm	Fitting Station 1 - 35869
1/22/2015 9:57:35 AM	941	Periodic Transmission	-69 dBm	-75 dBm	Fitting Station 1 - 35869
1/22/2015 9:58:06 AM	941	Periodic Transmission	-72 dBm	-73 dBm	Fitting Station 1 - 35869
1/22/2015 9:58:35 AM	941	Periodic Transmission	-74 dBm	-75 dBm	Fitting Station 1 - 35869
1/22/2015 9:59:06 AM	941	Periodic Transmission	-72 dBm	-71 dBm	Fitting Station 1 - 35869
1/22/2015 9:59:35 AM	941	Periodic Transmission	-70 dBm	-71 dBm	Fitting Station 1 - 35869
1/22/2015 10:00:06 AM	941	Periodic Transmission	-69 dBm	-70 dBm	Fitting Station 1 - 35869

Figure 4-7 Fabrication progress monitoring interface

At many construction projects, progress monitoring is very much neglected despite the fact that it is much desired by the owners. Progress monitoring enforces the requirements stated in a construction contracts by tracking construction time, ensuring that milestones are met, and coordinating activities on site. One reason construction process is not traced more closely is that it still takes a large amount of effort to collect status and progress data on site and process it. It is desirable to have a tool that enables the project control manager to measure the construction progress efficiently. Marking construction progress in a drawing and translating or transferring this data into a progress measurement system or figure is not an efficient system. New technologies such as data collection systems and wireless networks could provide the updated changes and the impact new progress of an updated element has on the progress of the single activities or the overall project.

With the availability of the pipe spools' location and job status and labour-hours, progress monitoring could be another feature of the iPMF that can help to make the data for supporting decisions available. Figure 4-7 demonstrates a snapshot of fabrication progress monitoring interface for Location server and client. The real-time data acquisition system generates raw data such as date of the event, ID of the tagged workpiece, workstation, etc. Performance data, such as current zone each piece or an incomplete spool is located in, man-hours spent on each task, project percent complete, and production rate and so on can be extracted from these raw data. Interpretation of these raw data can be automated by correlating location and timing of the spool pieces with fabrication activities. The following sections will explain this process.

4.4 Tagging Strategy

Sensor technologies can provide increased efficiency, security and visibility into a company's business processes, and make a firm more profitable-but only when implemented smartly. It is also very important to develop a plan for the tagging, de-tagging and re-tagging events in conjunction with fabrication or construction process planning. The tag must be attached, detached and read at the right time in each stage. Unique design and configurations of pipe spools cause the fabrication sequence to vary from one pipe spool to another. Since most fabrication operations (e.g. cutting, fitting and welding) involved are similar, the variation mainly lies in the sequence of these operations.

The fabrication sequence determines steps that pipe spools go through from raw materials to the final product. As mentioned earlier, pipe spools are fabricated from a number of raw pipes and pipe fittings (e.g. elbows, flanges, tees, etc.) in fabrication shops. Raw pipes are cut to the required sizes and moved with pipe fittings to a fitting table, where some of the components are fitted together (i.e.

temporarily connected). The resulting sub-assembly (part of the final pipe spool) continues with welding operations (i.e. permanently connected) before it comes back to the fitting table and gets fitted with other spool components.

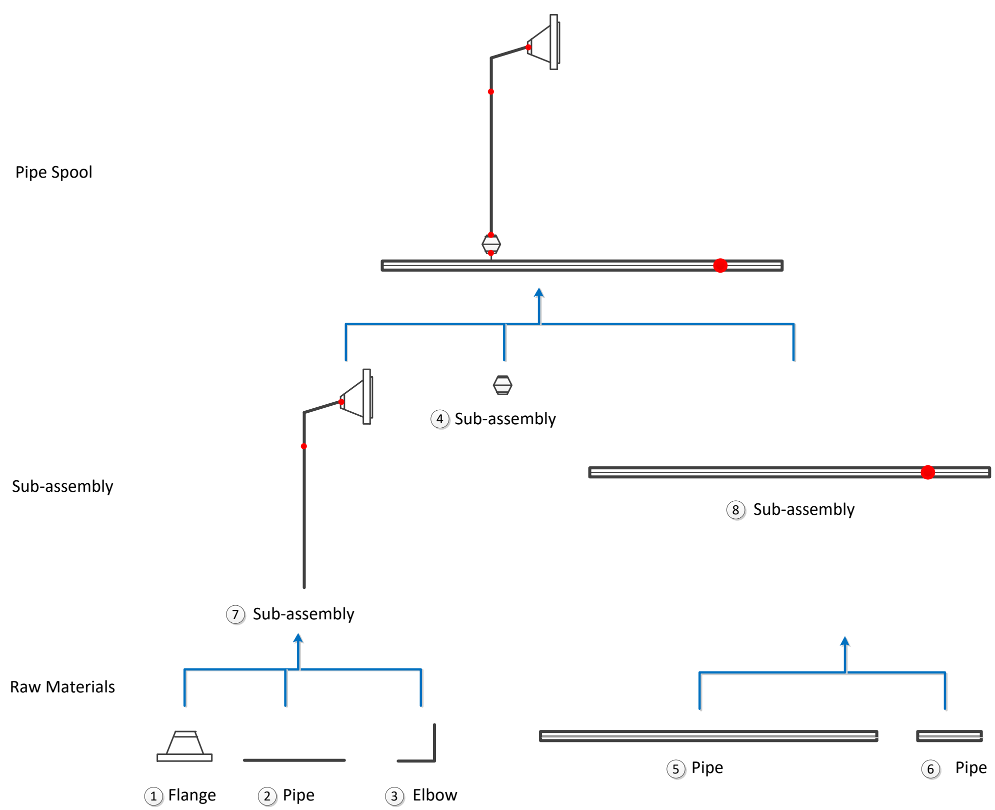


Figure 4-8 Pipe spool fabrication sequence

Figure 4-8 shows an example of a pipe spool with relatively simple configuration. Each fabrication step represents a pair of a fitting operation and a welding operation. Fabrication steps depicted in a vertical direction have to be performed in a sequential way (i.e. the final pipe spool cannot be produced before subassembly 7 and 8 are fabricated), while processes depicted on the same horizontal level can be performed concurrently (i.e. sub-assembly 7 and sub-assembly 8 can be performed independently). In tagging plan, pipes and pipe fittings are all tagged in the cutting station before they are moved to the fitting station. Depending on the fabrication requirements, the tagging plan might be different. Though, as a general rule, one tag is removed when two pieces are joined. The remaining tag records the fitting, welding and handling durations.

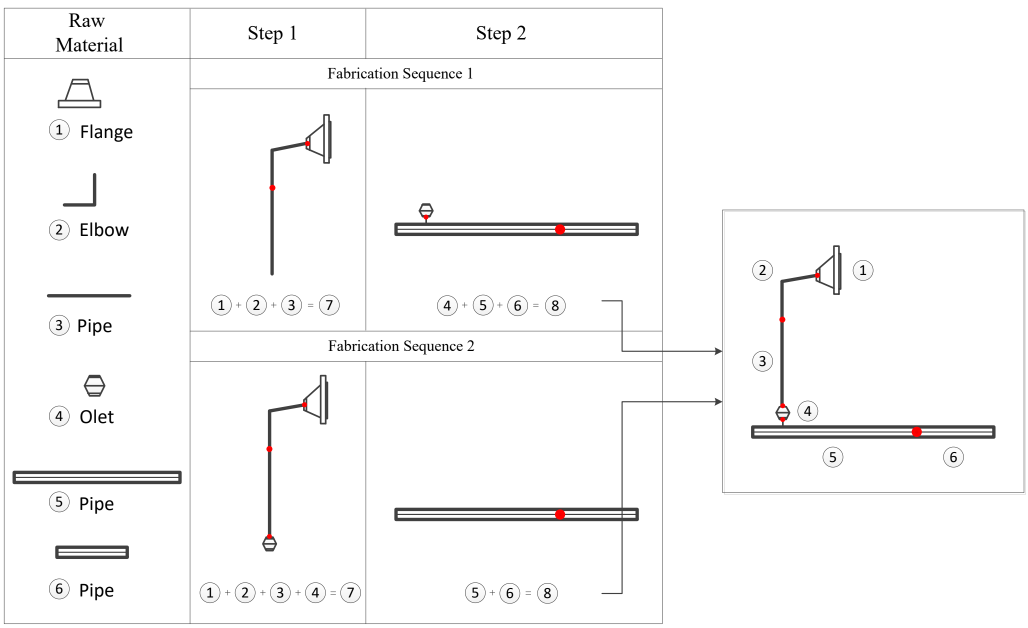


Figure 4-9 Pipe spool fabrication alternatives

Figure 4-9 shows that the pipe spool can at least be fabricated by two different sequences from the same raw materials. Both fabrication sequences require two operations to produce the final product. Moreover, handling is needed between these operations. The tagging plan is developed for the two possible fabrication sequences and is given to the fabrication shop workers with the design drawings and cut sheets.

4.5 Field testing and evaluation of integrated Management Framework (iPMF)

Experiments were conducted at the same pipe fabrication shop shown in Figure 4.3 with the same setup. The objective of this test was to simulate the feasibility of the pipe spool monitoring system to identify the work progress and labour-hours for each task of fitting, handling and welding of pipe spools. The work-package selected for the experiment included 8 engineering drawings with thirteen 6” pipes, one 3” pipe, one 2” pipe, twenty three butt welds, three olet welds and four socket welds. This work package was selected from an ongoing mega project called Hangingstone Expansion Project in Fort McMurray, Alberta. The tags were attached to each spool component after being cut. The ISO drawings were also tagged since reading the drawings itself is considered as a productive part of the fabrication tasks. The Asset management components of the Asset Tracking server was used to introduce pipes, fittings and welds into the database, associating the assets with the unique ID of the tag attached to it.

Pipes were moved in the planned order determined by the foreman and fitters to fitting stations with other spool components to be joined together. Once the pipes and other components of the spool were fitted, overhead cranes were used to move the assemblies to the welding stations. Assemblies moved between fitting and welding stations a couple of times until the spool was completed. This process is explicitly explained in the next chapter. As described earlier in chapter 3, iPMF is expected to automatically collect real-time data about process progress and labour-hours information related to all three fabrication tasks and labour activities inside the fabrications shop. In order to mimic this process, actual data of the labour-hours was collected manually by observing the fabrication activities to simulate labour-hours data that can be collected automatically by iPMF in order to demonstrate its value proposition.

Table 4-2 Actual cumulative labour-hours for the welding tasks of the work-package

Items	Quantity	Actual man-hours
3" Butt-Weld Sch 40	2	3.42
6" Butt-Weld Sch 40	18	25.95
2" Butt-Weld Sch 80	3	3.08
.75" Socket Weld 3,000# Sch 160	4	1.48
.75" Olet Weld #3,000	2	2.17
2" Olet Weld Sch 80	1	1.75
	Total man-hours	**37.85**

Table 4-2 demonstrates the actual cumulative labour-hours for the welding tasks of the work-package. It is noteworthy that the labour content of these items for welding pipework also include activities such as the preparation, beveling of the pipe ends, together with any subsequent grinding, fitting etc. Therefore, collected values incorporate them all. iPMF system can potentially serve the needs of tracking spool components within a typical work zone inside the fabrication shop and the labour-hours in connection with handling and connecting those components into the final spool. The fabrication of sample pipe spools in the experiment work-package were chosen as the case studies , and was described in the next chapter to illustrate the processes in iPMF to provide the actual labour productivity norms for the partner company.

4.6 Conclusions

This chapter presented the system validation and provides details of a series of experiments that were conducted in the fabrication shop of the partner company. A dynamic error test was conducted in the fabrication shop for tracking and localizing pipes and fittings to evaluate the accuracy and reliability of the proposed collision-based localization methodology explained in chapter 3.

The test results indicated that combining the zone localization with colliding method and Kalman filter can provide an average accuracy location down to half meter. Practically speaking, beacon readers deployed using the proposed zone-based system, along with colliding method and Kalman filter can warrant high percentage accuracy in tag localization. These results showed that the system is practically able to collect labour-hour data with sufficient accuracy by correlating location and timing of the spool pieces with fabrication activities.

The applicability of the iPMF framework to the industrial labour data collection was simulated through a number of experiments conducted in the same fabrication shop. Actual data on the labour-hours was collected manually by observing the fabrication activities to simulate labour-hours data that can be collected automatically by iPMF in order to demonstrate its value proposition. In the end, the experiment measurements were analyzed to simulate the feasibility of the iPMF in tracking actual labour-hours. In next chapter, the detail of data analysis is presented.

CHAPTER 5

5 Experimental case studies

5.1 Introduction

This chapter includes the results and discussion of a real-world case study, the fabrication of eight pipe spools that form the experiment work-package, which was carried out to verify the feasibility of the implemented iPMF in terms of providing the actual labour productivity norms for the collaborating partner company. The details of the experiment were explained in previous chapter. An overview of common practices for estimating the cost of industry pipe work is presented in the first part of this chapter. Subsequently, a parametric study is conducted to calculate the labour productivity norms and adjusting factors. In the end, the process of project performance assessment in iPMF is presented.

5.2 Industrial Piping Cost estimation

Calculation of piping man-hour is a very complicated task. Many factors have to be considered in order to arrive at the correct amount that will ensure the contractor will account for all the costs in the contract and meet the required target completion date on implementation of the job. A piping estimator is required to have knowledge in s regarding piping works so that the contractor can do the job as expected, without errors that may cause large cost overrun or job delays. In estimating piping man-hours, it is necessary for the piping estimator to know all the tasks and activities needed to complete the job. Piping estimation will require not only his or her piping job site experience but also his or her expertise in doing all kinds of piping calculations. The estimating, planning and scheduling can be very challenging if the contractor does not know any correct or reasonable norms to base their estimate or schedule on. Unreasonable labour-hour estimate would also be reflected on schedule and unattainable deadlines would start to appear during the progress of the project. Therefore, there is a definite need for developing an efficient system that can process data associated with pipe configurations, the type of work involved in their preparation, and the labour-hours required to perform this task.

5.3 Use of norms in cost estimation

In compiling the unit rates in a tender the contractor‘s estimator usually utilize a set of 'norms' or standard productivity outputs, to assess the unit costs for labour (Davison 2008). These norms will most often be sets of data compiled by the contractor's staff from their own experience, or from data recorded on similar projects undertaken by the contractor or from the published books of norms or pricing information.

The difference between a productivity norm and a unit-rate is that there are no costs involved in a productivity norm, only hours. This makes it more usable for different industries and practices because costs are very much related to volumes, economic circumstances, availability, taxes, and etc. Labour productivity norms can easily be calibrated to the local circumstances by applying location factors.

These norms do not fluctuate with the economic environment and are fairly stable over time.

These norms will underpin the labour element of the unit rates and prices in the estimate. In most building and civil engineering estimates the norms will not be apparent from the unit rates, as composite rates are provided for each item. It is commonplace, however, in estimates for many heavy mechanical engineering works and process type projects, for the contract bills to have two 'price' columns, one for the monetary value and the other for the number of labour-hours contained within the item. Alternatively separate columns may be provided for labour pricing. In such estimates there is therefore an indication of the labour content of each item, which can be used to produce a reasonably accurate assessment of the for that item, although the items may require more than one labour activity and therefore include more than one norm. For instance, the labour content of an item for welding pipework might include activities such as the preparation, beveling of the pipe ends, together with any subsequent grinding, fitting etc. There may be norms available for these individual activities separately but the item will incorporate them all.

There is a large range of published information that provides the unit rates and prices including the labour-hour content for construction estimation. These publications range from the price books for building and civil engineering works, to books of norms for industrial and mechanical engineering works. For industrial works, there are industry recognized books of norms such as the *Estimator's*

Piping Man Hour Manual (Page and Nation 1999) and the *Cost Estimating Manual for Pipelines and Marine Structures* (Page 1999), both published by Gulf Publishing and often referred to collectively as the 'Gulf Norms' or by the names of the authors 'Page and Nation'. *Richardson's Process Plant Construction Estimating Standards* is often referred to as Richardson. Each of these sources differs in the manner in which the work hours are developed from piping quantity. However, when all work hours are totaled from the various detailed calculations, the estimates are supposed to be directly comparable.

The overriding principle when using such information in connection with any particular project is that they should not be regarded as directly applicable without careful consideration of the basis of the published data as compared to the circumstances of the particular project. As an example, Page and Nation is a commercially available labour productivity norms standard considered by many to be reflective of "Gulf Coast" labour productivity. It is based on numerous time and method studies both in the shop and field on many piping jobs located on projects in the US, ranging in cost from $1,000,000 to $5,000,000 (Van Vliet 2011). Labour is the most important element and the most difficult cost to predict in an estimate.

According to John S. Page (1999), the most important area to be considered before calculating labour costs is productivity efficiency factor. This is a required if the many labour-hour tables are to be correctly applied. Productivity efficiency factor in conjunction with the production elements must be considered for each individual project. By carefully analyzing many reports he has established an average productivity rate of 70 percent. All the labour-hours or percentages in the manual are based on this percentage. The Page and Nations publication lacks many of the elements required for a comprehensive understanding of each individual labour productivity norm (Davison 2008).

Page and Nations system includes the productivity factors in the labour productivity norms. So this means, for example, the estimator will need to measure and apply different location and other adjustment factors to the labour productivity norms. Adjustment factors are generally applied based on experience alongside rule of thumb guidelines in practice (Lu 2001).

5.4 Current Best Practice

The costs of process industry pipe work are usually sub-divided as below:

- Piping design and engineering: The cost of design work associated with the pipe work including layout studies, scheming, analysis and detailing.
- Materials: The cost of all procured materials, i.e. pipe flanges, fittings, valves, expansion units, etc.
- Fabrication: The cost of site fabrication, off-site fabrication, done in a shop away and adjacent to site.
- Erection: The cost of erecting on-site fabricated pipe work and pressure testing. This includes preliminaries, variation orders and error rectification if any.

In this study, we focus on the cost estimation of pipe fabrication. The contents of fabrication cost estimation include cut ends, beveling, pipe handling and welding. There is no norm available for fitting activity separately, but it is incorporated in welding item. Estimates are developed by populating a Material Take Off (MTO) and Work Breakdown Structure (WBS) with labour-hours for all spooling operations. MTO is a term used in engineering and construction, and refers to a list of materials with quantities and types (such as specific grades of steel) that are required to build a designed structure or item. This list is generated by analysis of a blueprint or other design document.

The piping labour-hour estimation is made up of a number of estimating process and elements. There are three types of methods used for piping labour-hour estimation (Chugh 2016) including: Piece by piece method (Detailed costing), finagling factor (a percentage of total cost of the project) and Dickson N system. The first requires picking of each length of pipe with its fittings, valves and welding points and pricing the labour costs in detail, then adding them all up for the total cost. The second consists in taking a percentage of the total cost of a project as the cost of the piping. This percentage which is also referred to as the "finagling factor," is supposed to be around 40 percent. The Dickson N system method or N system is based on the fact that the costs of strings of pipes of different sizes but of the same material and class of pipe have constant relations to each other. In order to use the N system, first the cost of the reference sizes of the strings of pipe is calculated. Then the N factors are used to get the cost of the same string in the required size. The N system was first introduced by R.A. Dickson in chemical engineering (Dickson 1947).

To estimate the cost of the major piping systems, a combination of the two well-established methods by the chemical industries, Piece by piece method and N system is typically employed by estimators. In this method, it is required first to consult the available tables from the norm books which provide the factor for the cost of the Nominal Pipe Sizes (NPS) of the pipe and fittings in man-hour. Then use the factors to get the cost of the same element in the required quantity. The cost data can then be "factored" to the date of use based on historical data or by using the available cost variation indexes. There are usually individual tables available for pipe handling, welding, bolt-up, valve handling, etc. Nipples and elbows are treated like pipes and the same table for the pipe handling is used for the cost estimation of nipple and elbow handling. Nominal Pipe Size (NPS) is a North American set of standard sizes for pipes used for high or low pressures and temperatures. Pipe size is specified with two non-dimensional numbers: a nominal pipe size (NPS) for diameter based on inches, and a schedule (Sch.) for wall thickness. Schedule, often shortened as sch, is a North American standard that refers to wall thickness of a pipe or pipe fitting. Higher schedules mean thicker walls that can resist higher pressures. Pipe standards define these wall thicknesses: SCH 5, 5S, 10, 10S, 20, 30, 40, 40S, 60, 80, 80S, 100, 120, 140, 160, STD, XS and XXS. (S following a number is for stainless steel. Sizes without an S are for carbon steel). Higher schedules are heavier, require more material and are therefore more costly to make and install.

