COMPUTER AIDED PROCESS PLANNING SYSTEM FOR PIPE WELDING

A Thesis in
Industrial Engineering
by
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ABSTRACT

In this thesis, a Computer Aided Process Planning (CAPP) system for pipe welding is presented. The focus of the CAPP system is for highly variable pipe assemblies, each to be produced in low quantity. In this environment, welding machinery is mechanized, as opposed to robotic. The CAPP system encompasses machine selection, operation sequencing and setup planning. The goal is to produce a process plan (or plans) with the maximum use of automated equipment. A second goal is to minimize the number of fitting setups. The CAPP logic evaluates the geometry of each pipe assembly, with respect to pre-defined machine capabilities.

The CAPP logic is then applied to five example assemblies; each assembly is composed of between four and six commonly used pipe parts. For machine selection, the examples consider three commonly available mechanized welding machines and a manual welder. The returned process plans demonstrate the ability of the proposed decision logic to create process plans for fabricating the pipe assembly with the maximum use of automated equipment and the minimum number of setups at that automation level.
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Chapter 1

Introduction

In an ongoing effort to minimize cost and increase productivity, manufacturing engineers often turn to Computer Aided Process Planning (CAPP) systems to aid in preparing accurate and reliable process plans. By providing a well constructed plan containing selected and sequenced processes along with relevant process parameters, fabricators can efficiently transform an engineering design into a final part.

To create such a CAPP system requires a detailed understanding of the manufacturing system and product. Within this thesis, the manufacturing system considered is for the production of a large number of pipe assemblies, each one being unique and to be produced in low quantity. This is often a common concern for industries such as utility, petrochemical and shipbuilding.

The focus of this CAPP system is to improve the manufacturing system by planning the welding processes. This considers two steps; initial weld tacking, followed by a full weld over the entire joint. The process plans should provide a fabricator with the steps necessary to efficiently construct the assembly from the individual parts.

The first step towards designing a CAPP system for the intended application is to research relevant literature and past efforts to accomplish similar goals. Chapter 2 will begin with a discussion of process planning and CAPP systems. It will then evaluate pipe welding and automated equipment. Lastly, a similar CAPP system designed for the mass production of pipe assemblies will be presented.

Chapter 3 will begin by explicitly defining the objectives and manufacturing system. Next, procedures for ranking and storing geometric data will be discussed. Following this, a
CAPP system for Pipe welding will be presented along with a method for finding the sequences with the most automation and minimum number of setups.

The forth chapter uses the methodology proposed in Chapter 3 to process plan 5 example assemblies. The first example will provide a step by step guide through the CAPP logic as decisions are made. For the remaining 4 examples, the results are shown and analyzed, but the step by step logic is omitted.

The fifth chapter summarizes the work presented in this thesis. It also provides some ideas of potential future work to improve the CAPP system for process planning.
Chapter 2

Literature Review

In this chapter, previous research endeavors related to the topics of Computer Aided Process Planning (CAPP) and pipe welding are discussed. First, the reasons for creating a CAPP system are introduced and the typical methodology is presented. Specific components of process planning relevant to pipe welding such as the sequencing of operations, grouping of operations and collision detection are individually analyzed. Next, the intricacies of the pipe welding and mechanized welding procedures are explored. Finally, previous work developing CAPP systems for pipe welding are discussed.

2.1 Computer Aided Process Planning

According to Halevi and Weill (1995), a process plan “defines in detail the process that transforms raw material into the desired form.” The major challenge of process planning is to determine how to make decisions such as process selection, machine selection, operation sequence and tool selection (Kiritsis, 1995). Traditionally, process planning was a task performed by human engineers based on knowledge of a machine shop and estimations based on experience and calculations. The more modern approach is to integrate this knowledge into a Computer Aided Process Planning (CAPP) system often using inputs directly from a CAD environment. This idea has been around since at least 1965 when Nieble (1965) suggested the concept of using the abilities of computers to assist in process planning. Since then, numerous endeavors to develop process planning systems have been undertaken (Wang, Lihui and Shen, 2007).
Starting from a known product form, typical inputs to a process planning system for each part include (Kiritsis, 1995):

- Dimensions.
- Dimensional Tolerances.
- Form Tolerances.
- Surface quality Data.
- Material Type and properties.
- Blank information.

Using the inputs, and known data about the manufacturing shop’s capabilities, a number of tasks will be performed to create a process plan. While the processes will be subject to the type of system being analyzed and the output detail desired, a common list of tasks would include the following (Kiritsis, 1995):

- Selection of machining operations.
- Selection of tools.
- Selection of machine tools.
- Grouping of operations.
- Selection of fixturing systems and data.
- Sequencing of machining operations.
- Determination of machining data.
- Generation of tool paths and NC programs.
- Calculation of machining times and costs.
- Document generation (process plan sheets).

Among the many approaches applied to process planning are genetic algorithm based approaches (Vancza and Markus, 1991; Usher and Bowden, 1996), Petri net based approaches
(Kiritsis and Porchet, 1996), feature driven approaches (Liu and Wang, 2007) and Knowledge (also referred to as Expert) based approaches (Kiritsis, 1995). Most CAPP systems are engineered for repetitive manufacturing operations are inflexible and function offline (Wang, Lihui and Shen, 2007). More advanced approaches have been taken, using real-time intelligence to actively adapt to job shop conditions (Wang, Lihui and Shen, 2007) with operational uncertainty such as job delay or urgent-job insertion, a shortage of fixtures or tool, or machine downtime (Wang, Lihui and Weiming, 2007).