This takeoff system is more efficient than the piece-by-piece, and more accurate than the "finagling-factor" system, the two methods ordinarily used by estimators. For example, the required man-hour for handling a 12 meters pipe 6" Size with sch 40 will be:

Total Man- Hour = Quantity (Length of Pipe in foot) × MH per Foot (Factor from Page & Nation norms table) × = 12 m × 3.28 ft. /m × 0.051 MH/ft. = 2.01 MH

This cost can then be "factored" to the date of use based on historical data or by using the available cost variation indexes. For instance, if for a particular company, the fabrication location factor is 1.5 then the total man-hours for the above mentioned pipe will be:

Total Man- Hour (To Date) = 2.01 MH × 1.5 = 3.2 MH

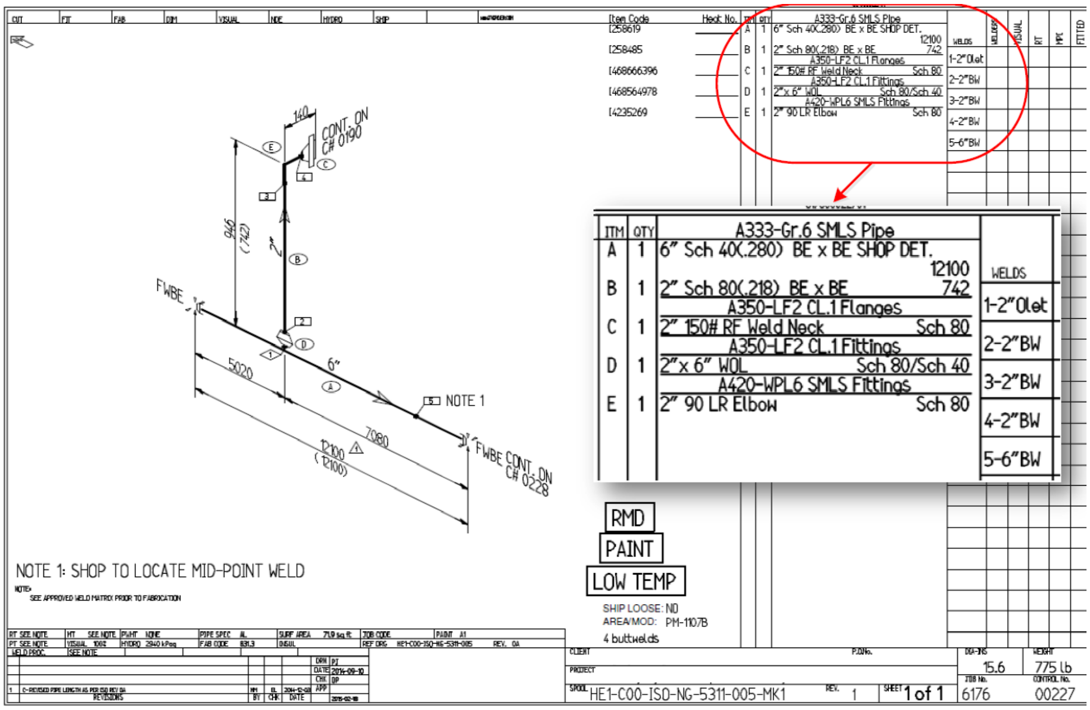


Figure 5-1 ISO drawing for the sample pipe spool (Hangingstone Expansion Project)

The following example will illustrate the current cost estimation practice for a sample pipe spool using the combined method. Figure 5-1 shows the typical ISO drawing for the pipe spool which was prepared for Hangingstone Expansion Project in Fort McMurray, Alberta. To estimate the required man-hours for the activities, first the take-off for the fabrication activities and their corresponding quantities for the pipe spool are identified from the information on the ISO drawing. The N Factors, or in other words labour productivity norms, (MH/Per Unit of measure) are derived from norms tables in *Estimator's Piping Man Hour Manual* (Page 1999). To calculate the labour-hour, the quantities are then multiplied by the N Factor. Table 5-1 demonstrates this process.

Table 5-1 The estimates process for the sample pipe spool fabricated in the shop

Item	Size (in.)	Wall Thickness (Sch)	Quantity	MH/Per Unit of measure (N Factor)	Total Man-Hours
Pipe handling	6	40 (0.280)	12.1 m (39.7 ft)	0.051/ft	2.02
Pipe handling	2	80 (0.218)	1.1 (3.61 ft)	0.044/ft	0.16
Bevel End	6	40 (0.280)	2	0.23	0.46
Cut End	6	40 (0.280)	1	0.29	0.29
Olet Weld	2	80 (0.218)	1	4.2	4.2
Butt Weld	6	40 (0.280)	1	1.80	1.80
Butt Weld	2	80 (0.218)	2	0.90	1.80
Weld-neck flange	2	80 (0.218)	1	1.05	1.05
			Total Man-hour for the spool		11.78

5.5 Case studies

This case study, the fabrication of eight sample pipe spools in the experiment work-package, was carried out to verify the feasibility and accuracy of the implemented iPMF to provide the actual labour productivity norms for the partner company. In this section, the piping man-hour estimation is illustrated using man-hour tables in *Estimator's Piping Man Hour Manual* (Page 1999). Actual labour data was collected manually by observing the fabrication process for two fitters and one welder at each station and two handlers. The actual labour data along with the analysis are illustrated for each pipe spool in the following sections. In order to practice the tagging strategy, tagging plans were developed which are explained in the remaining of this chapter for each pipe spool. The report is customized to track any spool as it travels from drawing release to final inspection. Isometric drawing of the pipe spools are drawn in AcornPipe software (Acornpipe 2016). The original ISO drawings for the spools can be found in

Appendix 1. The drawings are the key to all fabrication controls and tracking production status through the fabrication. One Spool is put per drawing as this will be the only way to track individual spools. All tracking records are generated by drawing. For example it will not be possible to issue part of a drawing for fabrication. Pipe specs on the ISO drawing indicates the pipe size, dimensions, material, wall thickness, type of weld and weld point. Each weld will display all information needed for complete traceability.

As with all welding, one of the first and most important steps is the preparation of the materials to be welded. It will start by preparing the ends of the pipe so that it meets the requirement of the welding procedure. Tack welding, a necessary preliminary step in many welding projects, must also be performed correctly to achieve optimal results from the final weld and to minimize part defects. Quality is as important in tack welding as it is in the final weld. After items to be welded together have been positioned as required, generally by clamping them on suitable fixtures, tack welds are used as a temporary means to hold the components in the proper location, alignment, and distance apart, until final welding can be completed. In short-production-run manual welding operations, tack welding can be used to set up the work pieces without using fixtures. Typically, tack welds are short welds. In any construction, several tack welds are made at some distance from each other to hold edges together. In general, tack welding is performed by the same process that is used for the final weld. For example, aluminum-alloy assemblies to be joined by friction stir welding are tack-welded by the same process using a small tool developed for this purpose. Tack welding is real welding; hence fitting man-hour is incorporated in welding man-hour.

There are many different pipe and fitting standards to be found worldwide. To allow easy functionality and inter-changeability, these are designed to have standardized dimensions. Common world standards include ASA/ANSI/ASME (USA), PN/DIN (European), BS10 (British/Australian), and JIS/KS (Japanese/Korean). As stated on all the ISO specifications, the pipe spool is made of ASTM A333 grade 6 seamless carbon steel material which is used for low temperature service applications. It covers seamless and welded steel pipe for use at cold temperature service up to minus 50° F (minus 45° C).

5.5.1 Pipe spool No. 1

Figure 5-2 shows the Isometric drawing of this pipe spool. The pipe spool comprises one 2" olet weld (weld point 1), three 2" butt welds (weld points 2, 3, 4) and one 6" butt weld (weld point 5). The pipe specs shows that Pipe A's schedule (wall thickness) is 40 and Pipe B's schedule is 80 and both need beveling (shown as BE×BE). Pipe B should be attached to flange (C) from one end through a 2" - 90 degree elbow (E) and to a 6" pipe (A) from the other end through a 2" olet (D). Pipe A's length is 12.1 meters. Coupling is thus used to join two smaller pipes in a straight line since a single length of pipe is not long enough. The pipe cutter decides which length of pipes to cut off based on the pipes availability (here 11.1 meters and 1 meter), thus the lengths are not shown on the drawing.

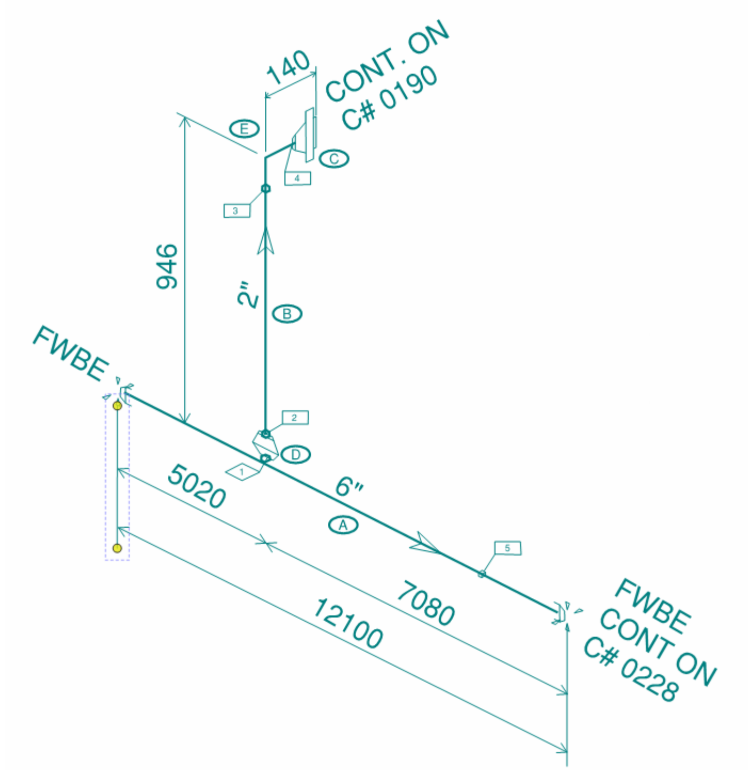


Figure 5-2 Isometric drawing of the pipe spool No.1

Welding man-hours estimate

To estimate the required direct man-hours for the complete fabrication of given pipe spool using *Estimator's Piping Man Hour Manual* (Page 1999), first takeoff for the fabrication activities and their corresponding quantities are identified from the information on the ISO drawing. Labour productivity norms are derived from man-hour tables in the book. To calculate Man-hour, the quantities are then multiplied by the labour productivity norms. Table 5-2 shows the quantity take-off for this pipe spool derived from ISO drawing. The following sections illustrate the estimation process for pipe spool fabrication job.

Table 5-2 Quantity take-off for pipe spool No.1

Size	Description	Wall	Quantity
6"	Handling	Sch 40	12.1 (m)
2"	Handling	Sch 80	1.1(m)
6"	Bevel End	Sch 40	2
6"	Cut End	Sch 40	1
2"	Olet Weld	Sch 80	1
6"	Butt-Weld	Sch 40	1
2"	Butt-Weld	Sch 80	2
2"	Weld-neck Flange	Sch 80	1

Flange

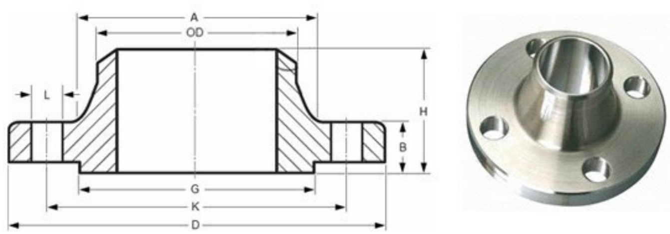


Figure 5-3 ASME B16.5 Class 150 Weld Neck Flanges

The current estimation practice in the company treats flange welds as common butt welds. However, there is a separate man-hour table in Page & Nation book for butt welding flanges. Pipe flanges that are made to standards called out by ASME B16.5 or ASME B16.47 are typically made from forged materials and have machined surfaces. B16.5 refers to nominal pipe sizes (NPS) from ½" to 24". B16.47 covers NPSs from 26" to 60". Each specification further delineates flanges into pressure classes: 150, 300, 400, 600, 900, 1500 and 2500 for B16.5, and B16.47 delineates its flanges into pressure classes 75, 150, 300, 400, 600,

900. Flange designs are available as weld neck, slip-on, lap joint, socket weld, threaded, and also blind.

Figure 5-3 represents ASME B16.5 Class 150 Weld Neck Flanges which was used in the spool No.1. To calculate direct man-hour for attaching the weld neck type flange, first the rate is extracted from man-hour table for attaching flange - weld neck type for carbon steel material (Appendix 2) for flange size (2") and pressure (150 Lb.). Man-hours include aligning and tack welding carbon steel weld neck flange to pipe. Man-hours are for any wall thickness of pipe used with listed flanges. Table 5-3 illustrates the estimation process for welding the flange.

Table 5-3 Estimation process for welding the flange

Item	Size	Pressure	Quantity	MH/Per Unit of measure	Total Man-Hours
Weld-neck flange	2"	Sch 80	1	1.05	1.05×1 = 1.05

Weld Olet

Figure 5-4 represents olet specification. Whenever branch connections are required in size where reducing tees are not available and/or when the branch connections are of smaller size as compared to header size, olets are generally used. Configurations of olet connections include Flanged Olet, Socket-Weld and Threaded Olet, Lateral and Elbow Olets, Nipple Olet, Butt-Weld Olet and Swage Nipples.

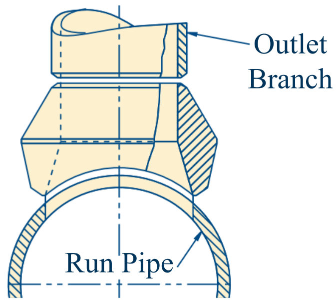


Figure 5-4 olet specifications

To calculate direct man-hour for butt-weld olet in the spool, the rate is extracted from man-hour table for olet type welds for carbon steel material (Appendix 2) using olet size (2") and weight (Extra strong fittings are the same as schedule 80 through 8"). Man hours are based on the outlet size and schedule except when the run schedule is greater than the outlet in which case the man hours are based on the outlet size and run schedule. Table 5-4 illustrates the estimation process for this butt weld olet.

Table 5-4 Estimation process for butt weld olet

Item	**Size**	**Wall Thickness**	**Quantity**	**MH/Per Unit of measure**	**Total Man-Hours**
Olet Weld	2"	Sch 80	1	4.20	$4.20 \times 1 = 4.2$

Butt Weld

A butt weld is a weld along the seam of pipe, so that two pipes are butted edge to edge as shown in Figure 5-5. Wall thickness of the pipe determines the man-hours that will apply for pipe butt welding process. Man-hours do not include cutting and beveling or threading of pipe. If preheating is specified or required by Codes, it should be added for this welding operation from another table. Stress relieving of welds in carbon steel material is required by the A.S.A., Code of Pressure piping where the wall thickness is 3/4" or greater. All sizes of butt welds shown below the ruled lines are 3/4" or greater in wall thickness and must be stress relieved. Where stress relieving is required, an extra charge should be made which is available in man-hour table for stress relieving. Man-hour table for manual butt welds is presented in Appendix 3.

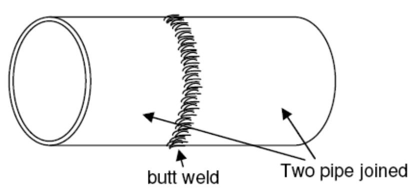


Figure 5-5 Butt weld specification

Table 5-5 demonstrates the estimation process for 2" and 6" butt welds.

Table 5-5 Estimation process for welding the flange

Item	Size	Wall Thickness	Quantity	MH/Per Unit of measure	Total Man-Hours
Butt Weld	2"	Sch 80	2	0.9	0.9 × 2 = 1.8
Butt Weld	6"	Sch 40	1	1.8	1.8 × 1 = 1.8

Handling man-hours estimate

The man-hour table for handling pipe per foot for fabrication in the fabrication shop is provided in Appendix 3. Man-hours include unloading pipe from railroad cars or trucks and placing in shop storage, procuring necessary pipe and materials to fabricate spool piece, transporting necessary materials to point of fabrication and the transporting of finished work to temporary storage. Units apply to any length spool piece or segment of work.

Table 5-6 demonstrates handling man-hour estimation for pipe spool calculated the same way as welding man-hours using Page & Nation book. Current cost estimation practice uses length of the pipe spools for calculating the required man-hours for handling them.

Table 5-6 Handling man-hour estimation for pipe spool No.1

Item	Size	Wall Thickness	Quantity (m)	Quantity (ft)	MH/Per ft	Total Man-Hours
Pipe handling	6"	Sch 40	12.1	39.7	0.051	39.7 × 0.051 = 2.02
Pipe handling	2"	Sch 80	1.1	3.61	0.044	3.61 × 0.044 = 0.16

Cost estimation summary for pipe spool No.1

Table 5-7 summarizes welding man-hours estimated using Estimator‘s Piping Man Hour Manual.

Table 5-7 Cost estimate summary for pipe spool No.1

Item	Size	Wall Thickness	Quantity	MH/Per Unit of measure	Total Man-Hours
Pipe handling	6"	Sch 40	39.7	0.051	2.02
Pipe handling	2"	Sch 80	3.61	0.044	0.16
Weld-neck flange	2"	Sch 80	1	1.05	1.05
Olet Weld	2"	Sch 80	1	4.20	4.20
Butt Weld	6"	Sch 40	1	1.80	1.80
Butt Weld	2"	Sch 80	2	0.90	1.80
				Total Man-hour for the spool	**11.03**

Analysis of the actual labour data

As drawings were released for fabrication, the material for them was transferred to the shop. Table 5-8 demonstrates the tagging plan which includes the ID of the tags attached to each pieces and the corresponding weld point for which the data is collected.

Table 5-8 Tagging plan for pipe spool No.1

Part No.	Description	Symbol	Tag ID	Weld point
1	Flange		1	
2	Elbow		2	4
3	2" Pipe		3	3
4	Olet		4	2
5	6" Pipe - Large		6	1
6	6" Pipe - Small		5	5

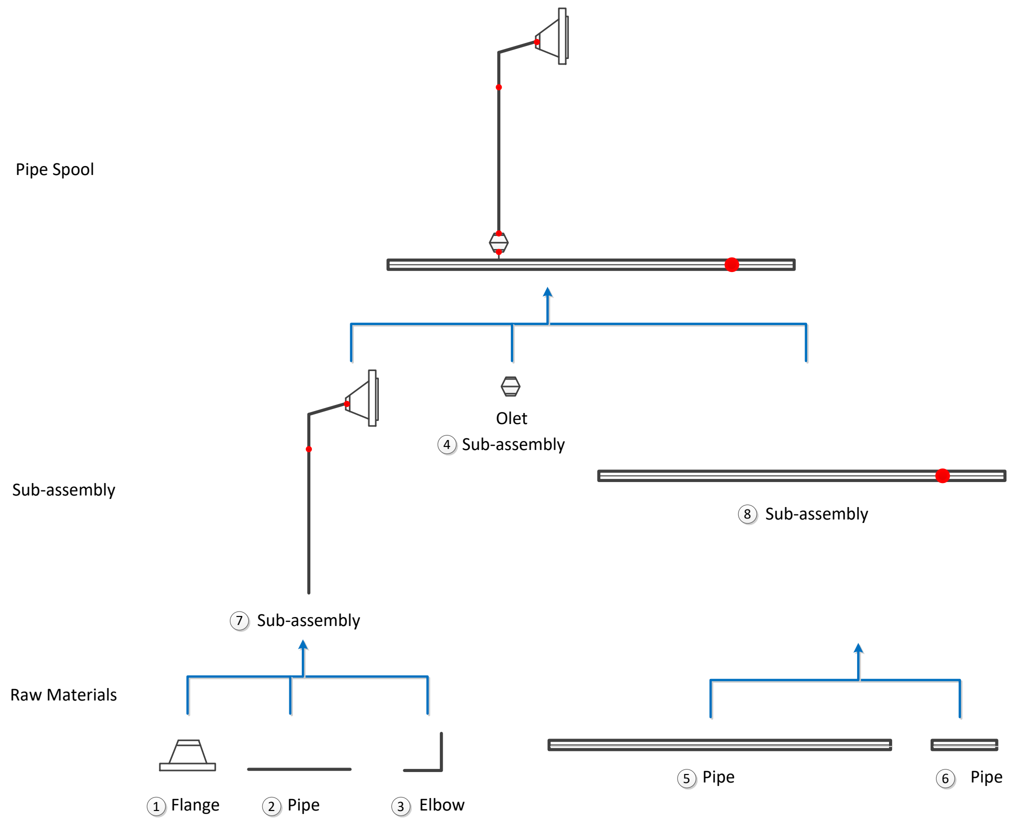


Figure 5-6 planned fabrication order for pipe spool No. 1

Figure 5-6 shows planned fabrication order determined by the foreman for this pipe spool. A tagging plan was developed for the fabrication sequences specified in Figure 5-6 and Table 5-8, and was given to the fabrication shop workers with the design drawings and cut sheets. When a new piece was welded to the previous part, the old tag was removed and its information was transferred to the new tag. The new tag then recorded the fitting and welding durations for the assigned welding points in Figure 5-8. For instance, when flange (Tag ID: 1) was attached to elbow (Tag ID: 2), Tag 1 was removed and the data for the weld point 4 which was a 2" butt weld was recorded on Tag 2.

On the first day, sub assembly 7 was fabricated and on the second day sub assembly 8 was fabricated and attached to sub assembly 7 to form the final pipe spool.

- First, fitters started to join flange (tag 1) and elbow (tag 2) in fitting station. Before starting fitting, the tag on the flange was removed. Thus, Tag 2 hypothetically recorded fitting duration for weld point 4. The work piece was then sent to the welding station for welding the butt weld. However, after welding was completed welder noticed that the elbow was connected to a wrong flange which belonged to another pipe spool (Spool No. 2). So, he sent the work piece back to the fitting stations to cut off the flange.
- After breaking the flange and elbow, fitters again joined flange and elbow. Tag 1 was already removed. Thus, tag 2 recorded the re-work for fitting duration for weld point 4.
- The resulting piece was fitted and sent to the welding station 2 (Small pipes' welding station) for welding by welder 2. Tag 2 also recorded welding duration for the same weld point.
- Later on, the welding was done and tag 2 was then removed. The piece was sent back to the fitting station to be attached to the 2" pipe. Tag 3 recorded the fitting duration for weld point 3.
- Fitting was the performed and the handlers took the resulting assembly back to the same welding station for welding point 3 and Tag 3 recorded the welding duration.

- Tag 3 was removed. Since the olet was small, its tag (tag 4) was taken and placed on the connecting pipe. Thereafter, fitter started to join the olet to the assembly at point 2 and handlers took the piece to the welding station. The sub assembly was completely done and Tag 4 recorded both fitting and welding duration. Figure 5-7 depicts the fabrication process on day one for the sub assembly 7.

Figure 5-7 Fabrication process of sub assembly 7

- Day two started with preparing and fitting two parts of pipe A at point 5. After pipe A(x) was prepared in the fitting station, handlers moved it along with pipe A(y) to a bigger space in fitting station and placed them on the stands in the same line. Tag 5 from A(x) which had been attached close to point 5 recorded the fitting duration.
- Tag 6 was not removed and had been attached to pipe A(y) close to the point 1.
- After connecting the two parts, the whole pipe spool was then moved to the welding station (large pipes' station) to be welded at point 5 with a 6" butt weld. Tag 5 recorded the welding duration.
- The pipe was sent back to the fitting station and fitters moved to point 1 to make a hole for the olet.
- Before attaching the sub assembly 7 to pipe A with an olet weld, tag 4 was removed. Thereafter, tag 6 recorded the fitting duration of point 1.
- The whole piece was then moved to the welding station (large pipes' station) for welding point 1 with an olet weld. Tag 6 recorded the olet welding durations.
- The pipe spool was completely done and was sent for final inspection.

Figure 5-8 depicts fabrication process on day two for the sub assembly 8 and the final pipe spool.

Figure 5-8 Fabrication process for sub assembly 8 and final pipe spool

Actual labour data report

Table 5-9 shows actual fitting, handling and welding durations collected for the pipe spool and its welding points.

Table 5-9 Fitting, welding and handling durations for pipe spool No.1

Day	Point No.	Size (DI)	No. of Fitters	No. of Handlers	No. of Welders	Duration (Minutes)		
						Fitting	Welding	Handling
1	4	2"	2		1	25	20	
1	4	2"	2		1	13		
1	4	2"	2		1	30	30	
1	B	2"		1				1
1	3	2"	2		1	11	30	
1	CEB	2"		1				3
1	CEB	2"		1				2
1	CEB	2"		1				2
1	CEB	2"		1				3
1	2	2"	2		1	13	17	
1	CEBD	2"		1				2
2	A(x)	6"		2				3
2	A(y)	6"		2				6
2	A(x)	6"		2				4
2	5	6"	2		1	2		
2	5	6"	2		1	3		
2	5	6"	2		1	31	44	
2	A	6"		2				3
2	A	6"		2				8
2	A	6"		2				6
2	1	2"	2			14		
2	CEBD	2"		1				3
2	A	6"		2				7
2	1	2"	2		1	10	57	
2	A	6" & 2"		2				3

Table 5-10 summarizes welding and fitting duration collected in hours (see table 11). For the sake of later comparison, we did not include the rework man-hours (1.60 MHR) for connecting the wrong flange in the report. However, note that the system would be able to record the extra man-hour for welding point 4 (weld-neck flange weld) and eventually pipe spool No.1.

Table 5-11 and Table 5-12 demonstrates the steps for calculating welding and handling man-hours out of collected fitting, welding and handling durations and Table 5-13 summarizes the actual labour data.

Table 5-10 Fitting and welding durations for pipe spool No. 1

Weld Point No.	Description	Size	Fitting Duration (HR)	Welding Duration (HR)
1	Olet Weld	2"	0.40	0.95
2	Butt-Weld	2"	0.22	0.28
3	Butt-Weld	2"	0.18	0.50
4	Weld-neck flange	2"	0.50	0.50
5	Butt-Weld	6"	0.60	0.73

Table 5-11 Steps for calculating welding man-hours

Weld Point No.	Description	Size	Fitting MHr	Welding MHr	Total Welding MHr
1	Olet Weld	2"	0.40 × 2 = 0.80	0.95 × 1 = 0.95	0.80 + 0.95 = 1.75
2	Butt-Weld	2"	0.22 × 2 = 0.44	0.28 × 1 = 0.28	0.44 + 0.28 = 0.72
3	Butt-Weld	2"	0.18 × 2 = 0.36	0.50 × 1 = 0.50	0.36 + 0.50 = 0.86
4	Weld-neck flange	2"	0.50 × 2 = 1.00	0.50 × 1 = 0.50	1.00 + 0.50 = 1.50
5	Butt-Weld	6"	0.60 × 2 = 1.20	0.73 × 1 = 0.73	1.20 + 0.73 = 1.93

Table 5-12 Steps for calculating handling man-hours

Item	Size	Handling Hr	No. of handlers	Total Man-Hours
Pipe handling	6"	0.12	1	0.12 × 1 = 0.12
Pipe handling	6"	0.55	2	0.55 × 2 = 1.10
Pipe handling	2"	0.27	1	0.27 × 1 = 0.27
Pipe handling	2"	0.05	2	0.50 × 2 = 0.10

Table 5-13 Summary of the actual fabrication man-hours for spool No.1

Weld Point No.	Description	Size	Actual man-hours
	Pipe Handling	6"	1.22
	Pipe Handling	2"	0.37
1	Olet Weld	2"	1.75
2	Butt-Weld	2"	0.72
3	Butt-Weld	2"	0.86
4	Weld-neck flange	2"	1.50
5	Butt-Weld	6"	1.93
	Total man-hours		**8.35**

Comparison of data (Actual vs. Page & Nation)

Table 5-14 compares experimental and Page & Nation man-hours for spool No.1.

Table 5-14 Experimental vs. Page & Nation man-hours for spool No. 1

Point No.	Description	Size	Actual man-hours	Page & Nation	% Difference
A	Pipe handling	6"	1.22	2.03	39.90
B	Pipe handling	2"	0.37	0.16	131.25
1	Olet Weld	2"	1.75	4.20	58.33
2	Butt-Weld	2"	0.72	0.90	20.00
3	Butt-Weld	2"	0.86	0.90	4.44
4	Weld-neck flange	2"	1.50	1.05	42.86
5	Butt-Weld	6"	1.93	1.80	7.22
				Average	**43.34**

It should be noted that handling man-hour by Page and Nation also includes unloading pipe from railroad cars or trucks which is not captured in our experiment, so they might not be fully comparable with the data collected. Yet, Page & Nation considerably underestimated labour productivity norm for handling 2" pipes. Even if we ignore the handling data, still the error for welding data would be 26.57 %.

Compared with Page & Nation, it is indicated that Page & Nation substantially overestimated labour productivity norm for olet weld and butt weld connecting the pipe to the olet while extremely underestimated labour productivity norm for flange weld. Moreover, the labour productivity norms for regular butt welds have not changed much during the time despite recent technological advances in design, fabrication and machinery of the industrial construction which is questionable findings and need to be addressed and discussed through deeper research studies. Experimental data can be used to determine labour productivity norms (also called man-hour rates) for fabrication activities (Table 5-15).

Table 5-15 labour productivity norm for fabrication activities

Description	Size	Actual man-hours	Quantity	Labour productivity norm
Pipe handling	6"	1.22	39.7'	0.03
Pipe handling	2"	0.37	3.61'	0.10
Olet Weld	2"	1.75	1	1.75
Butt-Weld	2"	0.72 + 0.86 = 1.58	2	0.79
Weld-neck flange	2"	1.50	1	1.50
Butt-Weld	6"	1.93	1	1.93

5.5.2 Pipe spool No. 2

Figure 5-9 shows the Isometric drawing of pipe spool No.2. The pipe spool comprises six 6" butt welds (weld points 1-6), one hydro weld (weld point 9) and two 3" butt welds (weld points 7 and 8). The specs show that pipes include two different dimensions (6" for Pipe A, B, C and 3" for D) all with the same schedule (wall thickness which is 40 here). As shown, all pipes require beveling. Pipe C will be attached to Hydro piece (J) from one end through a 6" - 90 degree elbow (G) and to a 6" pipe (B) from the other end through another 6" - 90 degree elbow (F). A pipe tee (I) in the middle connects two 6" and one 3" pipes (Pipes A, B and D). The 3" pipe is connected to the tee through a reducer (H) and on the other side it is connected to a flange.

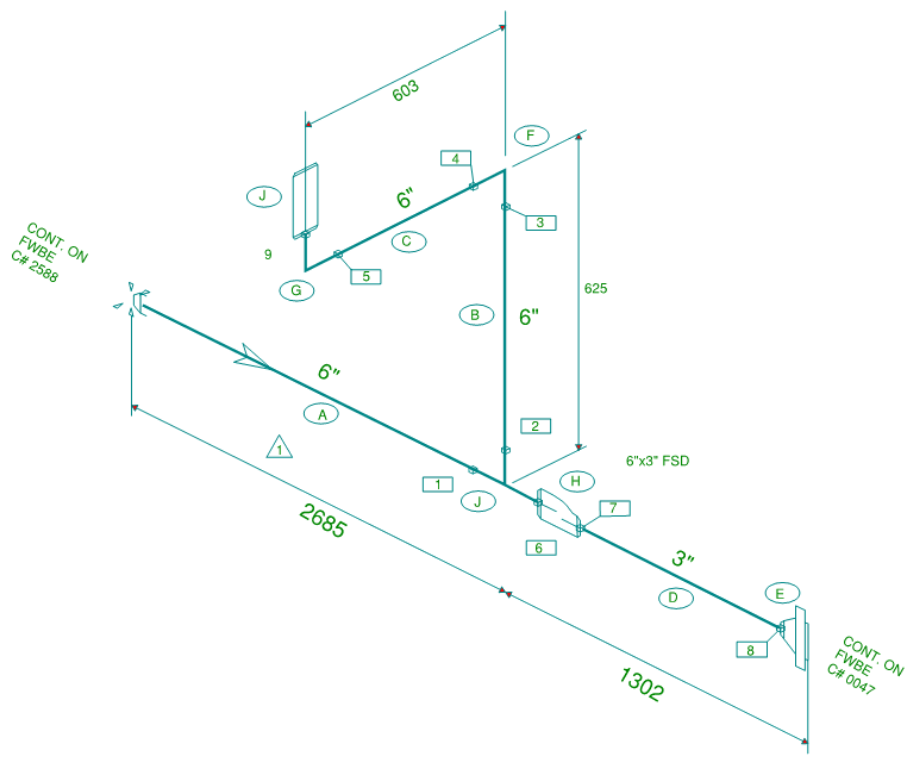


Figure 5-9 Isometric drawing of pipe spool No.2

Man-hours estimate

Similar to pipe spool No.1, required direct man-hours for the complete fabrication of pipe spool No.2 are estimated using *Estimator's Piping Man Hour Manual*. In the same way, takeoff for the fabrication activities and their corresponding quantities are first identified from the information provided on the ISO drawing. Table 5-16 shows quantity take-off for this pipe spool derived from ISO drawing.

Table 5-16 Quantity take-off for pipe spool No.2

Size	Description	Wall	Quantity
6"	Handling	Sch 40	5.4(m)
3"	Handling	Sch 40	1.4(m)
6"	Bevel End	Sch 40	1
6"	Cut End	Sch 40	1
6"	Butt-Weld	Sch 40	2
2"	Butt-Weld	Sch 40	6
2"	Hydroweld	Sch 40	1

Labour productivity norms are then derived from man-hour tables in the book accordingly. To calculate Man-hour, the quantities are subsequently multiplied by the Labour productivity norms. Table 5-17 summarizes welding man-hours estimated using Estimator's Piping Man Hour Manual. Total length of 6-inch pipes is 5.4 meters and total length of 3-inch pipes is 1.4 meters. These numbers are converted to17.72 and 4.59 feet respectively. The hydro weld is also considered as a butt weld.

Table 5-17 Cost estimate summary for pipe spool No.2

Item	**Size**	**Wall Thickness**	**Quantity**	**MH/Per Unit of measure**	**Total Man-Hours**
Pipe handling	6"	Sch 40	17.72	0.051	0.90
Pipe handling	3"	Sch 40	4.59	0.041	0.19
Weld-neck flange	3"	Sch 40	1	1.70	1.70
Butt Weld	3"	Sch 40	1	1.10	1.10
Butt Weld	6"	Sch 40	6	1.80	10.80
Hydro Weld	6"	Sch 40	1	1.80	1.80
			Total Man-hour for the spool		**16.49**

Analysis of the actual labour data

Table 5-18 demonstrates tagging plan for pipe spool No.2.

Table 5-18 Tagging plan for pipe spool No. 2

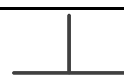
Part No.	Description	Symbol	Tag ID	Weld point
J	6" Hydro Pipe		1	
G	Elbow		2	9
C	6" Pipe		3	
F	Elbow		4	4,5
B	6" Pipe		5	2 , 3
A	6" Pipe		6	
I	Tee		7	1
H	Reducer		8	6
D	3" Pipe		9	7
E	Flange		10	8

Figure 5-10 shows planned fabrication order determined by the foreman for this pipe spool. A tagging plan was developed for the fabrication sequences specified in Figure 5-10 and Table 5-18, and is given to the fabrication shop workers with the design drawings and cut sheets.

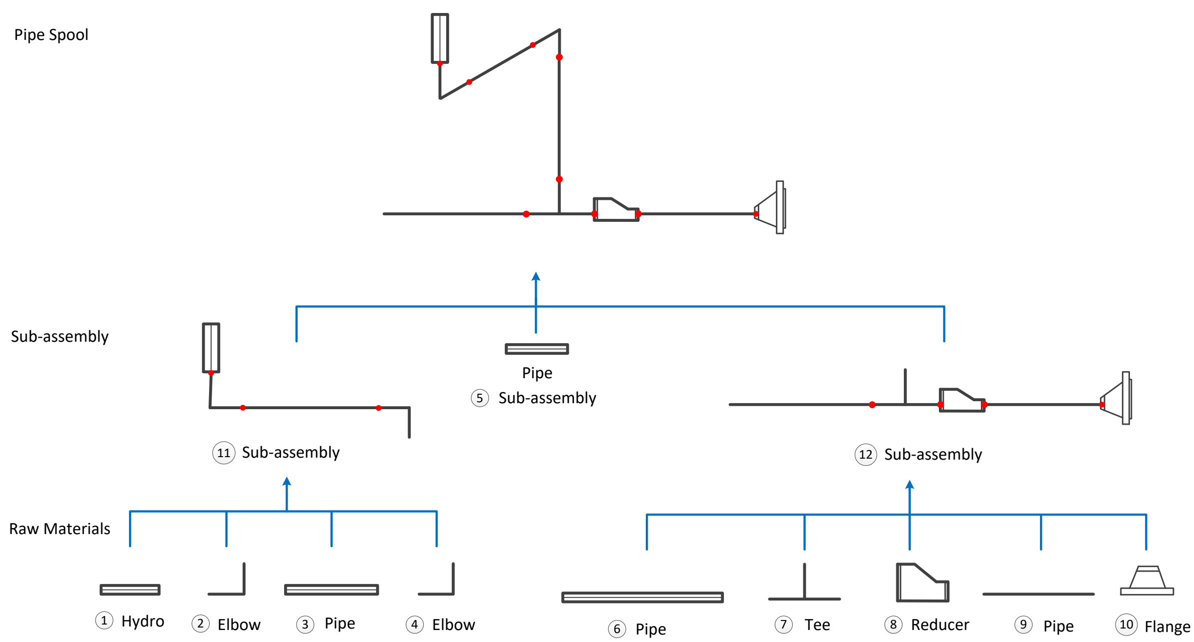


Figure 5-10 planned fabrication order

- On the first day, sub assembly 11 was fabricated. On the third day the sub assembly 12 was fabricated and attached to sub assembly 11 to form the final pipe spool.
- After Hydro pipe (tag 1) and elbow (tag 2) was positioned in the fitting station by fastening them on fixtures, tack welding at point 9 was performed to join the two pieces by fitters. No time was recorded for

handling these two components since they were not heavy and was moved to the fitting station from the laydown area by the fitters. Before starting fitting, tag 1 was removed. Tag 2 recorded fitting duration for weld point 9. Note that some fabrication activities for pipe spool No.2 were being done at the same day pipe spool No.1 was being fabricated.

- The connected piece (JG) was then moved to welding station 2 (short pipes' welding station) for welding by welder 2. In the middle of welding, welder left for a couple of minutes and finished the welding after he came back. Tag 2 recorded welding duration for the same weld point. Welder himself took the piece back to the laydown area after he was done since the piece was not heavy.
- A handler took pipe C to the fitting station around the same time to be attached to elbow F. Tag 3 was removed just before handlers was leaving and tag 4 recorded the fitting duration for weld point 4.
- After fitting was done, handlers took the resulting assembly (CF) to the welding station 2. Handler 2 joined handler 1 after a minute to help him fix the piece in the welding machine. However the piece did not fit in the welding machine after relentless effort because of its geometry. So, they decided to move the piece to welding station 3(long pipes' welding station). Welder 2 completed the welding after he came back from his lunch break and tag 4 recorded the welding duration as well.
- The two subassemblies (JG and CF) were then moved to the fitting station to be joined together at weld point 5 right after welding was done to

compose subassembly 11. Tag 2 was removed and Tag 4 recorded fitting duration. The resulting subassembly was again send to the same welding station (station 3) for welding. The connected piece (JGCF) was then placed in the laydown area as fitting station was occupied.

- While welding point 5 was being performed, fitters started preparing the tee section (I; tag 7) and handlers moved pipe A (tag 6) to fitting station to get preparation and be attached to the tee at welding point 1. The data collected by the two tags was transferred to tag 7 and was considered as fitting duration for welding point 1. After the preparation and fitting was done, point 1 was welded in three consecutive steps. Tag 7 recorded the durations. The pipe was then placed on the laydown area for the next day.
- On the third day, fitting and welding station were pretty much occupied by two other pipe spools (including pipe spool No.1). Therefore, the remaining fabrication work was postponed to the third day as this pipe spool was complicated and time consuming for having position welds.
- Third day started with preparation of reducer H on both ends and attaching it to the tee section at weld point 6 in welding station 2. Handling time of the resulting assembly (AIH) to the welding station had an overlap of one minute with welding duration as handlers and welder were working together to place the sub assembly into the welding machine. Tag 8 recorded the durations. After a while, the sub assembly (AIH) along with pipe D was taken to the fitting station with a little time away to be attached.

- The two pieces were joined and welded in two steps at welding point 7. Durations were recorded by tag 9.
- After attaching pipe D, the assembly was sent back to the fitting station to be attached to flange E. However, due to schedule change, another workpiece from another workpackage was brought to the fitting station and piece AIHD was sent to the laydown area. After the workpiece was completed, piece AIHD was again taken to the fitting station. Tag 10 collected the information for the extra handling duration as well.
- After subassembly 12 (AIHDE) was completed, subassembly 11 (JGCF), which was previously fabricated on day 1, was taken to the fitting station to join with pipe B at welding point 3. After fitting and welding stages for point 3 was done, the piece was finally welded to the tee section (at welding point 2) to form the final pipe spool. Tag 5 collected the man-hour information.
- All the welds were roll welding except for welding point 2 which was position welding. Pipe spool could not be rotated by a turner because the assembly had a branch (pipe B) longer than 5 feet. The position welding was a difficult procedure, and took much longer to perform than other butt welds.
- The final pipe spool (No.2) was then placed in the laydown area to be inspected at the end of the day.

Figure 5-11 depicts the fabrication process of the sub assembly 11.

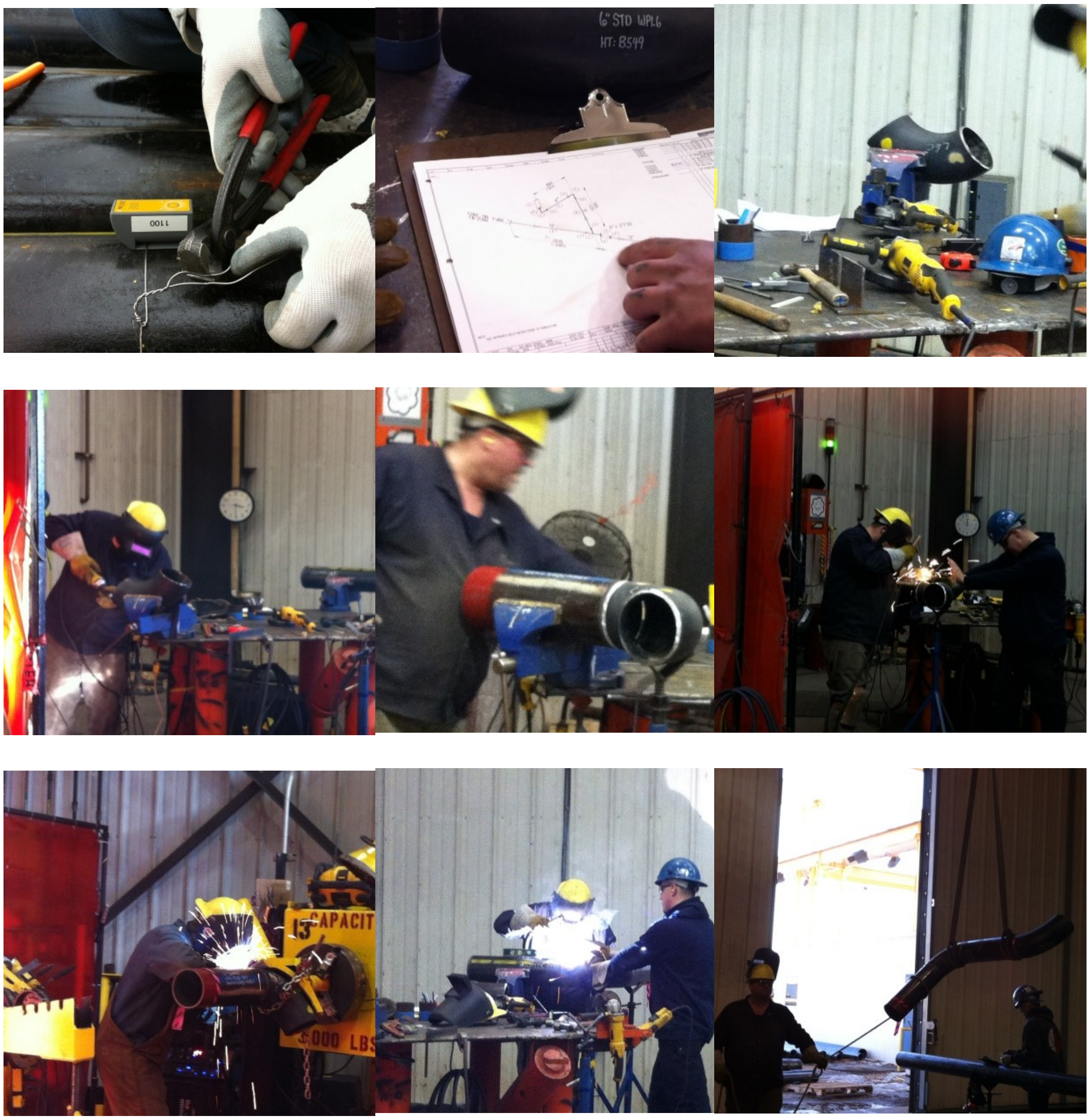


Figure 5-11 Fabrication process of sub assembly 11

Figure 5-12 depicts the fabrication process of the sub assembly 12 and its join with subassembly 11 to make the final pipe spool.