According to Kiritsis (1995), CAPP systems have been “conceived, designed and created in order to help manufacturing engineers to produce consistent and accurate process plans, reducing time and cost and increasing productivity”. The benefits are a result of several factors. A CAPP system incorporates the most experienced process planner’s knowledge into every process plan (Lee et al., 2001). Using these improved process plans, the divide between novice and experienced process planners can be eliminated (Kiritsis, 1995). Additionally, time can be saved, as novice planners no longer have to look to handbooks and other references when making decisions (Kiritsis, 1995).

2.1.1 Calculation of Machining Cost and Time

When creating a process plan it may be necessary to calculate an estimated machining cost, as it is often used when selecting machining operations (Scallan, 2003). A machining cost may be a measure of money, time, or other manufacturing expenditure. Additionally, computed cost may be used when evaluating between several real time alternatives due to unexpected conditions such as machine breakdown (Kiritsis, 1995).

Lee et al (2001) created a process planning system with the intention of minimizing the sum of machining, setup, and tool change costs, as these were found to be the biggest costs for
the system being considered. Each type of cost was calculated through a deterministic formula. The costs were then used when choosing between several process plans with varying sequences, setups and machine selections.

2.1.2 Sequencing of Operations

In most manufacturing systems a set of rigid precedence constrains exists which restricts the sequence of operations when process planning (Kiritsis and Porchet, 1996; Liu and Wang, 2007). For example, a hole must be drilled prior to boring the hole. These inflexible precedence constraints are termed strong constraints (Kiritsis and Porchet, 1996). The sequencing of these strong constraints are often solved through knowledge based systems, artificial neural networks and genetic algorithms (Liu and Wang, 2007). Lui and Wang (2007) created a process planning system that used both knowledge-based rules and geometric reasoning for operation sequencing. The first half of their approach determined strong constraints using a traditional knowledge based approach. This ensured the process plan created would be feasible for machining the desired part. The second half of the system was designed to sequence the operations such that the manufacturing process would not only be successful, but efficient. However, they did not allow for this second approach to interfere with the previously defined rigid constraints.

Kiritsis and Porchet (1996) also attempted to improve efficiency by creating constraints which do not influence the part’s feasibility or quality. They termed these constrains weak constraints. A weak constraint may arise due to criteria such as minimizing cutting tool changes, minimizing travel time, minimizing the number of machining setups or maximizing the use of automation. In the process planning system for machining designed by Kiritsis and Porchet, changing the cutting tool, repositioning of the tool axis and repositioning the rotary table were identified as “non-productive time-consuming actions.” They also recognized that the sequence of
operations may impact the number of non-productive time-consuming actions required. Therefore when generating a process plan, weak constraints were imposed to minimize the number of time-consuming actions. Thus, the CAPP as Kiritsis and Porchet have described chooses a sequence that is not only feasible, but also satisfies additional weak constraints to improve production efficiency.

2.1.3 Grouping of Operations

Often influenced by the sequencing of operations is the grouping of operations. When multiple features can be machined without re-fixturing, they are referred to as a single group. Each group can be identified as it will only require 1 fixturing configuration for the group’s features to be created (Liu and Wang, 2007). This single fixturing configuration is often referred to as a setup (Wang, Lihui and Shen, 2007). Setups are typically undesirable and labor intensive tasks, and will be minimized when possible (Scallan, 2003).

Lui and Wang attempted to create machining setups for milling through the use of tool approach directions, which define the required tool orientation when approaching the part. With a 3 axis machining center, access to multiple orientations can be performed by repositioning the part within the machining center. The process planning system created by Lui and Wang (2007) attempted to place as many operations as possible in each group by identifying their tool approach directions, unless the addition conflicted with a strong sequencing constraint (as discussed in section 2.1.2).
2.1.4 Collision Detection

When selecting machining operations, geometric data is compared to known technological knowledge to make a choice. The technological data will vary depending on the type of product and type of machine, as well as the detail of the process planning system, and will be unique to each machine. When choosing a machine, one factor often looked at is whether a machine has the proper clearance to perform a task. If the appropriate clearance is not met there will be an interference between the machining center or machining tool and part being machined. The result will likely be a defective part and possible damage to the machining center or tool. One approach for determining if multiple entities will interfere is by a function termed collision detection or interference detection (Boyse, 1979). Interference detection is commonly used for computer graphics, surgical simulations and robotics (Kockara et al., 2007).

Each part in an assembly is represented by one or several facets in space. The size and number of facets comprising a part will be governed by the part’s geometry and the level of accuracy required for the application. The most primitive approach of collision detection would be to test each facet of each entity against each facet for every other entity. However, entities may often be comprised of thousands of facets, which can create a “computationally heavy burden” (Kockara et al., 2007). Thus, algorithms for collision detection have been created to prune unnecessary overlapping tests. Each collision detection algorithm can be fit into one of two categories; broad-phase and narrow phase collision detection (Kockara et al., 1997; Kitamura, 1994). The intention is to use both phases together to achieve efficient results. The broad phase is to be executed first, identifying disjoint groups between entities through a comparison of bounding volumes. If the bounding volumes intersect, the narrow-phase “inspects further” by using contact determination algorithms to find the location (if any) of the collision between facets (Kockara et al., 2007).
A broad phase collision detection algorithm can function in several ways. The first is to perform an exhaustive comparison between all object’s bounding volumes. A popular way to execute an exhaustive search is to perform a sweep and prune algorithm (Kockara et al., 2007). It projects each object’s bounded volume onto each principal coordinate axis. If overlapping appears on the principal coordinate axes, then there is a collision between bounding volumes. An alternative broad phase collision detection is to use hierarchical hash tables (Kockara et al., 2007). The hash tables separate the relevant world space into grids along the principal axes. If multiple objects exist in a grid territory there is a possibility of collision. Consequently, the narrow phase collision detection methods are to be applied to the shared region.