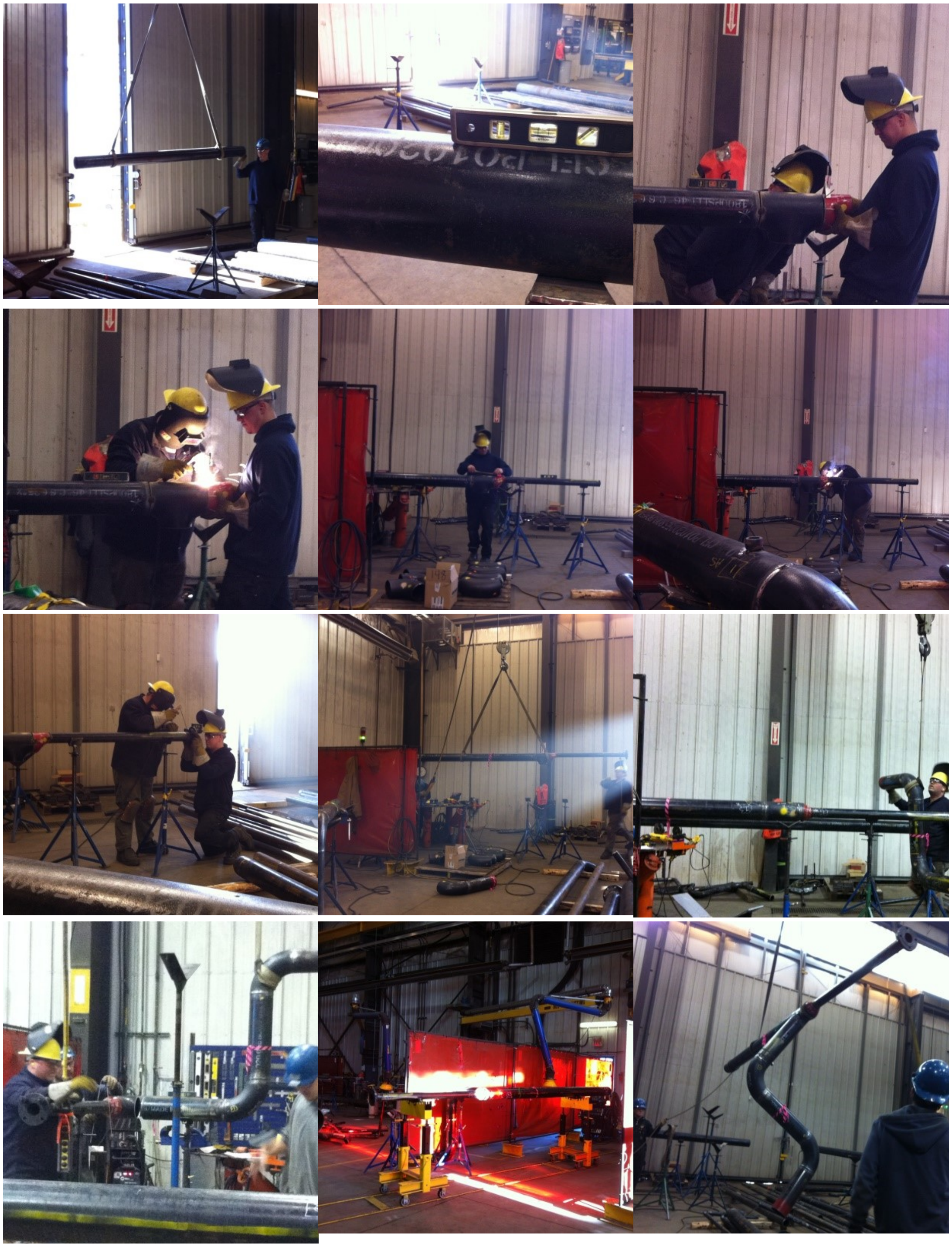


Figure 5-12 Fabrication process of sub assembly 12 and the final pipe spool

Actual labour data report

Table 5-19 Fitting, welding and handling durations for pipe spool No.2

Day	Point No.	Size (DI)	No. of Fitters	No. of Handlers	No. of Welders	Duration (Minutes)		
						Fitting	Welding	Handling
1	9	6"	2		1	12	38	
1	9	6"			1		4	
1	JG	6"		1				1
1	C	6"		1				1
1	4	6"			1	15	14	
1	CF	6"		1				6
1	CF	6"		2				5
1	CF	6"		2				5
	JG	6"		2				1
1	CF	6"		2				4
1	5	6"			1	18	12	
1	JGCF	6"						4
1	JGCF	6"						2
1	1-I	6"	2			4		
	A			2				3
1	1-A	6"	2			6		
1	1	6"	2		1	21	21	
1	1	6"			1		30	
1	1	6"			1		5	
1	AI	6"		2				4
1	AI	6"		2				4
3	6-H	6"	2			1		
3	AI	6"						3
3	6	6"	2		1	36	46	
3	AIH	6"		2				5
3	AIH	3"		2				3
3	D	3"		2				2
3	7	3"	2		1	19	5	
3	7	3"			1		10	
3	AIHD	3"		2				5
	AIHD	3"		2				4
3	AIHD	3"		2				5
3	8	3"	2		1	11	130	
3	8	3"			1			
3	AIHDE	3"		2				4
3	AIHDE	3"		2				4
3	JGCF	6"		2				5
3	3	6"	2			27	52	
3	JGCFB	6"		2				2
3	2	6"	1 & 2		2	20	80	
3	2	6"	1 & 2			9		
3	Pipe spool	6" & 3"		1 & 2				5

Table 5-19 indicates fitting, handling and welding durations for each welding point and pipe pieces collected manually. Table 5-20 presents the summary of the welding and fitting duration in hours (see Table 5-19).

Table 5-21 and Table 5-22 demonstrates the steps for calculating welding and handling man-hours out of collected fitting, welding and handling durations and Table 5-23 summarizes collected labour data.

Table 5-20 Fitting and welding durations for pipe spool No. 2

Weld Point No.	Description	Size	Fitting Duration (HR)	Welding Duration (HR)
1	Butt Weld	6"	0.52	0.93
2	Butt-Weld	6"	0.48	1.333
3	Butt-Weld	6"	0.45	0.87
4	Butt-Weld	6"	0.25	0.23
5	Butt-Weld	6"	0.30	0.20
6	Butt-Weld	6"	0.617	0.77
7	Butt-Weld	3"	0.317	0.25
8	Weld-neck Flange	3"	0.18	2.17
9	Hydro Weld	6"	0.20	0.70

Table 5-21 Steps for calculating welding man-hours

Weld Point No.	Description	Size	Fitting MHr	Welding MHr	Total welding MHr
1	Butt Weld	6"	0.52 × 2 = 1.04	0.93 ×1 = 0.93	1.04 + 0.93 = 1.97
2	Butt-Weld	6"	0.48 × 2 = 0.967	1.33 × 1= 1.333	0.967 + 1.333 = 2.30
3	Butt-Weld	6"	0.45× 2 = 0.90	0.87 × 1 = 0.87	0.90 + 0.87 = 1.77
4	Butt-Weld	6"	0.25 × 2 = 0.50	0.23 × 1 = 0.23	0.50 + 0.23 = 0.73
5	Butt-Weld	6"	0.30 × 2 = 0.60	0.20 × 1 = 0.20	0.60 + 0.20 = 0.80
6	Butt-Weld	6"	0.617 × 2 = 1.23	0.77 × 1 = 0.77	1.23 + 0.77 = 2.00
7	Butt-Weld	3"	0.317 × 2 = 0.63	0.25 × 1 = 0.25	0.63 + 0.25 = 0.88
8	Weld-neck Flange	3"	0.18 × 2 = 0.36	2.17 × 1 = 2.17	0.36 + 2.17 = 2.53
9	Hydro Weld	6"	0.20 × 2 = 0.40	0.70 × 1 = 0.70	0.40 + 0.70 = 1.10

Table 5-22 Steps for calculating handling man-hours

Item	Size	Handling Hr	No. of handlers	Total Man-Hours
Pipe handling	6"	23/60 = 0.383	1	0.383 ×1 = 0.383
Pipe handling	6"	62/60 = 1.033	2	1.033 × 2 = 2.067
Pipe handling	3"	29/60 = 0.483	2	0.483 × 2 = 0.967

Table 5-23 Summary of the actual fabrication man-hours for spool No.2

Weld Point No.	Description	Size	Actual man-hours
	Pipe handling	6"	2.45
	Pipe handling	3"	0.97
1	Butt Weld	6"	1.97
2	Butt-Weld	6"	2.30
3	Butt-Weld	6"	1.77
4	Butt-Weld	6"	0.73
5	Butt-Weld	6"	0.80
6	Butt-Weld	6"	2.00
7	Butt-Weld	3"	0.88
8	Weld-neck Flange	3"	2.53
9	Hydro Weld	6"	1.10
		Total man-hours	**17.5**

Comparison of data (Actual vs. Page & Nation)

Table 5-24 compares actual and Page & Nation man-hours for spool No.2. Considering that handling man-hour by Page and Nation also includes unloading pipe from trucks, data indicates that handling man-hours is considerably underestimated compared with actual data. Even if we ignore the handling data, still the difference for welding data would be 30.30 %.

The difficulty in making position connecting butt often means the need to put a long time and effort with the most commonly used welding equipment. Collected data shows that welding butt weld point 2, which is a position weld, could take almost 1.5 times the average welding time and effort for the other butt welds. In addition, welding point 6 butt weld for connecting tee to the reducer, and weld-neck flange at weld point 8 proved to be extremely time consuming. Because the pipe could not be rotated by the turner, welding manually around the static workpiece entailed a lot of effort. These conditions, however, are not considered in man hour norms in Page & Nation tables as you can see in Table 5-24 and these butt welds are treated as regular butt welds which need much less effort.

Table 5-24 Actual vs. Page & Nation man-hours for spool No.2

Weld Point No.	Description	Size	Actual man-hours	Page & Nation man-hours	% Difference
	Pipe handling	6"	2.45	0.9	172.22
	Pipe handling	3"	0.97	0.16	506.25
1	Butt Weld	6"	1.97	1.8	9.44
2	Butt-Weld	6"	2.30	1.8	27.78
3	Butt-Weld	6"	1.77	1.8	1.67
4	Butt-Weld	6"	0.73	1.8	59.44
5	Butt-Weld	6"	0.80	1.8	55.56
6	Butt-Weld	6"	2.00	1.8	11.11
7	Butt-Weld	3"	0.88	1.1	20.00
8	Weld-neck Flange	3"	2.53	1.7	48.82
9	Hydro Weld	6"	1.10	1.8	38.89
				Average	**86.47**

5.5.3 Pipe spool No. 3

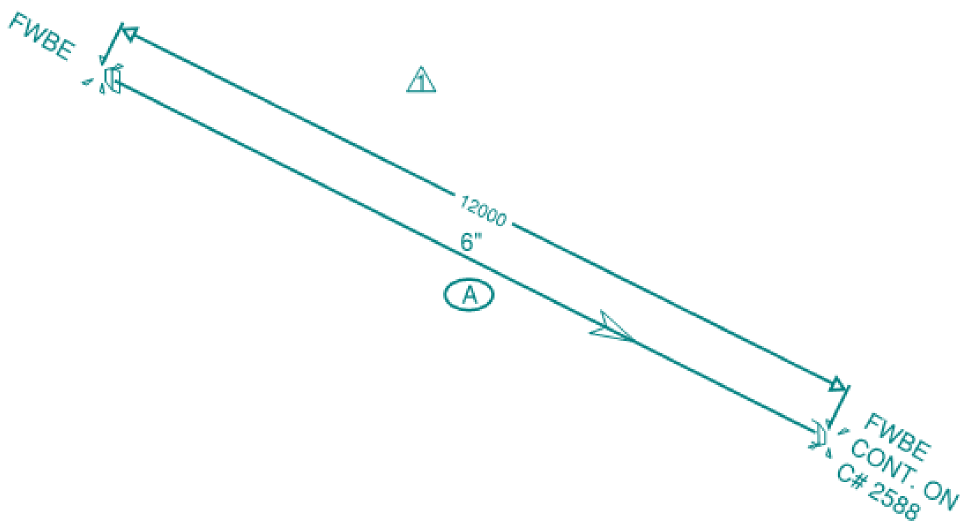


Figure 5-13 Isometric drawing of pipe spool No.3

Figure 5-13 shows the Isometric drawing of pipe spool No. 3. This type of spool is not a favorite since its fabrication process only comprises fitting, handling and inspection hours from which fitting is not billable. However, fitters still need to check whether the pipe spool size, dimensions and heat number matches the specification, and prepare the two ends by grinding the end of the pipe. The common sense in the fabrication shop is that if at least one end of the pipe is welded to another pipe spool later, it will cover for cutting and fitting costs. As seen on the ISO drawing (Appendix 2), the pipe will be welded to another pipe spool (#2588) on one end.

Handling man-hours estimate

Quantity take-off for handling is derived from the length information provided on the ISO drawing (Table 5-25). Table 5-26 demonstrates cost estimation for handling man-hour of the pipe spool using Page & Nation book.

Table 5-25 Quantity take-off for pipe spool No.3

Size	Description	Wall	Quantity (m)	Quantity (ft)
6"	Handling	Sch 40	12	39.37

Table 5-26 Handling man-hour estimation for pipe spool No.3

Item	Size	Wall Thickness	Quantity (ft)	MH/ft	Total Man-Hours
Pipe handling	6"	Sch 40 (0.280)	39.37	0.051	$39.37 \times 0.051 = 2.01$

Analysis of the actual labour data

As the pipe was long and required preparation on both end, two tags were attached to the ends of pipe to collect the handling and fitting data. Each tag collected data for one handler and one fitter at each end. After fitters checked the specifications, they prepared the ends of the pipe to make sure it meets the requirement of the welding procedure and sent it for final inspection on day 2. Each fitter was working on one end of the pipe. Figure 5-14 represents this process. Both handling and fitting man-hour were collected. Table 5-27 shows fitting and handling durations for the pipe spool.

Figure 5-14 Fabrication process for pipe spool No.3

Table 5-27 Fitting and handling durations for pipe spool No.3

Day	Size (DI)	No. of Fitters	No. of Handlers	Duration (Minutes)	
				Fitting	Handling
2	6"		1		6
2	6"		1		6
2	6"	1		2	
2	6"	1		3	
2	6"		1		3
2	6"		1		3

Table 5-28 demonstrates the steps for calculating handling and fitting man-hours.

Table 5-28 Calculating handling and fitting man-hours

Item	Size	Handling MHr	No. of labours	Total Man-Hours
Pipe handling	6"	0.15	2	0.15 × 2 = 0.30
Pipe handling	6"	0.05	1	0.05 × 1 = 0.05
Pipe handling	6"	0.03	1	0.03 × 1 = 0.03

Table 5-29 summarizes actual data.

Table 5-29 Summary of the actual fabrication man-hours for spool No.3

Description	Size	Actual man-hours
Pipe Handling	6"	0.30
Pipe fitting	6"	0.08
	Total man-hours	**0.38**

5.5.4 Pipe spool No. 4

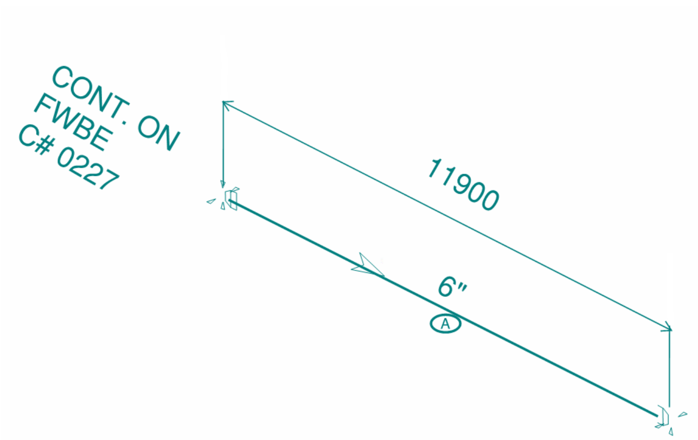


Figure 5-15 Isometric drawing of pipe spool No. 4

Figure 5-15 shows the Isometric drawing of pipe spool No. 4. Like pipe spool No. 3, this type of spool is not billable, yet fitters need to check the pipe spool size, dimensions , schedules and heat number against the specifications on the drawing and grinding the two ends.

Handling man-hours estimate

Quantity takeoff for handling pipe is derived from the length information provided on the ISO drawing (Table 3-1). There is no data provided for fitting cost estimation in Page & Nation.

Table 5-30 Cost estimate summary for pipe spool No.4

Size	Description	Wall	Quantity (m)	Quantity (ft)
6"	Handling	Sch 40	11.9	39.04

Table 5-31 demonstrates cost estimation for handling man-hour of the pipe spool using Page & Nation book.

Table 5-31 Handling man-hour estimation

Item	Size	Wall Thickness	Quantity (m)	Quantity (ft)	MH/ft	Total Man-Hours
Pipe handling	6"	Sch 40	12	39.04	0.051	39.37 × 0.051 = 1.99

Analysis of the actual labour data

Like pipe spool No.3, two tags were attached to the ends of pipe to collect the handling and fitting data. For this pipe, one fitter did all the preparation on both ends. Figure 5-16 represents this process. Table 5-32 shows fitting and handling durations for the pipe spool.

Table 5-32 Fitting and handling durations for pipe spool No.4

Day	Size (DI)	No. of Fitters	No. of Handlers	Duration (Minutes)	
				Fitting	Handling
4	6"		1		4
4	6"		1		3
4	6"	1		2	
4	6"	1		2	
4	6"		1		4
4	6"		1		4

Figure 5-16 Fabrication process for pipe spool No. 4

Table 5-33 demonstrates the steps for calculating handling and fitting man-hours.

Table 5-33 Steps for calculating handling and fitting man-hours

Item	Size	Handling Hr	No. of labours	Total Man-Hours
Pipe handling	6"	0.120	1	0.120 × 1 = 0.120
Pipe handling	6"	0.130	1	0.130 × 1 = 0.130
Pipe fitting	6"	0.033	1	0.030 × 1 = 0.033
Pipe fitting	6"	0.033	1	0.030 × 1 = 0.033

Table 5-34 summarizes the collected actual data.

Table 5-34 Summary of the actual fabrication man-hours for spool No.4

Description	Size	Actual man-hours
Pipe Handling	6"	0.250
Pipe fitting	6"	0.067
	Total man-hours	0.317

5.5.5 Pipe Spool No. 5

Figure 5-17 shows the Isometric drawing of pipe spool No. 5.

The pipe spool comprises one 6" butt weld (weld point 4), one 3/4" olet weld (weld point 1) and two 3/4" socket welds (weld points 2 and 3). Both pipe and olet has the same schedule (40) while pipe nipple‘s schedule is 160. There is a note on the drawing stating “shop to locate mid-point weld”. This means that the measurements are not defined on the drawing so the cutter can cut the desired length of pipes based on their pipe length availability.

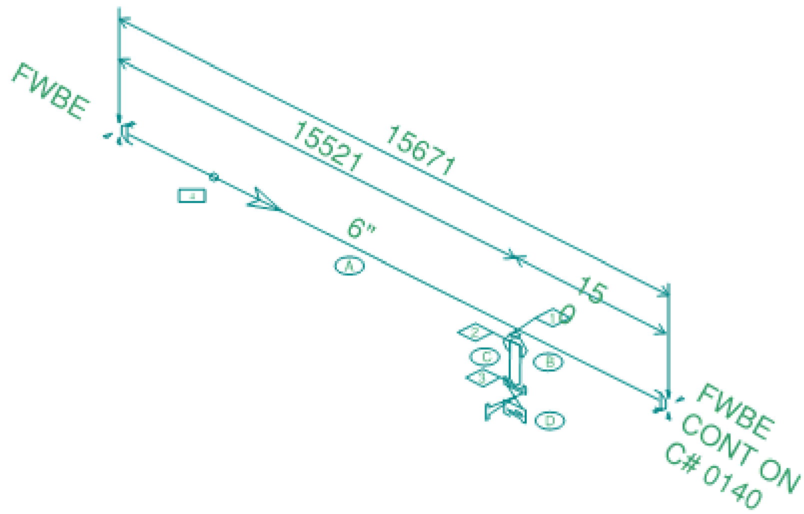


Figure 5-17 Isometric drawing of pipe spool No.5

Length of pipe A is indicated to be 15671 cm. Since the maximum length of pipe available is around 12 m, pipe cutter provided two pipe pieces with 12040 cm and 3631 cm length respectively. On the drawing the olet is located on the larger piece. Though, according to the note fitters decided to put the olet on the shorter piece because it will be then easier for the welder to work on one side of the pipe only and do all the welding at the same time. One gate valve (D) will be attached to the pipe through a pipe nipple (C) and a sockolet (B).

Man-hours estimate

Table 5-35 shows a list of items for cost estimation derived from ISO drawing.

Table 5-35 List of items for cost estimation derived from ISO drawing

Size	Description	Wall	Quantity
6"	Handling	Sch 40	15.671(m)
3/4"	Handling	Sch 160	0.2(m)
6"	Bevel End	Sch 40	2
6"	Cut End	Sch 40	1
6"	Butt-Weld	Sch 40	1
3/4"	Socket Weld 3000	Sch 160	2
3/4"	Olet Weld 3000	Sch 40	1

Table 5-36 presents the summary of cost estimates using Estimator's Piping Man Hour Manual. Total length of 6-inch pipes is 15.671 meters and total length of 3/4-inch pipes (pipe nipple) is 0.2 meters. These numbers are converted to 51.41 and 0.66 feet respectively.

Table 5-36 Cost estimate summary for pipe spool No.5

Item	Size	Wall Thickness	Quantity	MH/Per Unit of measure	Total Man-Hours
Pipe handling	6"	Sch 40	51.41	0.051	2.62
Pipe handling	3/4"	Sch 160	0.66	0.039	0.026
Butt-Weld	6"	Sch 40	1	1.80	1.80
Socket Weld 3000	3/4"	Sch 160	2	0.6	1.2
Olet Weld 3000	3/4"	Sch 40	1	1.9	1.9
			Total Man-hour for the spool		**7.55**

Analysis of the actual labour data

Table 5-37 and Figure 5-18 and demonstrate tagging plan and planned fabrication order respectively developed for this pipe spool.