Narrow phase collision detection methods are used to investigate the possible colliding of objects as determined through broad phase methods. While there are numerous methods for narrow phase collision detection according to Kockara et al. (2007), they can all be classified into 4 major categories: Feature-based, simplex-based, volume based, and spatial data structures. Feature based approaches work directly on the geometric primitives of objects in motion. At various moments in time (frames), it finds the closest point by searching the points neighboring the point found to be closest during previous frames. Simplex based algorithms use the simplex (convex hull) of an independent set of points and find the Euclidean distance and closest points between the simplexes. Volume Based collision detection algorithms are derived from Image space based algorithms (ISB’s). Both methods use image-space occlusion queries implemented on graphics hardware. Spatial data structures work through spatial partitioning, which recursively divides the space into smaller cell sizes.
2.2 Pipe Welding

Tubular product, often simply referred to as pipe, is commonly used for a broad spectrum of applications. In the United States, roughly 10% of steel produced is made into tubular products (Cary and Helzer, 2005). Popular applications include mechanical and structural designs, but can also include artistic endeavors. The product chosen for the design will depend on the functional requirements and can vary significantly in dimension and material composition. Due to the vast array of tubular products and applications, the processes for welding them are also very extensive.

2.2.1 Procedure

Several steps are necessary to construct a pipe weld. The first is to prepare the required parts and equipment. Next, the parts must be aligned to ensure a quality weld. Then, if necessary, the parts may be tacked using a manual process. Then finally, the parts are welded using the specified process. If desired, a final quality assurance step may be employed (Cary and Helzer, 2005).

The preparation step begins by locating and gathering all the necessary materials (pipe, consumable insert rings, welding fuel, etc). Next the pipe must be cut to length. This step can be accomplished through oxyfuel gas cutting, flame cutting, plasma arc cutting, or more traditional procedures such as a rotary wheels or grinders. Next, an additional step to create a specified edge design may be required. The criteria for selecting an edge design are discussed later. If the specified angle of the edge is to be 90 degrees (flat), then typically the edge is simply cut (or supplied) to that specification. If a V or other simple style groove is indicated, the pipe may be cut to length before having an angled cut create the appropriate edge style. The same list of cutting procedures may be used for creating a simple angled edge. If however, a more complex
edge is specified, up to five-axis computer-controlled machining tools may be employed to create the specified shape (Cary and Helzer, 2005).

Once the individual pipes have been machined to create the specified edge types, they must be fixed into a position that will allow for welding. This is often performed through the use of clamps. For small diameter pipes, typically external style clamps will be used such as those shown in Figure 2.1. For larger diameter pipes, internal lineup clamps have become increasingly popular (See Figure 2.2). The clamps are to ensure the orientation of each axis and the distance across the root face opening (the gap between parts) are within tolerance limits.

![Figure 2.1: External Clamps (Image Source: Cary and Helzer, 2005)]
The pipes may be welded with the clamps in place. However, if the clamps pose an interference a tacking step may be performed to permanently fix the parts in position. Typically performed using manual or semi-automated hand-held equipment, the tacking step creates a rigid bond to maintain the joint parameters after the clamps are released. Several tacks will be placed quickly at set increments around the pipe joint.

The next step is to create the weld. Pipe welding is typically accomplished through any one of several arc welding processes, such as flux cored arc welding (FCAW), gas metal arc welding (GMAW), gas tungsten arc welding (GTAW) and submerged arc welding (SAW). Arc welding is a group of processes that produces coalescence of materials by heating through an arc (Cary and Helzer, 2005). The process may or may not use a consumable electrode. The consumable electrode is melted in the arc as molten metal is brought across the arc gap. Alternatively, a nonconsumable electrode will not melt in the arc and filler metal is added separately to the welding pool. Each welding processes can be applied via one or more methods such as manual welding, mechanized welding or fully automated welding.

Lastly, if the pipe is intended for a critical application, it may undergo additional quality assurance steps. In addition to a visual inspection, advanced techniques may be employed, such as...
as ultrasonic or x-ray inspections (Cary and Helzer, 2005). These methods allow for defects to be detected and assessed.

2.2.2 Joint Design

As with much of welding technology, the joint design for pipe welding has become heavily standardized. Pipe welding is typically accomplished through butt welds. The basic designs are shown in Figure 2.3.

Figure 2.3: Pipe Welding Joint Designs (Image Source: Cary and Helzer, 2005)

Thinline walled pipe can typically be welded using a square groove weld (See Figure 2.3). As the pipe thickness is increased, a V shape joint becomes the standard. The V-Groove has been standardized at either 60 or 75 degrees, depending on the application. As the wall thickness is
increased further, the joint design continues to change such that less weld metal will be required (Cary and Helzer, 2005).

2.2.3 Material

Material is typically chosen as part of a product design and must be considered when selecting a welding process, method of application, joint edge design and other welding parameters. These parameters should be selected using established written procedures for the environment in which the weld is to be used. Pipe size is typically classified into one of three categories, small (4 in. and smaller), medium (4 in. to 12 in.) or large (12 in. and larger) (Cary and Helzer, 2005). Wall thickness is categorized as thin (less than standard), standard (schedule 40), and heavier (greater than standard) (Cary and Helzer, 2005). These parameters will dictate the welding process (FCAW, GMAW, etc.), travel speed, number of passes, edge type, etc.

In addition, critical welds (as specified by the design) often receive consumable insert rings. These rings are categorized as type 1 through type 5 (See Figure 2.4). Class 1 is often referred to as A-shaped, class 2 as J shaped, class 4 as Y shaped and classes 3 and 5 are deemed rectangular. When used, the ring is placed into the root weld prior to any tacking or welding and will be fused as the weld is completed. The size and composition is selected to match that of the pipe.

![Figure 2.4: Consumable Insert Rings (Image Source: Cary and Helzer, 2005)]
2.3 Automated Pipe Welding Equipment

The methods for applying welding processes may be as numerous as the welding processes themselves (Cary and Helzer, 2005). However, they can each be categorized into one of the following groups:

- **Manual Welding**
- **Semiautomatic welding**
- **Mechanized welding**
- **Automatic welding**
- **Robotic welding**
- **Adaptive control welding**

Manual welding is the most basic form and involves holding a welding torch and sometimes separate filler wire (subject to the welding process) by hand. Semiautomated welding is an improvement over the manual technique in that one or more conditions are automatically controlled, such as the feeding of a flux cored wire through a hand-held torch (Cary and Helzer, 2005). Mechanized welding allows an operator to upgrade to non-hand-held equipment, but he must adjust the equipment controls in response to known control values and visual observations. Automatic welding requires occasional observation of the welding, and does not need any manual adjustment of the equipment controls (Cary and Helzer, 2005). Robotic Welding involves using robotic machinery. Adaptive control welding is “welding with a process control system that determines changes in welding conditions automatically and directs the equipment to take appropriate action” (Cary and Helzer, 2005).

For pipe welding, manual, semi-automated, mechanized and automatic welding methods are most common. Manual and semi-automated methods for pipe are identical to those used throughout the welding world. However, the mechanized and automatic equipment is highly
specialized and unique to pipe welding. While numerous products exist, the mechanized and automatic welding equipment can typically be categorized into one of two groups, Orbital Head Welders or Roll Welders (often referred to as Horizontal Welding Machines, HWM’s).

Orbital Head Welders (as shown in Figure 2.5) operate by revolving a welding torch around a fixed pipe to perform the weld (Cary and Helzer, 2005). Orbital Head Welders permit welding in any orientation and have been engineered to accommodate a number of welding processes such as GMAW and FCAW. The only processes an Orbital welder can not accommodate are ones that must be performed entirely horizontal, such as Submerged Arc Welding. Each Orbital Head welder is built to accommodate a limited range of pipe diameters. However, Orbital welders are not built to accommodate large diameter pipe as the equipment becomes too heavy for operators to transport and lift onto pipe assemblies.

An operator can place the Orbital Head Welder over a tacked or clamped pipe perpendicularly. Once around the pipe, remote control pendants or controls on the head permit the operator to setup the details of the weld. Once the equipment begins the weld, the operator will often oversee the procedure and make adjustments if necessary. The cable containing any necessary gasses, electricity, filler wire or other vital materials will wrap around the pipe while the weld is being completed. Most Orbital Head Welders are limited to a set number of revolutions (equivalent to the number of passes) before the welder must detach (or manually reverse) the head to unwind the cord (Cary and Helzer, 2005). At that point the weld operator may restart the welding procedure to continue the weld.
Roll Welders (See Figure 2.6) have the disadvantage of being larger and have a larger number of restrictions, resulting in fewer occasions where a roll welder can be used. Though their welding head is highly adjustable, it is stationary during operation (See Figure 2.7). The pipe is physically rolled by holding one end (in line with the weld) and turning. Since the assemblies can often be quite large and heavy, additional supports with rollers attached to the top are placed at various points under the revolving pipe assembly. Thus, it is important to consider the possibility of colliding the assembly (often composed of complicated geometry) into the welding head, supports and floor beneath.

Though these disadvantages limit the applications where roll welders can be used, they are often the preferred method. Welds can be made more rapidly in the flat or roll position (Cary and Helzer, 2005). They permit any welding process, included processes that must be performed horizontally, such as submerged arc welding. Since there is no cord to wrap around the pipe, they do not limit the number of consecutive passes. If multiple welds are to be performed along a single axis, multiple welding heads may be operated at once. Additionally, unlike orbital welders which must be purchased for a limited range of diameters, the horizontal roll welding head may be lifted or lowered to accommodate a very large range of pipe diameters.
When using a Roll Welder, it is important that the geometry allows the assembly to be secured and rotated around an axis passing through the weld. This allows for the stationary torch to access the joint’s entire circumference. The pipe rotator secures itself to the assembly using a collett that can be expanded or contracted onto a range of pipe sizes. However, in situations where a more complicated fixture such as an elbow or flange must be secured, the collett is not...
capable of the task. Therefore to increase the opportunities to use roll welding, specialized
fixturing devices have been created that can hold select fittings and spin them in line with the axis
of the weld. These specialized work-holders are also commonly referred to as jigs (Scallan,
2003). Each specialized fixturing device is unique to a style of fitting, and often limited to a range
of diameters.

2.4 Process Planning for Pipe Welding

Significant research exists in the area of process planning for welding. However, the
focus of most of the efforts is in the area of process planning for robotic systems (Kim, Choi and
Nnaji, 2008; Dolgui, Pashkevich and Semkin, 2005; Kim, Kim and Nnaji, 2002). These systems
are designed for a broad range of products, but each system is typically designed for mass
production with little variety.