Table 5-37 Tagging plan for pipe spool No.5

Part No.	Description	Symbol	Tag ID	Weld point
A(x)	6" Pipe		1	
A(y)	6" Pipe		2	4
B	Olet		3	1
C	3/4" Pipe nipple		4	2
D	Valve		5	3

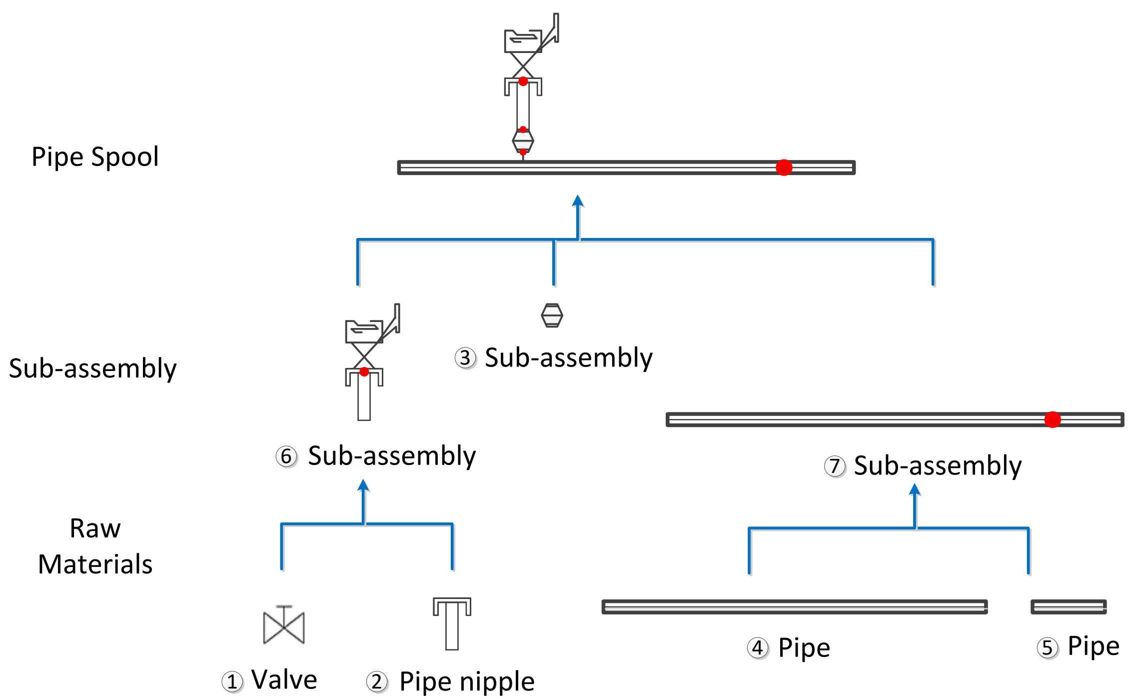


Figure 5-18 planned fabrication order

Figure 5-19 Fabrication process for pipe spool No. 5

On the fourth day, both sub assembly 6 and 7 were fabricated. The olet was then attached to the pipe by the fitters. Though, sub assembly 6 was attached on the fifth day as the job was interrupted by another work order. Figure 5-19 depicts the fabrication process of this pipe spool and Table 5-38 presents the job durations for the pipe spool. Table 5-39 then summarizes the welding and fitting duration for each welding point.

Table 5-38 Fitting, welding and handling durations for pipe spool No.5

Day	Point No.	Size (DI)	No. of Fitters	No. of Handlers	No. of Welders	Duration (Minutes)		
						Fitting	Welding	Handling
4	3	3/4"	2			2		
4	A(x)	6"		2				6
4	A(y)	6"		2				4
4	A(x) & A(y)	6"	2			5		
4	1	3/4"	2			11		
4	1	3/4"	2			6		
5	A	6"		2				7
5	4	6"			1		9	
5	4	6"			1		36	
5	1	3/4"			1		35	
5	2	3/4"	2		1	2	10	
5	A	6"		2				3

Table 5-39 Fitting and welding durations for welding points

Weld Point No.	Description	Size	Fitting Duration (HR)	Welding Duration (HR)
1	Olet Weld 3000	3/4"	17	35
2	Socket Weld 3000	3/4"	2	10
3	Socket Weld 3000	3/4"	2	16
4	Butt Weld	6"	5	45

Table 5-40 and Table 5-41 demonstrates the total welding and handling man-hours and Table 5-42 summarizes the actual collected data.

Table 5-40 Welding Man-hours for pipe spool No. 5

Weld Point No.	Description	Size	Fitting Duration (HR)	Welding Duration (HR)	Total welding MHr
1	Olet Weld 3000	3/4"	0.28	0.58	1.15
2	Socket Weld 3000	3/4"	0.03	0.17	0.23
3	Socket Weld 3000	3/4"	0.03	0.27	0.33
4	Butt Weld	6"	0.08	0.75	0.92

Table 5-41 Handling man-hours for pipe spool No. 5

Item	Size	Wall Thickness	Handling MHr	No. of handlers	Total Man-Hours
Pipe handling	6"	Sch 40	0.33	2	$0.33 \times 2 = 0.66$
Pipe handling	3/4"	Sch 160	0.33	2	$0.33 \times 2 = 0.66$

Table 5-42 Summary of the actual fabrication man-hours for spool No.5

Weld Point No.	Description	Size	Actual man-hours
	Pipe handling	6"	0.66
	Pipe handling	3/4"	0.66
1	Olet Weld 3000	3/4"	1.15
2	Socket Weld 3000	3/4"	0.23
3	Socket Weld 3000	3/4"	0.33
4	Butt Weld	6"	0.92
		Total man-hours	**3.95**

5.5.6 Pipe Spool No. 6

Figure 5-20 shows the Isometric drawing of pipe spool No.6.

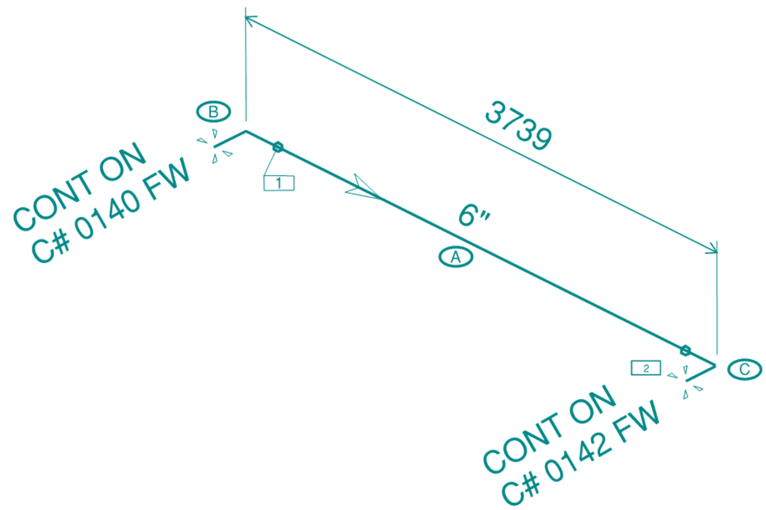


Figure 5-20 Isometric drawing of pipe spool No.6

The pipe spool comprises two 6" butt welds (weld points 1-2), the specs show that spool include two 6" elbows and one 6" pipe all with the same schedule (Sch40).

Man-hours estimate

Table 5-45 shows the cost estimate of this pipe spool. The pipe length is 4.7 meters which includes two elbows as well.

Table 5-43 the cost estimate for pipe spool No.6

Item	Size	Wall Thickness	Quantity	MH/Per Unit of measure	Total Man-Hours
Pipe handling	6"	Sch 40	15.42	0.051	0.77
Butt Weld	6"	Sch 40	2	1.80	3.60
			Total Man-hour for the spool		**4.37**

Analysis of the actual labour data

Table 5-44 presents the tagging plan for this pipe spool. After the 6” pipe was moved to the fitting station, it was connected to the elbow B and then the whole piece was joined to the elbow c in the fitting station. None of the tags were removed except tag 1 so as to record the fitting and welding duration for each weld point since both elbows were fitted to the pipe at the same time and the pipe would not go back to the fitting station. The whole piece was then taken to the welding station to perform both butt welds all at once.

Table 5-44 Tagging plan for pipe spool No. 6

Part No.	Description	Symbol	Tag ID	Weld point
A	6" Pipe		1	
B	Elbow		2	1
C	Elbow		3	2

Figure 5-21 demonstrates the planned fabrication order for the pipe spool and Figure 5-22 depicts its fabrication process.

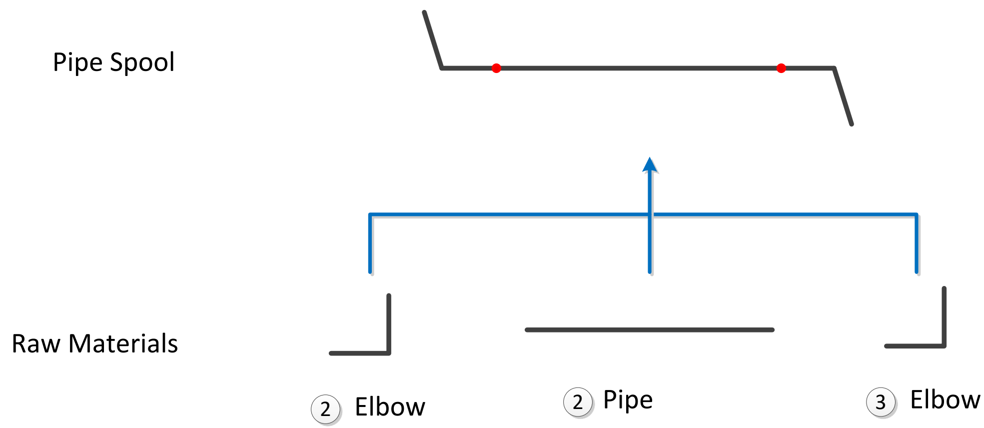


Figure 5-21 planned fabrication order for pipe spool No. 6

Table 5-45 presents fitting, handling and welding durations in details for the pipe spool.

Table 5-45 Fitting, handling and welding durations for pipe spool No.6

Day	Point No.	Size (DI)	No. of Fitters	No. of Handlers	No. of Welders	Duration (Minutes)		
						Fitting	Welding	Handling
4	A	6"		2				1
4	1	6"	2			10		
4	2	6"	2			5		
4	A	6"		2				5
4	1	6"			1		30	30
4	2	6"			1		39	39
4	BAC	6"		2				4

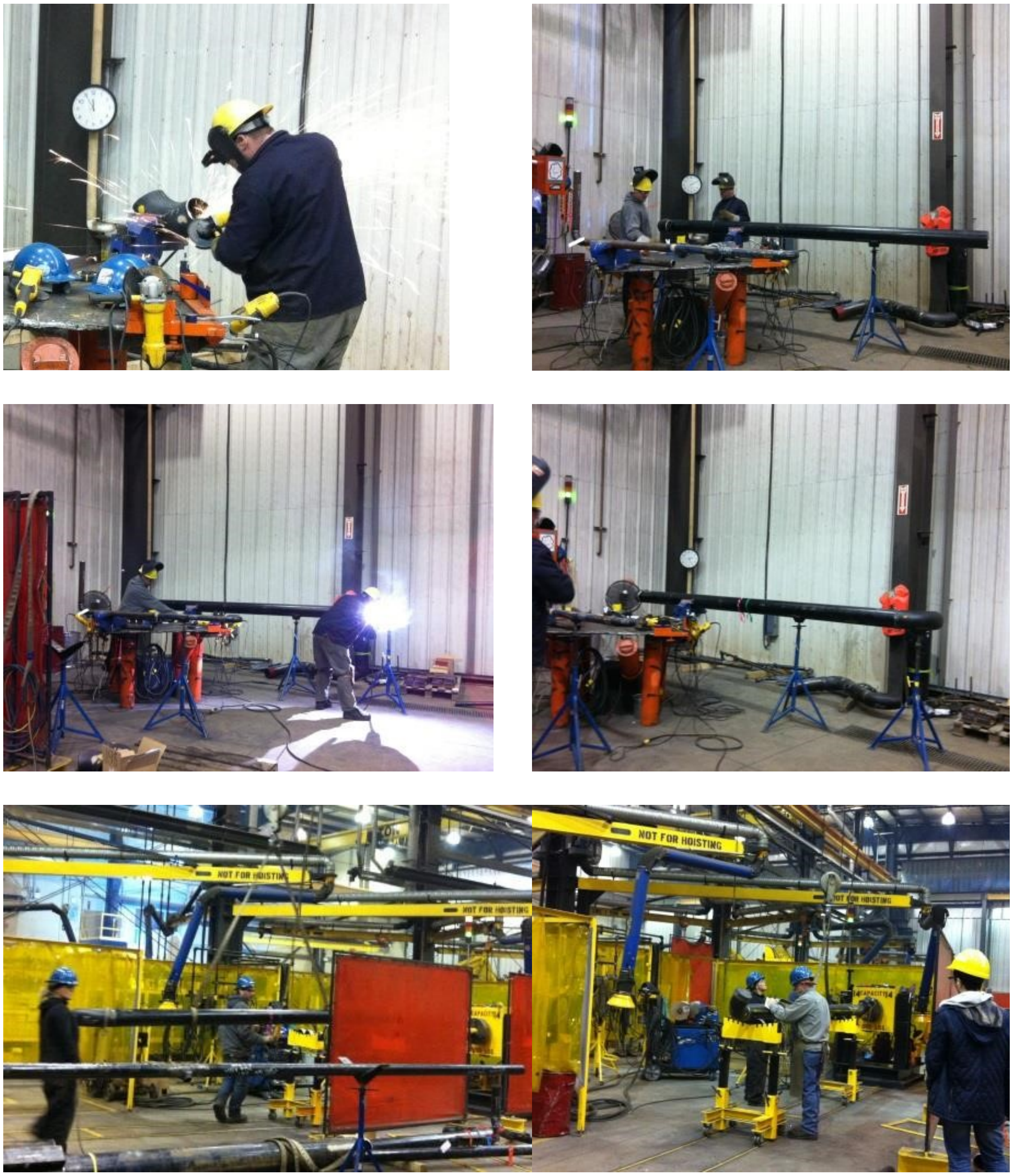


Figure 5-22 Fabrication process for pipe spool No. 6

Table 5-46 shows the welding and fitting man-hours for two fitters and one welder. Table 5-47 indicates handling man-hour for two handlers and Table 5-48 summarizes actual labour data.

Table 5-46 Fitting and welding Man-hours

Weld Point No.	Description	Size	Fitting Duration (HR)	Welding Duration (HR)	Total Welding MHr
1	Butt Weld	6"	0.17	0.50	0.83
2	Butt-Weld	6"	0.08	0.65	0.82

Table 5-47 Handling man-hours

Item	Size	Handling MHr	No. of Handlers	Total Man-Hours
Pipe handling	6"	0.17	2	0.17 × 2 = 0.34

Table 5-48 Summary of the actual labour data

Weld Point No.	Description	Size	Actual man-hours
	Pipe handling	6"	0.34
1	Butt Weld	6"	0.83
2	Butt-Weld	6"	0.82
		Total man-hours	1.99

5.5.7 Pipe Spool No. 7

Figure 5-23 demonstrates the Isometric drawing of pipe spool No. 7.

The pipe spool comprises four 6" butt welds (weld point 1-4), one 3/4" olet weld (weld point 5) and two 3/4" socket welds (weld points 6 and 7). Both pipe and olet has the same schedule (40) while pipe nipple‘s schedule is 160. Three pipes are connected with two elbows and one gate valve (H) is be attached to the pipe through a pipe nipple (G) and a sockolet (D).

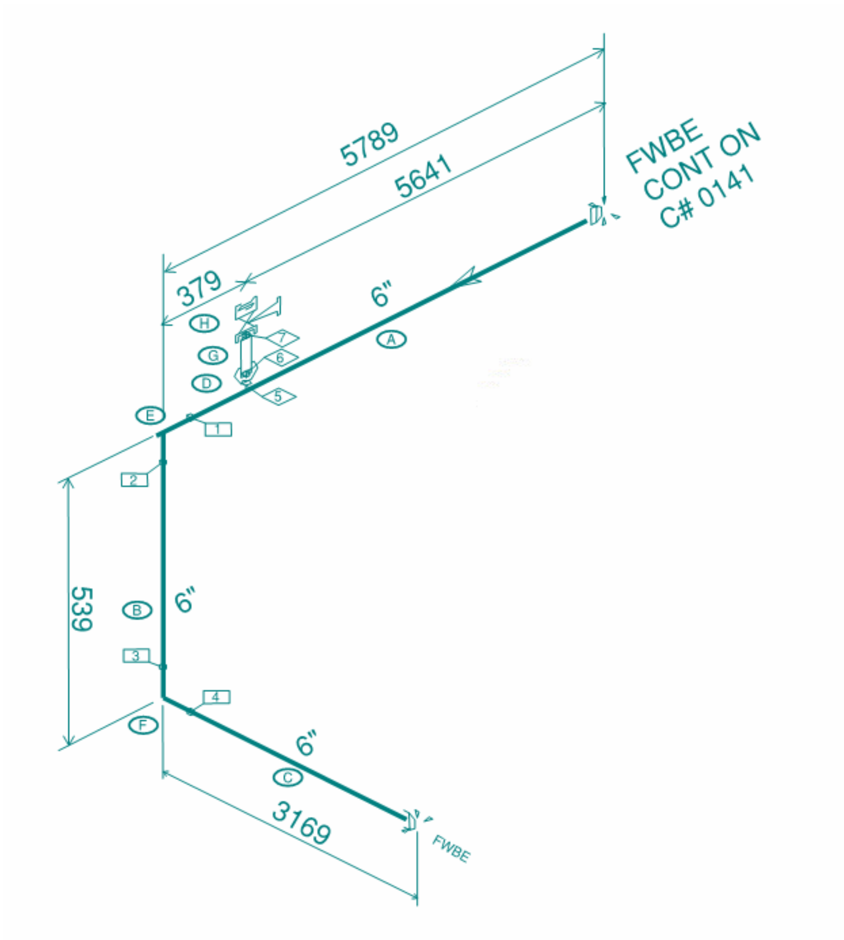


Figure 5-23 Isometric drawing of pipe spool No. 7

Man-hours estimate

Table 5-49 shows the quantity take-off and Table 5-50 demonstrates the cost estimates for this pipe spool. Total length of 6-inch pipes is 10.5 meters including elbows and total length of 3/4-inch pipes (pipe nipple) is considered to be 0.2 meters. These numbers are converted to 34.45 and 0.66 feet respectively.

Table 5-49 Quantity Take-off for pipe spool No. 7

Size	Description	Wall	Quantity
6"	Handling	Sch 40	34.45(ft)
3/4"	Handling	Sch 160	0.66(ft)
6"	Bevel End	Sch 40	2
6"	Cut End	Sch 40	2
6"	Butt-Weld	Sch 40	4
3/4"	Socket Weld 3000	Sch 160	2
3/4"	Olet Weld 3000	Sch 40	1

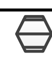
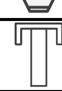
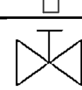
Table 5-50 Cost estimate for pipe spool No. 7

Item	Size	Wall Thickness	Quantity	MH/Per Unit of measure	Total Man-Hours
Pipe handling	6"	Sch 40	34.45	0.051	2.62
Pipe handling	3/4"	Sch 160	0.66	0.039	0.026
Butt-Weld	6"	Sch 40	4	1.80	1.80
Socket Weld 3000	3/4"	Sch 160	2	1.48	2.96
Olet Weld 3000	3/4"	Sch 40	1	2.17	2.17
				Total Man-hour for the spool	**9.58**

Analysis of the actual labour data

Figure 5-24 and Table 5-51 demonstrate planned fabrication order and tagging plan developed for this pipe spool.

Table 5-51 Tagging plan for pipe spool No.7

Part No.	Description	Symbol	Tag ID	Weld point
B	6" Pipe		1	
E	Elbow		2	2
F	Elbow		3	3
C	6" Pipe		4	4
C	6" Pipe		5	1
D	Olet		6	5
G	3/4" Pipe nipple		7	6
H	Valve		8	7

This pipe spool was built in three consecutive days. Figure 5-25 depicts the fabrication process for this pipe spool.

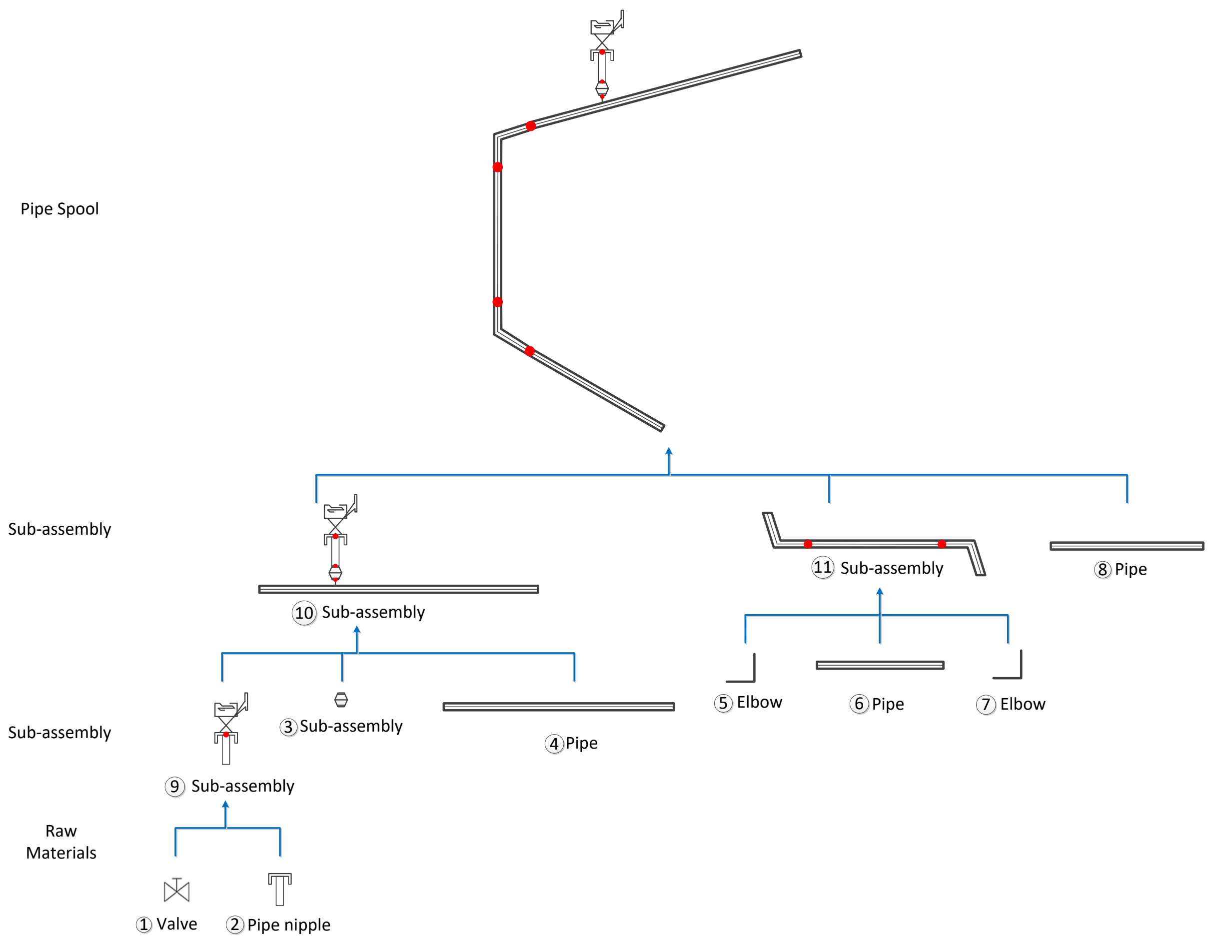


Figure 5-24 Planned fabrication order for pipe spool No. 7

Figure 5-25 fabrication process for pipe spool No. 7

Table 5-52 shows fitting, handling and welding durations for the pipe spool.