Little research exists in the area of process planning specifically for the welding of pipe.
Perhaps the most substantial research effort to date is by Yasuhisa Okumoto of Kinki University
(Okumoto, 2007). He has sought to create a process planning system for improving the mass-
production of pipe assemblies. The process planning system dealt chiefly with finding the optimal
sequence to weld parts. The objectives were to reduce Work In Progress (WIP) and total work
time for an existing manufacturing system. The assemblies were comprised of pipes, elbows,
flanges, valves, bent pipes, etc. To help pre-determine what effect, if any, the process planning
system would have on job shop WIP and completion time, a simulation was performed using
“Visual SLAM” for 300 parts a week. One model was constructed to simulate the “as-is”
condition, and another to analyze the changes. The final conclusion was that the systems created
successfully improved the delivery period and reduced the WIP.
Products that are produced in low quantity or are “one-of” designs are commonplace in industries such as chemical plants, shipbuilding, refineries and utility facilities. In such environments, robotic systems with a larger initial cost and setup time are less desirable. According to Edmondson and Redford (2001), automation, such as the robotic welding systems, is typically restricted to “low-variety high-volume production, where the capital cost can be easily justified.” Mechanized equipment is better suited for a manufacturing facility intended for low quantity production of highly variable assemblies, as it does not have the capital cost or lengthy initial setup associated with robotic systems. At present, the author is not aware of any research that has been performed in the area of process planning for pipe assemblies specifically for low quantity production.

2.5 Summary of Literature

Computer Aided Process Planning (CAPP) systems have been applied to numerous production systems to bridge the gap between designed product forms and manufacturing facilities. CAPP systems will often provide the fabricator with information such as machining operations, sequence of operations, grouping of operations and tooling. The approaches for creating a CAPP are also numerous and will typically depend on the type of product being manufactured, the features of the product, and available processes.

CAPP systems have been well researched for a variety of milling and robotic welding applications for mass production. However, little has been performed in the area of CAPP systems for pipe assemblies. Presently, there are no known research efforts to develop a CAPP system for the welding of pipe assemblies focused on using mechanized equipment for low quantity production.
Chapter 3
Methodology

This chapter will discuss an approach for the Computer Aided Process Planning of pipe assemblies using mechanized welding equipment. First, the objective of the CAPP system is described. Then, a method for ranking process plans on the basis of machine selection is presented. Next which, the logic for the computer aided process planning system is introduced and explained. The system selects machines and sequences operations to satisfy the objective.

3.1 Objective

The intent of any Computer Aided Process Planning (CAPP) system is to assist the manufacturing engineer by providing a list of sequenced operations for efficient manufacturing. In this thesis, the manufacturing environment considered is a pipe shop for the purpose of tacking and welding assemblies using Horizontal Welding Machines (HWM’s), orbital welding, and manual welding equipment. The objective is to develop a list of instructions detailing the operations sequencing, machine selection and selection of fixturing systems. An implementation of such a CAPP should be able to provide good results within a reasonable amount of time.

The process plan created should accomplish two goals. The primary goal is to generate a process plan (or process plans) allowing for the maximum use of mechanized (automated) welding equipment. A secondary goal is to develop a process plan (or process plans) with the fewest number of setups at the fitting station without impeding the primary goal.

The process planning approach presented in this thesis makes several assumptions related to weld quality. The CAPP system presented here does not consider heat effects such as distortion
when sequencing operations. For instance, creating two welds within close proximity sequentially may cause more distortion than alternative sequences. Additionally, factors for creating a weld, such as choosing a welding process (gas metal arc welding, flux core arc welding, etc.) or specifying consumable insert rings are not explicitly considered. Lastly, machine selection does not consider the possibility of failed welds and the varying success rates among welding machines.

One of the key elements in creating a CAPP system for pipe welding is the sequence of operations. In most manufacturing environments, the sequence is dictated by strong precedence constraints; for example, drilling a hole must precede tapping of the hole. In the pipe welding system being considered, any weld can be performed at any time. The only precedence that exists is that each weld must be manually tacked prior to welding. Yet, similar to welding, joints can be tacked in any sequence.

The sequence of construction influences machine selection through the augmentation of the physical geometry. In an assembly with several joints, the machine selection for a joint may be different depending on what other joints have been tacked or welded previously. It is possible that what could initially be a highly automated weld using a HWM station if performed first, could not use the same machine if done later on. For example, Figure 3.1 represents a pipe assembly showing all parts in their final position. Two tee’s are attached to each other, and two 4.5” diameter straight tubes extend from two of the tee’s ends. If joint A is tacked prior to joints B or C, it will likely pose an interference for most mechanized welding equipment (subject to specific machine clearances and dimensions). However, if joint C or B were completed prior to A, this interference would no longer exist. Thus, a significant part of the objective is to determine the sequence that allows for the most automation.
The machine selection of mechanized welding equipment will consider several criteria. Each machine is capable of accommodating a range of weld diameters; the outer weld diameter of the joint being evaluated must fall within this range for the weld to be performed successfully. Assemblies will also be evaluated to determine if and how each of them can be fixtured. Additionally, the geometry of the assembly must be evaluated to ensure that there is no potential for collision between the pipe assembly and welding device. It is assumed that manual (i.e. handheld) welding can be performed on any weld regardless of geometry, diameter, etc. and will be recommended wherever mechanized welders can not be used.

3.1.1 Manufacturing Assemblies

The CAPP system has been designed for a manufacturing system producing pipe assemblies featuring up to 6 parts in an assembly. Each assembly is a transportable unit intended for relocation prior to final installation. At the final location, installation may involve welding, bolting or other joining methods. The final installation method is not analyzed, nor does it bear any influence on the CAPP system for the manufacturing of each assembly.
The assumption is that each assembly is unique, either a one-off design or to be produced in low quantity. The quantity is an important governing factor towards the type of machinery being considered and process planning system analysis.

The assemblies considered are composed of a limited number of commercially available pipes and fittings. For simplicity, the types of fittings are limited to elbows (standard radius 45’s and 90’s), tee’s and flanges. All pipe and fittings are medium sized (4 in. to 12 in. outer diameter), standard schedule 40 and less than 40 inches in length. All connection joints between parts will be butt-welds.