Table 5-52 Fitting, welding and handling durations for pipe spool No. 7

Day	Point No.	Size (DI)	No. of Fitters	No. of Handlers	No. of Welders	Duration (Minutes)		
						Fitting	Welding	Handling
6	B	6"		2				5
6	2	6"	2			17		
6	3	6"	2			18		
6	B	6"		2				2
6	7	3/4"	2			3		
6	B	6"		2				4
6	2	6"			1		18	
6	2	6"			1		22	
6	3	6"			1		20	
6	3	6"			1		8	
7	C	6"		2				1
7	4	6"	2			8		
7	EBFC	6"		2				2
7	7	3/4"	2		1		28	
7	EBFC	6"		2				5
7	4	6"			1		34	
7	EBFC	6"		2				1
7	A	6"		2				3
7	5	3/4"	2			9		
8	A	6"		2				3
8	5	3/4"			1		43	
8	6	3/4"	2		1	1	19	
8	A	6"		2				1
8	EBFC	6"		2				9
8	4	6"	2		1	39	1	
8	AEBFC	6"		2				4

Table 5-53 and Table 5-54 presents the total welding and handling man-hours for each welding points and pipe size for pipe spool No. 7. Table 5-55 summarizes actual collected labour data.

Table 5-53 Total welding man-hours for pipe spool No. 7

Weld Point No.	Description	Size	Fitting Duration (HR)	Welding Duration (HR)	Total Welding MHr
1	Butt Weld	6"	0.65	1.00	2.30
2	Butt Weld	6"	0.28	0.67	1.23
3	Butt Weld	6"	0.30	0.47	1.07
4	Butt Weld	6"	0.13	0.57	0.83
5	Olet Weld 3000	3/4"	0.15	0.72	1.02
6	Socket Weld 3000	3/4"	0.02	0.32	0.35
7	Socket Weld 3000	3/4"	0.05	0.47	0.57

Table 5-54 Total handling man-hours for pipe spool No. 7

Item	Size	Handling HR	No. of handlers	Total Man-Hours
Pipe handling	6"	0.67	2	1.33
Pipe handling	3/4"	0.13	2	0.27

Table 5-55 Summary of the actual fabrication man-hours for spool No.7

Weld Point No.	Description	Size	Actual man-hours
	Pipe handling	6"	1.33
	Pipe handling	3/4"	0.27
1	Butt Weld	6"	2.30
2	Butt Weld	6"	1.23
3	Butt Weld	6"	1.07
4	Butt Weld	6"	0.83
5	Olet Weld 3000	3/4"	1.02
6	Socket Weld 3000	3/4"	0.35
7	Socket Weld 3000	3/4"	0.57
		Total man-hours	**8.97**

5.5.8 Pipe spool No. 8

Figure 5-26 shows the Isometric drawing of pipe spool No.8.

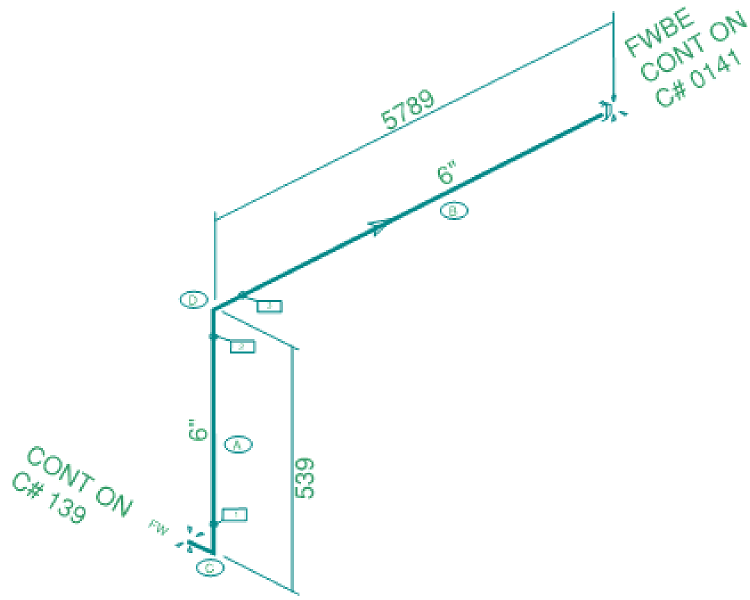


Figure 5-26 Isometric drawing of pipe spool No.8

The pipe spool comprises three 6" butt welds (weld points 1-3). The specs show that spool includes two 6" elbows and two 6" pipe all with the same schedule (Sch40).

Man-hours estimate

Table 5-56 shows the cost estimate of this pipe spool. The pipe length is 7.3 meters which includes two elbows as well.

Table 5-56 Cost estimate for pipe spool No.8

Item	Size	Wall Thickness	Quantity	MH/Per Unit of measure	Total Man-Hours
Pipe handling	6"	Sch 40	23.95	0.051	1.22
Butt Weld	6"	Sch 40	3	1.80	5.4
			Total Man-hour for the spool		**6.62**

Analysis of the actual labour data

Table 5-57 Tagging plan for pipe spool No. 8

Part No.	Description	Symbol	Tag ID	Weld point
A	6" Pipe		1	
B	Elbow		2	1
C	Elbow		3	2
A	6" Pipe		4	3

Table 5-57 presents the tagging plan for this pipe spool. After the pipe A is moved to the fitting station, it is connected to the elbow C and D from each pipe end in. None of the tags are removed except tag 1 as to record the fitting and welding duration for each weld point. The whole piece is then taken to the lay down area at the end of day 1 and was sent back to the welding station on the second day to perform both butt welds all at once. After the welding was done, the tags were removed. Pipe B was sent to the fitting station to get prepared and be joined to the last sub assembly (CAD). After the two pieces were welded in the welding station, the whole pipe spool was sent to the laydown area for the inspection. Tag 4 then recorded the fitting and welding for weld point 3. Figure 5-27 demonstrates the planned fabrication order for the pipe spool and Figure 5-28 depicts its fabrication process.

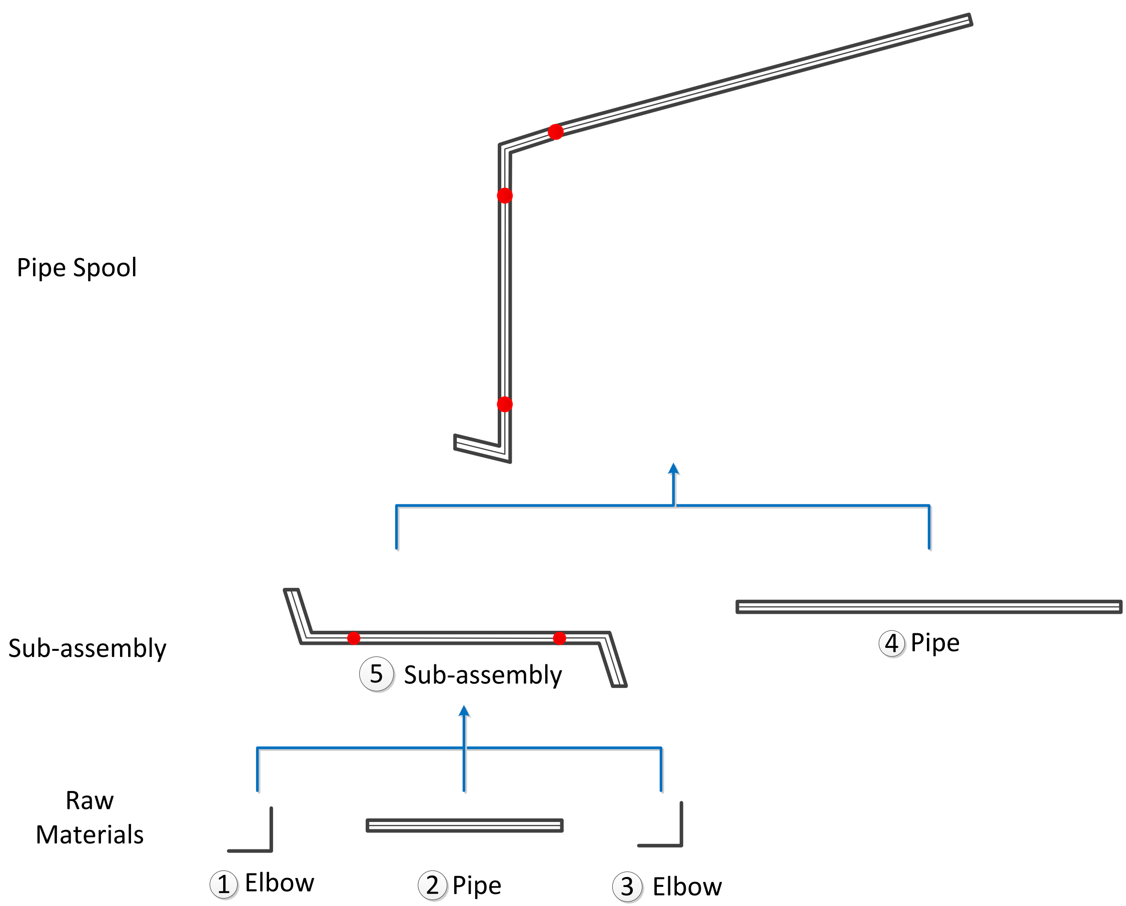


Figure 5-27 Planned fabrication order for pipe spool No. 8

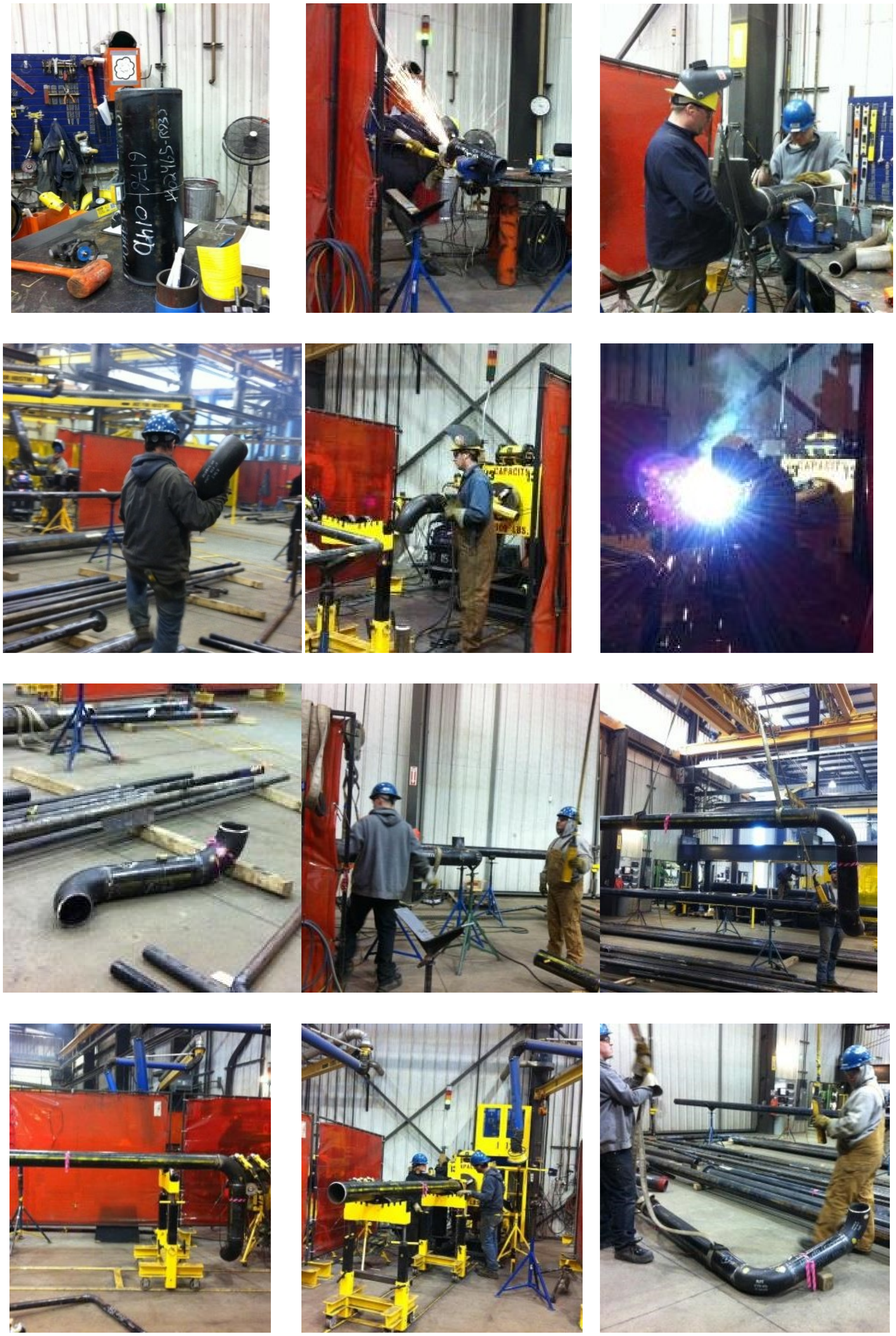


Figure 5-28 Fabrication process for pipe spool No. 8

Table 5-58 presents fitting, handling and welding durations collected for the pipe spool.

Table 5-58 Fitting, handling and welding durations for pipe spool No.8

Day	Point No.	Size (DI)	No. of Fitters	No. of Handlers	No, of Welders	Duration (Minutes)		
						Fitting	Welding	Handling
4	A	6"		1				1
4	1	6"	2			22		
4	2	6"	2			19		
4	A	6"		1				2
5	B	6"		2				2
5	B	6"	2			24		
5	ADC	6"		2				4
5	1	6"			1		28	
5	2	6"			1		40	
5	ADC	6"		2				4
5	3	6"				15		
5	3	6"				9		
5	ADCB	6"						8
5	3	6"			1		70	
5	ADCB	6"						4

Table 5-59 shows the welding and fitting man-hours for two fitters and one welder. Table 5-60 indicates handling man-hour for two handlers and Table 5-61 summarizes actual labour data.

Table 5-59 Fitting and welding Man-hours

Weld Point No.	Description	Size	Fitting Duration (HR)	Welding Duration (HR)	Welding MHr
1	Butt Weld	6"	0.37	0.47	1.20
2	Butt-Weld	6"	0.32	0.67	1.30
3	Butt-Weld	6"	0.65	1.15	2.45

Table 5-60 Handling man-hours

Item	Size	Wall Thickness	Handling Hr	No. of handlers	Total Man-Hours
Pipe handling	6"	Sch 40 (0.280)	0.37	2	0.73
Pipe handling	6"	Sch 40 (0.280)	0.05	1	0.05

Table 5-61 Summary of the actual fabrication man-hours for spool No.8

Weld Point No.	Description	Size	Actual man-hours
	Pipe handling	6"	0.78
1	Butt Weld	6"	1.20
2	Butt-Weld	6"	1.30
3	Butt-Weld	6"	2.45
		Total man-hours	**5.73**

5.6 Adjustment Factors

Similar to Page & Nation data, experimental data can be used to determine labour productivity norms for fabrication activities if the system is used over a long enough period of time. In addition, job-specific adjustment factor can be determined (by dividing actual labour productivity norms by Page and Nation norms) for estimating the fabrication tasks.

Table 5-62 Actual labour productivity norms vs. Page and Nation norms

Item	Description	Size	Actual labour productivity norms	Page & Nation 's labour productivity norms
1	Olet Weld	2"	1.75	4.2
1	Olet Weld 3000	3/4"	1.15	1.9
2	Olet Weld 3000	3/4"	1.02	1.9
1	Weld-neck flange	2"	1.5	1.05
1	Weld-neck Flange	3"	2.53	1.7
1	Butt-Weld	2"	0.72	0.9
2	Butt-Weld	2"	0.86	0.9
1	Butt-Weld	3"	0.88	1.1
1	Butt-Weld	6"	1.93	1.8
2	Butt Weld	6"	1.97	1.8
3	Butt-Weld	6"	2.3	1.8
4	Butt-Weld	6"	1.77	1.8
5	Butt-Weld	6"	0.73	1.8
6	Butt-Weld	6"	0.8	1.8
7	Butt-Weld	6"	2	1.8
8	Hydro Weld	6"	1.1	1.8
9	Butt Weld	6"	0.92	1.8
10	Butt Weld	6"	0.83	1.8
11	Butt-Weld	6"	0.82	1.8
12	Butt Weld	6"	2.3	1.8
13	Butt Weld	6"	1.23	1.8
14	Butt Weld	6"	1.07	1.8
15	Butt Weld	6"	0.83	1.8
16	Butt Weld	6"	0.83	1.8
17	Butt-Weld	6"	0.98	1.8
18	Butt-Weld	6"	1.97	1.8
1	Socket Weld 3000	3/4"	0.23	0.6
2	Socket Weld 3000	3/4"	0.33	0.6
3	Socket Weld 3000	3/4"	0.35	0.6
4	Socket Weld 3000	3/4"	0.57	0.6

Once more, it should be noted that handling man-hour by Page and Nation also includes unloading pipe from railroad cars or trucks which is not captured in our experiment, so they might not be fully comparable with the collected data. In addition, position welds are considered in butt welds group, however, a different productivity norm could be considered for these types of welds if desired.

Table 5-62 presents the actual labour productivity norms vs. Page and Nation norms. Table 5-63 demonstrates the adjustment factors. Wherever more than one data was observed for the same type of weld, the average of the data records was used.

Table 5-63 Adjustment factors for labour productivity norms

Description	Size	Actual Norms	Page & Nation Norms	Adjustment factor
Olet Weld 3000	2"	1.75	4.2	0.42
Olet Weld 3000	3/4"	1.09	1.9	0.57
Weld-neck flange	2"	1.50	1.05	1.43
Weld-neck Flange	3"	2.53	1.7	1.49
Butt-Weld	2"	0.79	0.9	0.88
Butt-Weld	3"	0.88	1.1	0.80
Butt-Weld	6"	1.35	1.8	0.75
Socket Weld 3000	3/4"	0.37	0.62	0.60

5.7 Project Performance Assessments

The process of comparing actual project performance against planned performance and identifying variances from planned performance is called project performance assessment (AACE International 2004). It also includes methods for identifying opportunities for performance improvement and risk factors to be addressed. Corrective or change actions are then implemented as appropriate through updated project control planning, which closes the project control cycle. At project closeout, the final assessments of project performance are captured in the project historical database for use in future project scope development and planning. Performance against each aspect of the project plan must be assessed. Project cost accounting measures of the commitment and expenditure of money are compared to the cost plan or budget. Resource tracking measures (e.g., consumption of labour-hours) are compared to the resource plans. Schedule status (as reflected in the statused network schedule) is compared to the baseline or target schedule. In other words, day-to-day performance of planning activities is assessed against the project control budget for that phase, while the scope being planned is assessed against the capital budget. The level of understanding of project performance is increased when the assessment integrates the evaluation of each aspect of the project plan. One method of integrating schedule and budget assessment is called earned value management (EVM). The method is objective, quantitative, and effectively identifies variances from planned schedule and budget performance. For complete performance assessment, earned value techniques must be augmented with practices that identify opportunities and risks, not just variances. For labour, work sampling measures, work inspection observations, and other surveillance inputs provide information for assessing labour productivity issues. In this research, the collected labour data provides the relative information for labour productivity assessment.

5.7.1 Assess Work Process and Productivity

In general terms, labour productivity is defined as the ratio of the value that labour produces to the value invested in labour. In an absolute sense, it is a measure of the extent to which labour resources are minimized and wasted effort is eliminated from a work process (i.e., work process efficiency). In earned value assessment, productivity is a ratio (i.e., a factor) that compares the labour effort expended to that which was planned (sometimes called the "spent-earned ratio") (AACE International 2004). In earned value terms, productivity is calculated as follows:

Labour Productivity Factor = Expended Man-Hours / Earned Man-Hours,

where the earned man-hours = percent physical progress x control budget man-hours. To be useful, the control budget must reflect the current scope and quantities. However, in this case, a factor less than 1.00 is favorable. For example, if work was 60 percent complete on the labour cost account of a work package that had a budget of 200 man-hours, and 100 man-hours had been spent, then the productivity factor is 0.83 (i.e., = 100/(0.6 x 200). Care must be taken to understand the nature of any productivity factor that is quoted because alternate sources may use the inverse (i.e., a factor less than one is not favorable).

5.7.2 Rules of Credit

In progress management, the breakdown of the effort required for each step is called the “rules of credit”. Below is an example of piping rules of credit. Rules of Credit system goes hand in hand with EVM and is an ideal remedy for managing the subjective nature of applying percent complete on project tasks.

For any workpackage in the work breakdown structure, a project manager can define any number of milestone events that define the incremental progress of that task. Below is an example milestone of piping rules of credit (Westney 1997).

Table 5-64 n example of piping rules of credit

Activity	% of work
Pipe spool connections are cut	20
Pipe spool connections are welded	70
Pipe spool is ready for hydrotest	10

5.7.3 Productivity factor by iPMF

An example of man-hour report that measures work progress and productivity factor using the equivalent units (rules of credit) method for the sample work-package can be found in Table 5-65. The detailed description of each field in the daily production report for cost account of 03120 appears below.