3.1.2 Manufacturing Equipment

The facility being considered is fictional and is not based on any real life manufacturing facility. However, it is a fair representation of what would be found in manufacturing environments creating a large variety of pipe assemblies, each in low quantity. In this setting, the use of mechanized and automated equipment often proves the best option. It does not have the initial setup time and cost associated with robotic machinery, yet produces higher quality welds quicker and more reliably than most manual welding methods (Cary and Helzer, 2005). Parts produced in larger quantity would likely justify the use of assembly lines, robotic welding and other specialized equipment requiring substantial one time setup costs for programming. The pipe shop considered here will use a combination of three types of equipment: Horizontal Welding Machines (HWM’s), orbital welders, and manual welders.
3.2 Ranking by Automation

Most Computer Aided Process Planning (CAPP) systems use either time or cost to justify decisions. For pipe welding, cost and time are dependent on a large number of factors, making both complex to properly estimate. The CAPP system described in this thesis uses automation to make decisions. Preference is given to the most automated machine (or machines) when choosing between capable welders. Selecting highly automated machinery reduces time, improves reliability, and lowers cost (Cary and Helzer, 2005). Each welding method has a pre-determined number of points assigned. Fewer points indicate a more automated process.

To determine the number of points for each type of machinery, typical performance data was used (Magnatech, 2006; All-Fab Corp, 2009). The maximum rate of travel was found for each of the three styles of welders (orbital and HWM rates of travel assumed a pipe diameter of 4.5”). The maximum speed was then adjusted using the duty cycle of each method. The duty cycle represents the amount of time the arc is in contact with the joint over a period of time. According to Emmerson (2007), manual welders have the lowest duty cycle at around 25 percent, most likely because a human operator must frequently reposition themselves or the parts being welded. Assuming each form of welding is operating at its maximum rate of travel during the entire duty cycle, an average rate of travel has been computed. The final step was to compare the average rates of travel and establish a point value for each form of welding based on the rate of travel. The point value determined is 1.0 for all HWM’s, 2.4 for Orbital welders, and 7.4 if a manual weld must be suggested.

Table 3.2: Average Rate of Travel For Welding Methods

<table>
<thead>
<tr>
<th></th>
<th>HWM</th>
<th>Orbital</th>
<th>Manual</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maximum Rate of Rotation (RPM):</strong></td>
<td>1.4</td>
<td>0.6</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Maximum Rate of Travel (in/min):</strong></td>
<td>19.8</td>
<td>8.4</td>
<td>8</td>
</tr>
<tr>
<td><strong>Duty Cycle (%):</strong></td>
<td>75</td>
<td>75</td>
<td>25</td>
</tr>
<tr>
<td><strong>Average Rate of Travel (in/min):</strong></td>
<td>14.85 in/min</td>
<td>6.3 in/min</td>
<td>2 in/min</td>
</tr>
<tr>
<td><strong>Penalty Points:</strong></td>
<td>1.0</td>
<td>2.4</td>
<td>7.4</td>
</tr>
</tbody>
</table>
3.3 Assembly Representation

The CAPP system for pipe welding uses geometry data for the final assembly to make decisions for machine selection. Modern CAPP systems frequently bridge the gap between design and production by extracting form representation directly from CAD systems (Kiritsis, 1995). Regardless of the CAD software used for the design environment, information can be extracted for creating a representation of the physical geometry. This may be obtained directly from the software’s proprietary data storage or through feature recognition. The geometry input to the CAPP system should identify each assembly as the sum of three or more parts. Each part will contain one or more line segments, a part type and a diameter.

Line segments are expressed as a parametric equation (See Equation 3.1).

\[
v(t) = \begin{bmatrix}
x_1 + (x_2 - x_1) t \\
y_1 + (y_2 - y_1) t \\
z_1 + (z_2 - z_1) t 
\end{bmatrix} \quad 0 \leq t \leq 1
\] (3.1)

The assembly data representation shown in Figure 3.2 is from the CAPP system for pipe welding. The first line includes the part name, its type, and its diameter. The part types being considered in this thesis can consist of up to 2 line segments. Each line segment consists of two Cartesian Coordinates \((x_1,y_1,z_1)\) and \((x_2,y_2,z_2)\) and will represent the centerline of the pipe segment.
3.4 Computer Aided Process Planning System for Pipe Welding

The structure of the Computer Aided Process Planning (CAPP) system (Figure 3.3) for the pipe assemblies is heavily influenced by the hierarchy of the system objectives. Since the foremost intent is to find the most automated sequence for operations, it is the first addressed. In the first step, each possible sequence will be created and evaluated to find which sequences permit the lowest automation score. Sequences that cannot produce the best (lowest) automation score will be discarded. The next step will use the stored sequences and find those that can achieve the best automation score (as determined in the first step) in the minimum number of fitting setups. Sequences which cannot achieve both the best automation score and minimum number of setups will be deleted. Lastly, the CAPP system will return instructions for the best sequence (or sequences) remaining.

--- Parts ---
"Part A", Tube, 4.5
  0,10,0 - 10,10,0

"Part B", Tee, 4.5
  10,10,0 - 18,10,0
  14,10,0 - 14,10,4

"Part C", Elbow (90 deg.), 4.5
  18,10,0 - 22,10,0
  22,10,0 - 22,6,0

"Part D", Elbow (45 deg.), 4.5
  14,10,4 - 14,10,8
  14,10,8 - 14,12,828,10,828 |

Figure 3.2: Example Data Representation
3.4.1 Find Sequences with Lowest Automation Score

One way to guarantee the best automation score for a given sequence is to analyze the sequence using a repetitive “tack then weld” procedure for each joint, continuing through the entire sequence. This ensures that the assembly geometry used for the machine selection of each joint is not influenced by having multiple joints tacked in a single setup. To find the sequences with the best automation score requires several steps, illustrated in Figure 3.4. The first step is to find all feasible weld sequences. Since this work assumes no precedence requirements, all sequences are feasible and the number of sequences will be equal to the factorial of the number of joints.

The next step in the flowchart (Figure 3.4) is to select a sequence for evaluation. Since all sequences will be evaluated, the order does not influence the outcome of the CAPP system. The first joint of the sequence is selected and sent to a machine selection function which will
determine the most automated machinery capable of completing the weld. When calling the machine selection function, the sender may provide a setup (setups are not used when finding the lowest automation score), the joint of interest, and the sequence in which the joints are to be welded (this allows consideration of previous welding steps when evaluating the current joint). The machine selection function will return an automation score for the current joint under the given criteria.

Once all of the joints have been evaluated, the sequence will be either stored or discarded. The decision will be based on the sum of the automation scores for the joints. The first score will always be saved as the best (BestTotalScore in Figure 3.4), until a superior score is found. If a better score is found, all stored sequences are deleted, and the improved sequence is stored. If a sequence yields an equivalent score it is stored along with any other sequences that yielded that score.
Figure 3.4: Find Sequences with Lowest Automation Score
3.4.2 Find Sequences with the Minimum Number of Setups

The second step in Figure 3.3 is to determine which sequence (or sequences) can achieve the same total automation score with the least number of tacking setups. Only the sequences stored by the “Find Sequences with the Lowest Automation Score” logic are evaluated in this step.

Unlike the previous step where the sequence of operations was pre-determined to be “tack then weld,” alternating through the sequence of joints, in this step the sequence of operations is no longer fixed. To reduce the number of tacking setups for each sequence, the logic will explore the possibility of tacking multiple joints in a single setup before welding any of the joints in the setup.

To begin each setup, the current joint (Jj in Figure 3.5) in the sequence will be added (each setup must have at least one joint). The logic will then check to see if all of the joints in the assembly have been completed. If there are joints remaining which are not tacked or welded, the system will consider adding them to the setup in sequence. The logic will test adding joints to a setup individually; each time checking to see if the next joint is physically connected to the present setup and performing a machine selection on all of the joints in the setup. The machine selection is performed on all of the joints, rather than just the next joint, because if the next joint (Jj+1 in Figure 3.5) is added to the setup it will change the geometry and possibly the machine selection for welding all of the joints in the setup. If adding the next joint is not found to have a negative impact on the machine selection (based on automation score) it is added to the setup, and the process will repeat for the next joint in sequence. If adding the next joint in sequence (Jj+1 in Figure 3.5 will have a detrimental effect on the automation score, or if joint Jj+1 is not connected to the present setup, it will be the first joint in a new setup.
Once all of the joints in the sequence have been evaluated, the logic must decide if this sequence is the best, or one of the best. It will determine if the sequence should be kept based on the number of setups (i in Figure 3.5). Sequences yielding more than the minimum number of setups (MinSetups in Figure 3.5) are deleted.
Figure 3.5: Find Sequences with the Minimum Number of Setups
3.4.3 Machine Selection

To determine which machines are suitable to perform a weld, the machine selection function will be called numerous times throughout the CAPP procedure, as described in sections 3.4.1 and 3.4.2. Each time the function is called, machines are evaluated in type order, beginning with the most automated machines, the Horizontal Welding Machines (See Figure 3.6). Each machine is analyzed individually, comparing machine capabilities to welding requirements. All capable HWM’s will be recorded. If no HWM’s can satisfy the necessary conditions for creating a weld, each of the available Orbital welding machines will be checked. All capable orbital welders will be noted. If neither form of mechanized welding is capable of satisfying the requirements, manual welding will be chosen.

![Machine Selection Function Diagram](image)

Figure 3.6: Machine Selection Function
3.4.4 Evaluating Horizontal Welding Equipment

To evaluate which, if any, available Horizontal Welding Machines are capable of completing the weld, geometry requirements are compared to known machine capabilities (see Figure 3.7). First, the geometry attached to the joint to be welded will be used to determine if the assembly can be securely attached to the rotating base. This is analyzed first without regard to machine parameters, as it is not specific to any machine. Additionally, the procedure will check if the assembly geometry will contact the rotating base, as the base’s geometry is also not unique to an individual HWM station. If the analysis indicates the probability of a collision with the rotating base or cannot identify a location by which to secure the assembly, then no HWM’s are capable of completing the weld.

If the geometry can be fixed and does not collide with the rotating base, each available HWM will be evaluated one at a time for criteria unique to each HWM. The procedure will determine if each machine is capable of satisfying the weld diameter, assembly’s vertical height, assembly’s horizontal length and clearing the geometry with the welding head. The remainder of this chapter will discuss the calculations necessary to make the aforementioned decisions regarding HWM selection.
Figure 3.7: Evaluate HWM Welders
Representing Horizontal Welding Machines

In order to decide if a HWM is capable of performing a weld, certain parameters must be known about the machine. In the present CAPP system, decisions are based on geometry data. Each HWM machine is capable of a range of outer diameters, a maximum vertical height and a maximum horizontal length. In addition, each HWM will have a unique welding head shape. These values will be unique to each machine and must be documented before any decisions regarding machine selections can be made.

When establishing a vertical clearance, the nearest non-portable object located perpendicularly from the axis of rotation (defined by the rotating base) is used (Figure 3.8). Typically the floor is the closest vertical obstruction. The horizontal clearance stretches out in the direction of the axis of rotation until a permanent structure is encountered (Figure 3.9). The nearest obstruction may be a machine, wall, or other unmovable object.