1. The description column lists all subtasks for each pipe spool cost account.
2. The system measures and records the quantity completed each day for each of the following task: Handling and Welding. The cutting man-hours quantity is recorded by the field engineer.
3. The subtask quantities are totaled through the report cutoff date.
4. Each subtask is weighted according to the estimated level of effort required for that subtask. These weights are “rules of credit” and are listed for each subtask in Table 5-65.

5. For this account 17.35 man-hours of pipe was cut, handled and welded by day 3. The subtotal for each subtask is totaled to obtain the actual quantity for the account. The total of 17.35 is the sum of 0.75 man-hours (Cutting) plus 2.52 man-hours (Handling) plus 14.08 man-hours (Welding).
6. Assume that the labour budget required to complete this cost account is 18.50 man-hours. This amount is multiplied by 0.90 (%20 + %70 = %90), the weight for welding pipes, to obtain a subtotal for the account of 16.65 man-hour.
7. The productivity factor is 0.90 (16.65/17.35) which is still less than 1.00.

Table 5-65 An example of man-hour report for the sample work-package

ISO Drawing No.	Cost Code	Description	Unit	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8
00045	03110										
		Cutting	Man-HR	0.47	-	-	-	-	-	-	-
		Handling	Man-HR	0.30	-	-	-	-	-	-	-
		Welding	Man-HR	0.08	-	-	-	-	-	-	-
		Ready for Hydrotest?	Y/N	Y	-	-	-	-	-	-	-
00046	03120										
		Cutting	Man-HR	0.75	-	-	-	-	-	-	-
		Handling	Man-HR	0.95	-	1.57	-	-	-	-	-
		Welding	Man-HR	4.60	-	9.48	-	-	-	-	-
		Ready for Hydrotest?	Y/N	N	N	Y	-	-	-	-	-
000139	03130										
		Cutting	Man-HR	0.52	-	-	-	-	-	-	-
		Handling	Man-HR	-	-	-	0.33	0.33	-	-	-
		Welding	Man-HR	-	-	-	1.07	1.57	-	-	-
		Ready for Hydrotest?	Y/N	N	N	N	N	Y	-	-	-
000140	03140										
		Cutting	Man-HR	0.70	-	-	-	-	-	-	-
		Handling	Man-HR	-	-	-	0.05	0.73	-	-	-
		Welding	Man-HR	-	-	-	1.37	3.90	-	-	-
		Ready for Hydrotest?	Y/N	N	N	N	N	Y	-	-	-
000141	03150										
		Cutting	Man-HR	0.48	-	-	-	-	-	-	-
		Handling	Man-HR	-	-	-	0.33	-	-	-	-
		Welding	Man-HR	-	-	-	1.65	-	-	-	-
		Ready for Hydrotest?	Y/N	N	N	N	Y	-	-	-	-
000142	03160										
		Cutting	Man-HR	1.04	-	-	-	-	-	-	-
		Handling	Man-HR	-	-	-	-	-	0.20	0.40	0.57
		Welding	Man-HR	-	-	-	-	-	2.40	1.60	2.38
		Ready for Hydrotest?	Y/N	N	N	N	N	N	N	N	Y
000227	03170										
		Cutting	Man-HR	0.65	-	-	-	-	-	-	-
		Handling	Man-HR	0.22	1.38	-	-	-	-	-	-
		Welding	Man-HR	4.68	3.68	-	-	-	-	-	-
		Ready for Hydrotest?	Y/N	N	Y	-	-	-	-	-	-

000228	03180	Cutting	Man-HR	0.80	-	-	-	-	-	-	-
		Handling	Man-HR	-	-	-	0.25	-	-	-	-
		Welding	Man-HR	-	-	-	0.07	-	-	-	-
		Ready for Hydrotest?	Y/N	N	N	N	Y	-	-	-	-

5.8 Conclusions

This chapter included the results and discussion of a real-world case study, the fabrication of eight pipe spools that form the experiment work-package, which was carried out to verify the feasibility of the implemented iPMF in terms of providing the actual labour productivity norms for the collaborating partner company. Subsequently, a parametric study was conducted to calculate the labour productivity norms and adjusting factors. Ultimately, the process of project performance assessment in iPMF was presented based on the actual daily labour-hours provided for each piping fabrication activity.

Similar to industrial benchmark data, experimental data can be used to determine labour productivity norms for fabrication activities if the system is used over a long enough period of time. In addition, job-specific adjustment factor can be determined for estimating the fabrication tasks.

CHAPTER 6

6 Conclusions

6.1 Remarks

Mega industrial projects frequently suffer from cost overruns and schedule slippages. As projects increase in size, and become more complex, managing these projects becomes more challenging. Insufficient project planning is identified as one of major factors contributing to poor project performance. On the other hand, progress measurement is a crucial component of effective project control. Unless we are aware of what is going on, the project team will be in a continual reactive mode. Effective progress measurement helps to identify the variances to the plan early enough to either mitigate the impact, or seize the opportunity of optimal decisions and actions. Ineffective progress measurement is costly, provides no useful data, and can serve to cloud the real issues.

In order to measure the progress of a project several prerequisites must occur first including an estimate, a plan and execution schedules.

1. The Estimate holds project hours from which the resource-loaded schedules can be built and provides the basis for which measurement becomes possible.
2. The plan allows the baseline for which to measure progress against and will inform project management if they are meeting planned objectives.

For both, visibility into actual labour costs (in terms of labour-hours) in a timely fashion is a key. In today's world of rising labour costs and labour shortages, advanced wireless technologies are utilized to improve efficiencies. In modularization of heavy industrial construction, the availability of actual labour cost and productivity data is important to accurate pricing and profitable billing but also provides a valid basis for cost estimating and progress monitoring on similar projects and also for shop production scheduling.

This research study is aimed at improving current project estimation practices, project progress monitoring and project performance assessment in industrial module construction through (1) conducting automation and real time computing research and (2) developing prototype systems and implementing innovative project management framework and solutions in the practical reality of module construction in piping fabrication shop.

6.2 Research conclusions

This research study advances the existing knowledge of industrial construction projects and, while improving the existing practice of industrial construction cost estimation for pipe spool fabrication processes with providing the actual labour productivity norms. For this purpose, this dissertation describes and implements an integrated framework called iPMF for a real-world case study in a pipe fabrication shop. The developed system utilizes a wireless sensor network based indoor positioning system for real time localizing and tracking pipe spool fabrication process.

In the first part of the research, the feasibility of applying Received Signal Strength (RSS) based methods in an indoor application setting was evaluated. The objective of this study was to identify the effective method for positioning and tracking resources with sufficient localization accuracy and reliability as needed in tracking pipe spools inside a fabrication shop. As given in Chapter 2, the RSS ranging method plus trilateration-based localization algorithms and a RSS profiling method are contrasted and illustrated with calculation examples. The feasibilities of applying both methods in a building site environment and the piping spool fabrication shop are specifically evaluated and compared so as to achieve the positioning accuracy of 1-2 meters with high reliability. This accuracy is generally accepted as the sufficient positioning performance for resource tracking and field productivity measurement in construction. In order to assess the performance of these methodologies, an indoor experiment was conducted in a carpark, identifying two limitations for the RSS ranging-based method: (1) the performance of the geometric trilateration algorithm depends on the accuracy of distance measurements from RSS; therefore, any error in the estimated ranges is directly propagated in the error of the positioning system; (2) it is impractical to produce sufficient positioning results due to large ranging errors. It was also found that localization performances in indoor environments can be improved by utilizing the RSS profiling-based method with achieving less than 2.14 meters position error with 95% likelihood.

The profiling-based method was then coupled with commonly used noise filtering algorithms in order to conduct field testing in a pipe fabrication shop and evaluate the accuracy of this method in a practical indoor environment. With 95% likelihood, consistent positioning accuracy of 1-2 meters away from the actual position of a tracked tag was obtained in the fabrication shop. The methodology was found to potentially serve the needs of tracking components and labour-hours in connection with handling and connecting those components within a typical work zone inside the fabrication shop. However, in a dynamic indoor application setting such as the spool fabrication, the RSS-based localization performance is susceptible to frequent reconfiguration of the work zone for handling different jobs. The positioning performances of this method would deteriorate accordingly, so there was a need to conduct re-profiling task frequently which was time-consuming and labour-intensive.

In Chapter 3, we introduce a fundamentally new approach for indoor localization that overlaps the transmissions of signals. While indoor localization is a very active research area in construction management, to the best of our knowledge, there was no previous attempt to evaluate and apply a collision-based approach in construction industry. The collision-based method employs the capture effect, which means that when several radio signals collide, only the strongest (nearest) signal is detected. Under normal circumstances overlapping transmissions cause all packets to be destroyed, or to be damaged to the extent that contents can't be recovered. However because of a phenomenon called the capture effect the mobile node does in fact receive the packet which has the strongest signal, which is from the closest beacon node.

The colliding localization method was first proposed by Braiman (2011) based on the beacon-based location architecture. The decay factor mechanism was added to the collider module in order to weaken the mass of cells that are no longer relevant over time. The colliding method is then combined with a zone detection method. In the proposed method, first the colliding localization algorithms calculate the location of the tag. Since one beacon, whose location is known, is placed in and allocated to each working zone, the server then compares tag location to the location of beacons in the zones to find the closest beacon and thus the closest zone. Subsequently, point-in-polygon (PIP) is used to determine whether the tag is located inside or outside the zone. Application of the proposed localization method is further demonstrated with lab testing examples.

Ultimately, the use of the proposed collision-based indoor positioning system was explained for real-time localizing and tracking pipe spools and to support the integrated Project Management Framework (iPMF) developed for monitoring the pipe spool fabrication process and to collect project labour cost. The development of the integrated Project Management Framework (iPMF) is also described. This framework integrates fabrication process planning and tracking with the drawings and document control system and the materials management system and allows its users to obtain information about the labour cost and production process.

As denoted in Chapter 4, the localization system validation was described with the details of a series of experiments that were conducted in the fabrication shop of the partner company. A dynamic error test was conducted in the fabrication shop for tracking and localizing pipe and fittings to evaluate the accuracy and reliability of the proposed collision-based localization methodology explained in chapter 3. The test results indicated that combining the zone localization with colliding method and Kalman filter can provide an average accuracy location down to half meter. It can be concluded that, beacon readers deployed using the proposed zone-based system, along with colliding method and Kalman filter can warrant high percentage accuracy in tag localization.

After validation of the positioning system, the proposed spool component tagging strategy was presented, which depends on the fabrication method and sequence. The applicability of the iPMF framework to the industrial labour data collection was simulated through a number of experiments conducted in the same fabrication shop. Actual data on the labour-hours was collected manually by observing the fabrication activities to simulate labour-hours data that can be collected automatically by iPMF in order to demonstrate its value proposition. In the end, the experiment measurements were analyzed to simulate the feasibility of the iPMF in tracking actual labour-hours.

Eventually, Chapter 5 includes the results and discussion of a real-world case study, the fabrication of eight pipe spools that form the experiment work-package, which was carried out to illustrate the essential features and capabilities of the implemented iPMF in terms of providing the actual labour productivity norms for the collaborating partner company. Subsequently, a parametric study was conducted to calculate the labour productivity norms and adjusting factors for estimating the cost of pipe fabrication for the experiment work-package. It was shown that, similar to industrial benchmark resources, experimental data can be used to determine labour productivity norms for fabrication activities if the system is used over a long enough period of time. In addition, job-specific adjustment factor can be determined for estimating the fabrication tasks. At last, the process of project performance assessment in iPMF was presented based on the actual daily labour-hours provided for each piping fabrication activity.

The proposed system is not only able to automatically track actual labour-hours and thus actual labour cost and project progress in real-time, it can also provide estimators with precise and accountable labour productivity norms for project cost estimation , if used over a long enough period of time.

The results from this study will help owners and contractors to understand the variability in process piping estimates and the importance of calibrating existing methods before applying them on real-world projects. This information can also be useful in analyzing the risk associated with the project's capital costs and resolving estimating issues.

6.3 Limitations and future works

This research also depicts a number of areas that have potential room for improvement. Further research efforts could be invested in following areas:

1. Realization of the full potential of iPMF, particularly to develop the precise labour productivity norms for each task in pipe fabrication process,

requires collecting sufficient and frequent amount of data. The developed project management framework needs to be tested with more real-world pipe spool fabrication projects to validate its contribution to the management and competitiveness of the projects. In addition, computing algorithms of the iPMF system can be fine-tuned to include the monitoring of the cutting phase in spool fabrication as well.

2. In reality, every operation from decision to weld can be legitimately charged to weld fabrication. The greater the number of factors considered when calculating welding costs, the more accurate the results will be. For instance, all of the following factors may be considered to be part of the cost of welding:

    a. Time for joint preparation
    b. Time to prepare the material for welding (blasting, etc.)
    c. Time for assembly
    d. Time for preheat the joint (when required)
    e. Time for tack-up
    f. Time for positioning
    g. Time for welding
    h. Time to remove slag or spatter
    i. Time for inspection
    j. Time for changing electrodes
    k. Time to move the welder from one location to another
    l. Change the welding machine setting

m. Time spent by personnel to consult about the operation

n. Time to repair or re-work defective welds

Unless the application requires unusually expensive alloys, the time associated with welding operations will typically dominate the welding cost. Of the factors identified in the preceding list, most are captured in our data collection. However, the accuracy of welding cost collection can be enhanced by exploring the ways to capture all of these factors.

3. Rule-based algorithms can be developed to recognize the wrong connections which would require rework. These algorithms will also be able to monitor the amount of the corresponding rework and evaluate the contributing factors to mitigate the cost overrun.

4. Module assembly yards are purpose built for erection of the largest transportable modules in each region and any other assemblies the clients need. This includes: pipe rack modules, horizontal process modules, vertical process modules, pump houses, well pads, compressor skids, and stair towers etc. While collaborating with the partner company, one of the biggest challenges facing the industry was found to be estimating the labour cost of module assembly process in the unstructured and uncontrolled environment of module assembly yard. Thus, it is also worth exploring opportunities of applying and extending the application of the iPMF from fabrication shop to the module assembly yard.

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Appendix 1 - Network infrastructure

The PrecyseTech Product Suite (PrecyseTech 2016) is a wireless real-time Remote Entity Awareness and Control (REAC) that surpasses the previous limitations of traditional RFID approaches. The foundation of the PrecyseTech N3 network protocol enables unparalleled operational scale and simplicity in deployment and maintenance. The product suite combines wireless sensor Smart Agents, network infrastructure and enterprise software to deliver end-to-end complete solutions for entity visibility and business process automation in the harshest environmental conditions like industrial construction sites.

Smart Agents

Offered in a variety of enclosures to address personnel, vehicle, equipment, and inventory tracking needs, the Smart Agent (Figure 0-1) can house multiple sensors and operate over two alternative ISM frequency bands. We employed smart agents as the receivers in our research study.

Figure 0-1 Smart agents from PrecyseTech

Beacon devices

The entity awareness network of the proposed localization architecture utilizes Precyse Beacons (Figure 0-2) that continuously transmit their ID over the air for location reference purposes. The Precyse Beacons is an alternative to the standard approach of most real time location systems, which are uni-directional and are based on densely wired reader architecture to determine location. These systems require at least three readers to provide a measurement for each "tag" to use triangulation to calculate location. This makes location accuracy dependent on a dense mesh of many readers, yielding a solution which is not very accurate and usually extremely expensive to purchase and install. A single beacon includes 4 independent beacon devices in one box and may operate over multiple radio frequencies simultaneously. With the N3 bi-directional network architecture, PrecyseTech was able to move from a reader-based to the Beacon-based approach, reducing infrastructure cost, simplifying the network, and increasing location accuracy.

Since the Precyse Beacon's transmission power can be wirelessly tuned to cover a changing range, the Precyse Beacons constitute an infrastructure that is capable to provide a suitable support to colliding localization method, combined with zone-based location from just three feet and up to a maximum of 1,000 feet accuracy. Smart Agent devices can use the beacon's data to either implement a zone location (one cell is enough) or colliding localization method in which multiple beacon signals are received by a Smart Agent to deliver high accuracy location. In our proposed localization method, both location approaches is combined together to further reduce cost, delivering business-need driven location accuracy for indoor environments of construction sites.

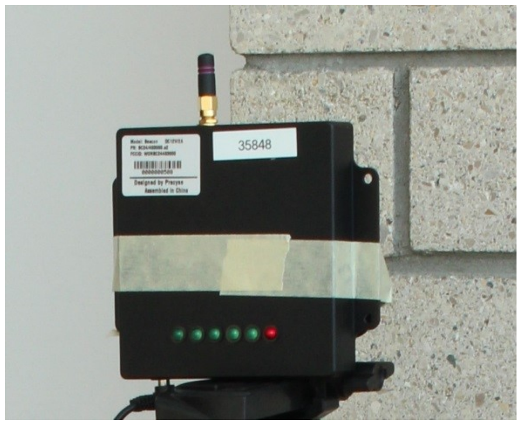


Figure 0-2 Beacon from PrecyseTech

Bridge Port

The PrecyseTech Bridge Port (Figure 0-3) is the network's wireless routing unit. The Bridge Port supports the N3 wireless protocol, providing two-way communication with Smart Agents and Precyse Beacons. It is a robust infrastructure device, built to operate under extreme environmental conditions, supporting thousands of Smart Agent transactions. The Bridge Port is available for indoor or outdoor operations, with custom models optimized for vehicle mounting, airborne operability or wall-mount.

The Bridge Port is a low maintenance, stand-alone device functioning over TCPIP networks – such as Ethernet, wireless LAN or cellular bridged. Utilizing two alternative ISM license-free frequency bands, the Bridge Port has an effective wireless range of up to one mile. It is configurable over the network and by default includes four RF channels.

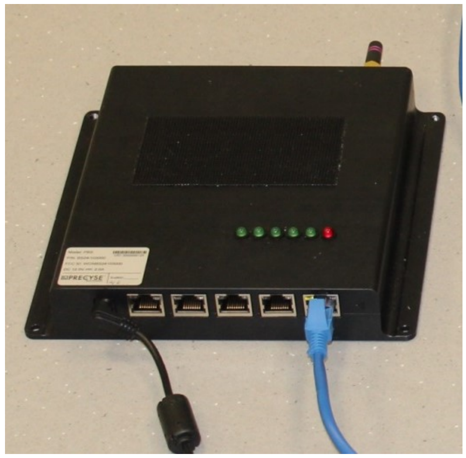
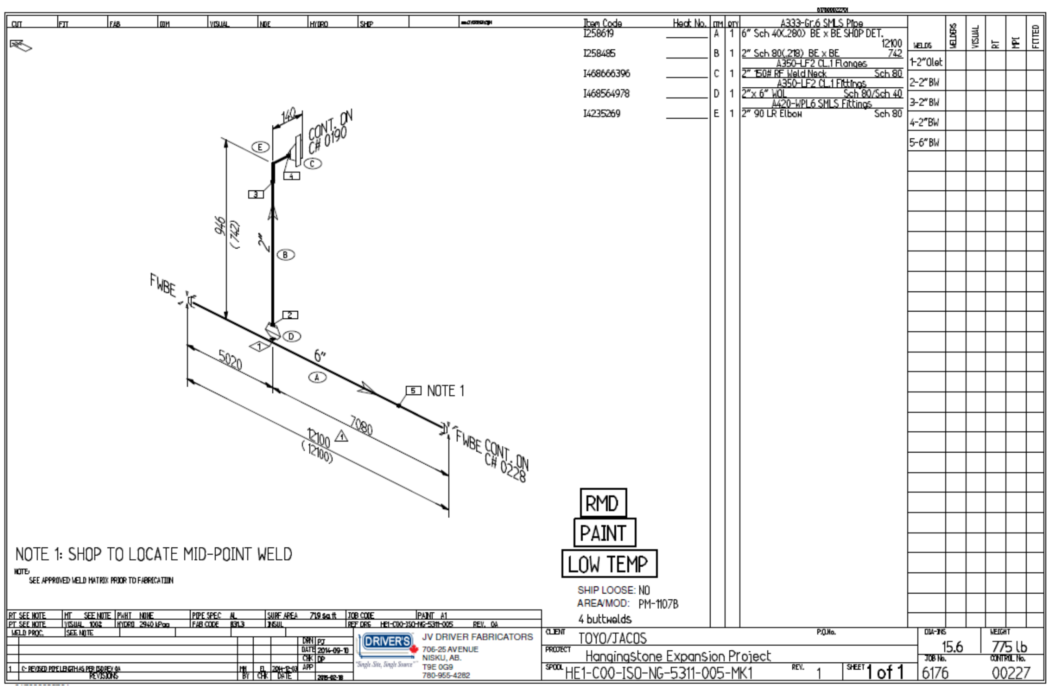


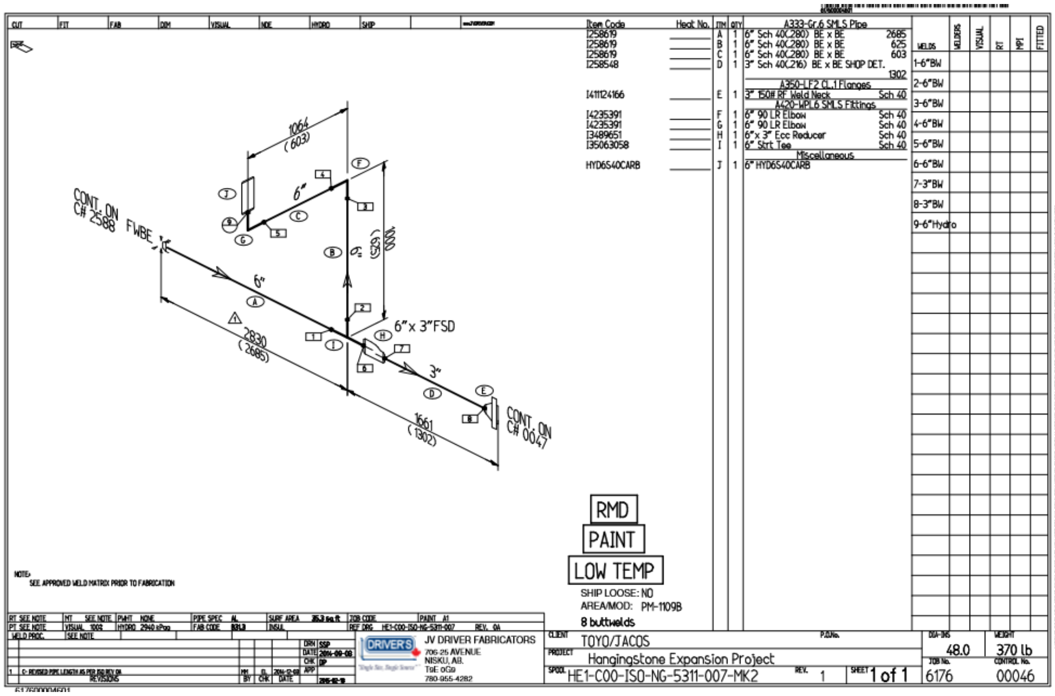
Figure 0-3 Bridge port from PrecyseTech

Appendix 2 - ISO drawings

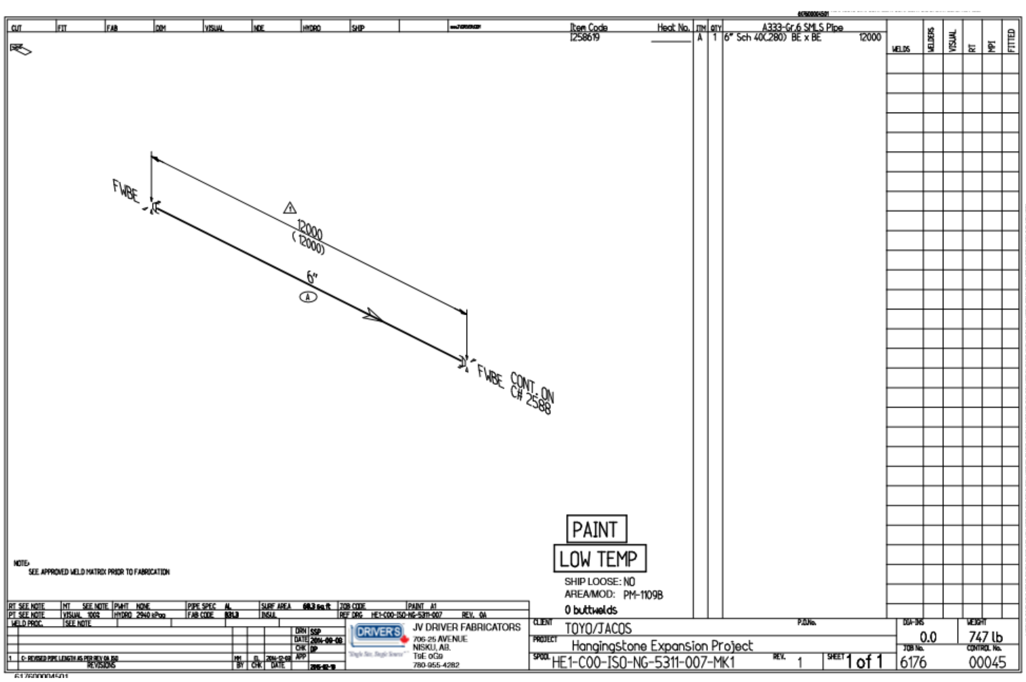
The following ISO drawings are selected from a work package for Hangingstone Expansion Project in Fort MacMurray, Alberta.



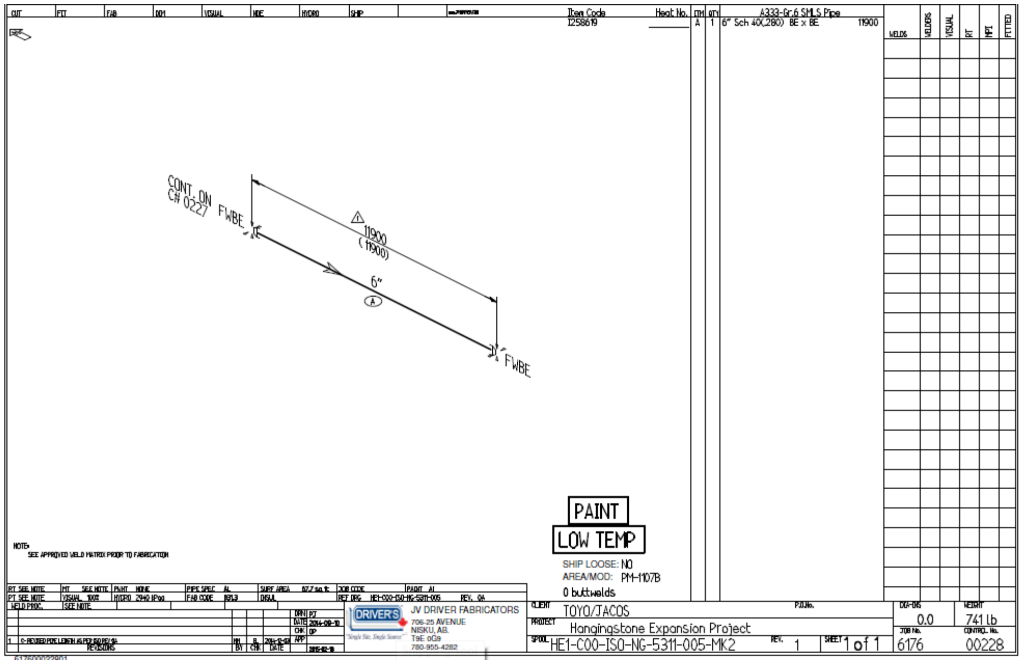
Isometric drawing of the pipe spool No.1



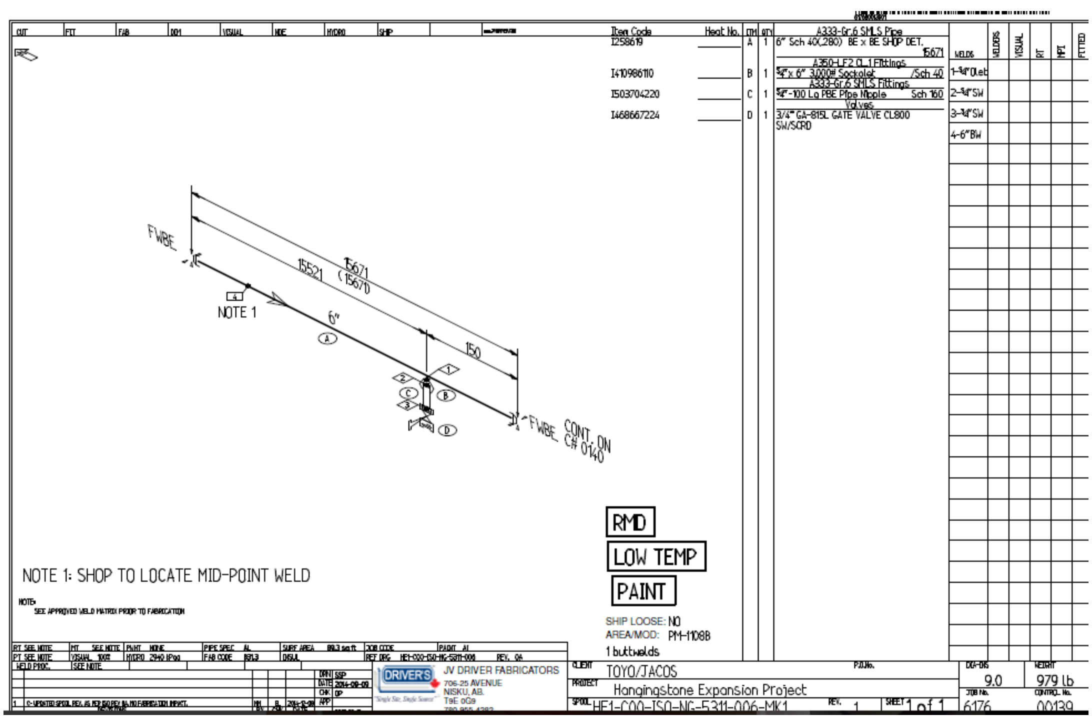
Isometric drawing of pipe spool No.2



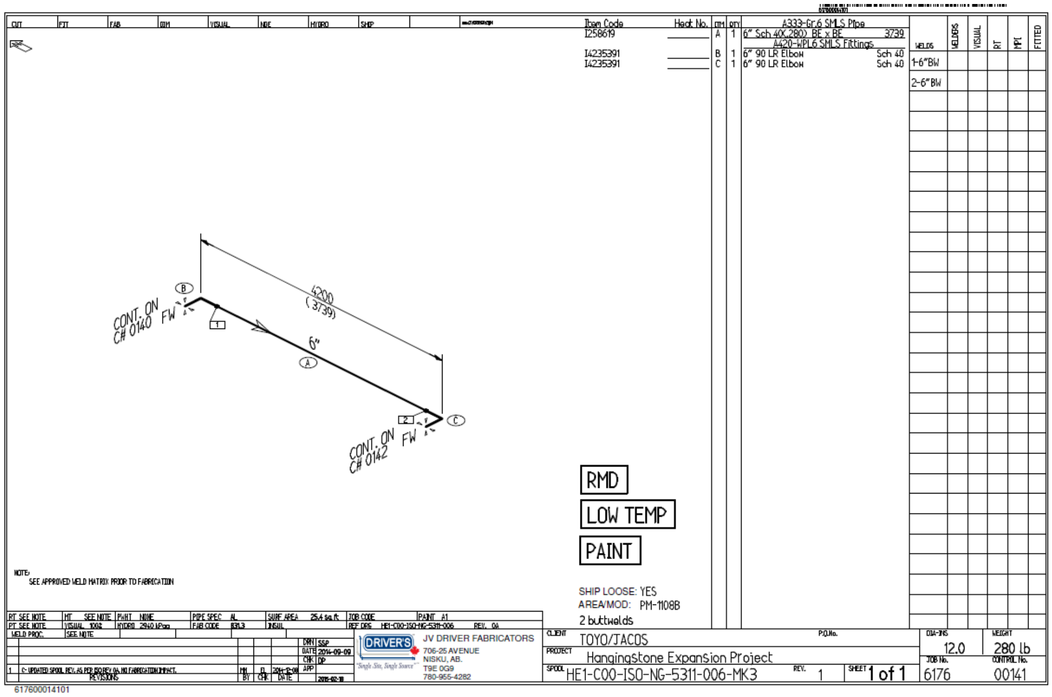
Isometric drawing of pipe spool No.3



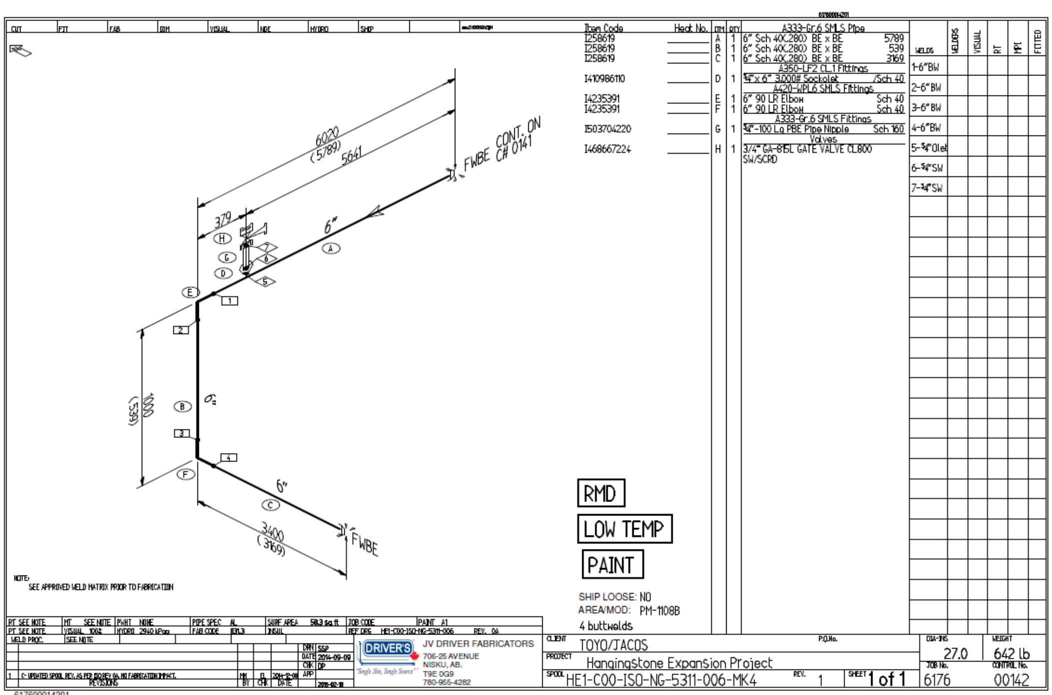
Isometric drawing of pipe spool No.4



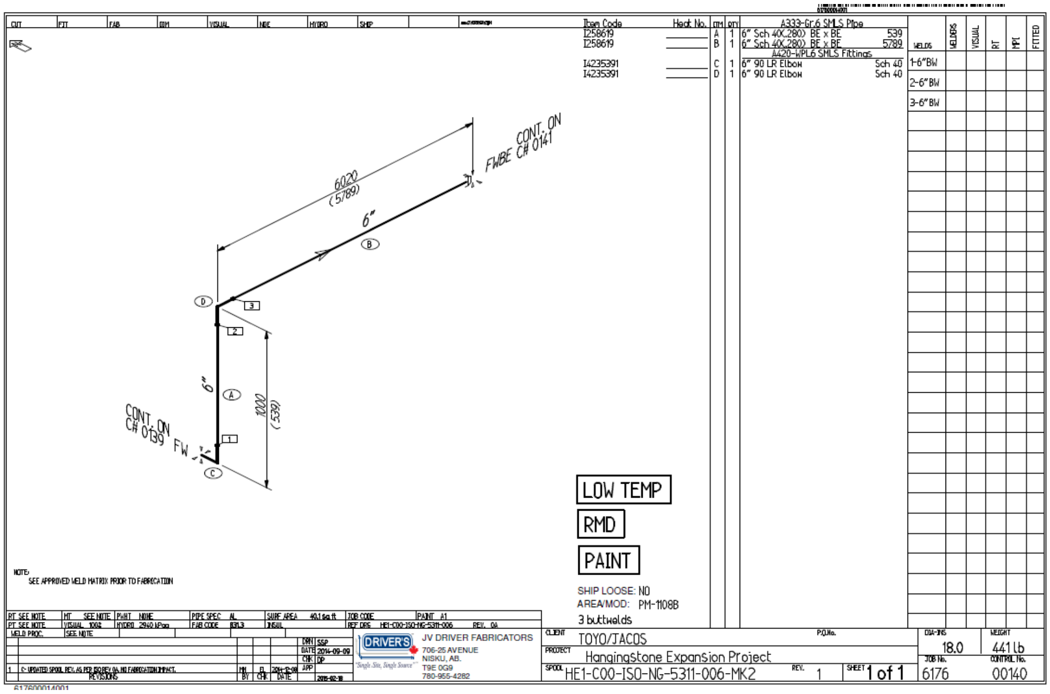
Isometric drawing of pipe spool No.5



Isometric drawing of pipe spool No.6



Isometric drawing of pipe spool No.7



Isometric drawing of pipe spool No.8

Appendix 3 - Man-Hour tables

All Man-Hour tables are selected from *Estimator's Piping Man Hour Manual* (Page 1999).

ATTACHING FLANGES—WELD NECK TYPE

Labor—Aligning Flange and Butt Welding

Carbon Steel Material
NET MAN HOURS EACH

Size Ins.	SERVICE PRESSURE RATING						
	150 Lb.	300 Lb.	400 Lb.	600 Lb.	900 Lb.	1500 Lb.	2500 Lb.
2	1.05	1.20	1.20	1.50	1.50	1.60	1.70
2½	1.40	1.60	1.60	1.80	1.80	1.90	2.20
3	1.70	1.90	1.90	2.20	2.20	2.30	2.40
4	2.10	2.30	2.30	2.60	2.60	2.90	3.00
6	2.90	3.20	3.20	3.50	3.50	3.90	4.00
8	3.60	3.90	3.90	4.30	4.30	4.90	5.10
10	4.50	4.80	4.80	5.30	5.30	6.10	6.20
12	5.25	5.70	5.70	6.30	6.30	7.40	8.00
14 OD	6.10	6.60	6.60	7.40	7.40	8.90	—
16 OD	7.10	7.70	7.70	8.60	8.60	11.30	—
18 OD	8.30	8.90	8.90	10.10	10.10	12.00	—
20 OD	9.10	9.90	9.90	11.20	11.20	14.30	—
24 OD	10.20	11.10	11.10	12.70	12.70	16.30	—
26 OD	—	—	12.03	13.76	13.76	—	—
30 OD	—	—	13.88	15.88	15.88	—	—
34 OD	—	—	15.73	18.00	18.00	—	—
36 OD	—	—	16.65	19.06	19.06	—	—
42 OD	—	—	19.43	22.23	—	—	—

Man-hour table for weld neck type flange for carbon steel material

'OLET TYPE WELDS

Labor For Cutting And Welding

Carbon Steel Material

NET MAN HOURS EACH

NOMINAL PIPE SIZE		Standard Weight And 2000#	Extra Strong And 3000#	Greater Than Extra Strong And 6000#
Outlet	Header			
1/2	All Sizes	1.3	1.7	2.2
3/4	All Sizes	1.6	1.9	2.6
1	All Sizes	1.8	2.2	2.9
1-1/4	All Sizes	2.0	2.5	3.3
1-1/2	All Sizes	2.5	3.2	4.3
2	All Sizes	3.4	4.2	5.6
2-1/2	All Sizes	4.0	5.1	6.7
3	All Sizes	4.6	5.9	9.2
4	All Sizes	6.1	7.4	9.8
5	All Sizes	6.9	8.1	11.9
6	All Sizes	7.6	8.6	13.9
8	All Sizes	8.4	9.2	16.4
10	All Sizes	11.8	16.9	26.3
12	All Sizes	16.5	19.6	38.9
14	14" and 16"	20.7	23.0	46.9
14	18" And Larger	18.4	20.7	51.0
16	16" and 18"	24.7	26.4	61.2
16	20" and Larger	21.8	23.8	66.3
18	18" and 20"	29.3	32.1	79.1
18	24" and Larger	25.8	28.4	85.2
20	20" and 24"	35.6	39.0	87.8
20	26" and Larger	31.0	34.7	94.6
24	24" and 26"	54.5	63.7	105.3
24	28" and Larger	45.9	55.1	113.5

Man-hour table for olet type welds for carbon steel material

MANUAL BUTT WELDS

Labor for Welding Only
Carbon Steel Materials

NET MAN HOURS EACH

Size Ins.	Standard Pipe & OD Sizes 3/8" Thick	Extra Heavy Pipe & OD Sizes 1/2" Thick	SCHEDULE NUMBERS								
			20	30	40	60	80	100	120	140	160
1	0.6	0.7	--	--	0.6	--	0.7	--	--	--	0.9
1-1/4	0.7	0.7	--	--	0.7	--	0.7	--	--	--	1.0
1-1/2	0.7	0.8	--	--	0.7	--	0.8	--	--	--	1.1
2	0.8	0.9	--	--	0.8	--	0.9	--	--	--	1.4
2-1/2	1.0	1.1	--	--	1.0	--	1.1	--	--	--	1.6
3	1.1	1.2	--	--	1.1	--	1.2	--	--	--	1.8
3-1/2	1.2	1.4	--	--	1.2	--	1.4	--	--	--	--
4	1.3	1.6	--	--	1.3	--	1.6	--	2.4	--	2.6
5	1.5	1.9	--	--	1.5	--	1.9	--	2.5	--	3.3
6	1.8	2.1	--	--	1.8	--	2.1	--	3.2	--	4.3
8	2.2	2.8	2.2	2.2	2.2	2.5	2.8	3.8	5.1	6.4	7.3
10	2.7	3.4	2.7	2.7	2.7	3.4	4.3	5.8	8.0	9.6	11.1
12	3.1	4.0	3.1	3.1	3.4	4.4	5.6	8.4	10.4	13.0	15.2
14 OD	3.6	4.8	3.6	3.6	4.2	5.8	8.1	11.2	13.7	16.3	19.2
16 OD	4.2	5.6	4.2	4.2	5.6	7.1	10.5	14.3	17.6	21.1	23.5
18 OD	4.9	6.5	4.9	5.7	7.3	9.5	13.9	18.5	21.7	25.4	28.6
20 OD	5.3	7.1	5.3	7.1	7.9	11.7	16.5	22.1	27.0	31.3	34.6
24 OD	5.9	8.5	5.9	10.5	11.2	17.0	26.3	30.4	36.9	41.8	50.2

Man-hour table for manual butt welds for carbon steel material

SHOP HANDLING PIPE FOR FABRICATION

Carbon Steel Material

Wall Thickness Through Schedule 160

DIRECT MAN HOURS PER FOOT

Pipe Size Inches	Schedule 10 to 60	Schedule 80 to 100	Schedule 120 to 160
1/4	0.029	0.031	0.033
3/8	0.029	0.031	0.035
1/2	0.030	0.033	0.036
3/4	0.030	0.034	0.039
1	0.031	0.036	0.041
1-1/4	0.033	0.039	0.044
1-1/2	0.035	0.041	0.049
2	0.036	0.044	0.053
2-1/2	0.039	0.048	0.059
3	0.041	0.053	0.065
3-1/2	0.044	0.055	0.068
4	0.045	0.058	0.071
5	0.048	0.063	0.079
6	0.051	0.070	0.091
8	0.063	0.088	0.119
10	0.079	0.110	0.149
12	0.096	0.134	0.183
14 OD	0.116	0.159	0.218
16 OD	0.138	0.186	0.254
18 OD	0.161	0.214	0.291
20 OD	0.189	0.241	0.329
24 OD	0.210	0.273	0.370

Man-hour table for shop handling pipe for fabrication for carbon steel material

90° COUPLING WELDS AND SOCKET WELDS

Labor For Cutting And Welding

Carbon Steel Material

NET MAN HOURS EACH

Pipe Sizes Inches	90°—3000# Coupling Weld	90°—6000# Coupling Weld	SOCKET WELDS	
			Sch. 40 & 80 Pipe	Sch. 100 & Heavier Pipe
1/2" or Less	1.4	1.7	0.5	0.5
3/4	1.6	1.9	0.5	0.6
1	1.8	2.2	0.6	0.7
1-1/4	2.1	2.5	0.8	0.9
1-1/2	2.3	2.8	0.8	1.0
2	2.9	3.6	0.9	1.3
2-1/2	3.4	4.2	1.1	1.4
3	4.0	4.9	1.2	1.7

Man-hour table for socket welds in fabrication shop for carbon steel material