![Figure 3.8: Vertical Clearance for HWM](image)

Figure 3.8: Vertical Clearance for HWM
The welding head is challenging to characterize since its form is complex and highly adjustable. Thus, a simplified representation of its shape is created. The HWM’s torch is most narrow at the point nearest to the joint. As one looks further away from the torch, gas lines, filler wire, controlling devices, monitoring equipment and other welding necessities begin to widen the torch’s form. While the exact shape will be unique to each welder (based on welding process and machine setup), in 2-D, the representation of the welding head can be approximated as a triangle, with a tip pointing at the weld head (See Figure 3.10). The key boundaries for characterizing the weld head are the left and right lines defining the lower “V” shape of the triangle. The two lines extend from the top of the joint to infinity. The angle defining these lines (θ) is assumed to be identical on both sides of the weld and will be unique to each machine. When determining the angle, a conservative approximation should be measured, based on the machine equipment.

Figure 3.9: Horizontal Clearance For HWM
When using a Horizontal Welding Machine, it is important that the assembly geometry permits the operator to securely fasten it to the rotating base. Additionally, the geometry must be attached to the pipe rotator (rotating base) such that the joint being welded remains directly below the weld head as the geometry rotates.

The first step for determining if the pipe geometry can be properly fixed is to identify the parts in the key locations for fixing (See Figure 3.11). In order for the joint to be completed, the assembly must be fixed such that the joint remains directly below the weld head as it is rotated. Keeping the joint in contact with the weld head requires the geometry to be spun about an axis passing directly through the joint. Thus, the location of the parts permitting proper rotation would have to be in line with that axis. The two furthest parts along the axis of rotation, one on each side, are identified to be in the necessary location for fixing.

*Fixing for Horizontal Welding Machines*
Identify parts for fixing based on location

For Each Part

- **Is Part Type Straight tube?**
  - Yes: Does Orientation permit fixing?
    - No: Can NOT be Fixed
    - Yes: Can be Fixed (Store Part)
  - No: Can NOT be Fixed

- **Is Part Type Tee?**
  - Yes: Does Orientation permit fixing?
    - No: Can NOT be Fixed
    - Yes: Can be Fixed (Store Part)
  - No: Can NOT be Fixed

- **Is Part Type Elbow?**
  - Yes: Can be Fixed (Store Part)
  - No: Can NOT be Fixed

Figure 3.11: Fixturing for Horizontal Welding Machines
The next step is to evaluate each part one at a time and determine if it can be fixed, based on part type and orientation. The analysis for a straight pipe requires the orientation to be checked. If the orientation is in line with the axis of rotation the part can be fixed securely into the rotating base’s chuck.

For determining if a Tee can be fixed, there is an added level of analysis because there are multiple line segments. The two line segments’ orientation and location will be used to find if the orientation is as shown in A (can be fixed) or B (can not be fixed) of Figure 3.12.

![Figure 3.12: Fixturing a Tee. A) Can be fixed. B) Can not be fixed](image)

If the fixturing part in question is an elbow, the standard chuck can not be used. However, there are specialized fixtures that can be used for common sizes and angles. The fixture will hold on to the part such that the weld can take place along the rotational axis, as shown in Figure 3.13. It is assumed in the present CAPP system that the manufacturing facility has fixtures capable of accommodating all 45’s and 90’s specified in the assembly drawings. Thus, if the part being evaluated is an elbow, it can be fixed.
The last type of part being considered in the CAPP system is the flange. Since the flanges considered in this thesis are all butt style flanges, the rotating base’s chuck would have to secure to the flange end. However, this is often a thin and critical connection. To be prudent, the CAPP system will not consider flanges as a suitable part for fixing.

_Evaluate Base Collision_

A second concern when fixing the HWM’s rotating base to the assembly is a collision between the two objects. To prevent the possibility of an interference, a collision detection analysis is performed. The collision detection algorithm checks the geometry of the assembly to see if any of it extends into a territory that could collide with the rotating base (Figure 3.14). The part established as fixable in the previous step serves as a reference. Any geometry that extends further horizontally from the joint than the fixed part will be deemed a collision (See Figure 3.15). If the previous step found two parts fixable, they will analyzed for base collision individually.
Figure 3.14: Evaluate Base Collision
To identify if the assembly geometry will extend horizontally past the fixed point (left of the dashed line in Figure 3.15), each line segment’s furthest location will be compared to the location of the fixed part. If any part extends further horizontally than the fixed part from the joint being welded, it will be deemed a collision. To identify if any of the geometry extends past the fixturing part will require looking at each line segment in the assembly. Using Equation 3.2, the horizontal displacement (Z) from the joint being welded (j) can be determined for each line segment’s two defining points (See Figure 3.16).

\[ Z_n = x_u (x_n - x_j) + y_u (y_n - y_j) + z_u (z_n - z_j) \]  

(3.2)

\( Z_n = \) Distance from the joint being welded to point \( n \) parallel to the rotating axis

\( u = \) Unit vector of rotating axis

\( n = \) point being evaluated

\( j = \) location of the joint being welded
In addition to the location of the furthest point on the line segment, the line segment’s volume may extend beyond the centerline representation. For example, if a line segment is located vertically, the horizontal location of the volume would truly be the horizontal location of the segment ± the radius. By using the orientation of each point’s line segment and its parent part’s diameter, the appropriate portion of the diameter can be added to the horizontal distance.

To determine the orientation of each point’s line segment relative to the orientation of the rotating axis, the distance of the line segment parallel to and perpendicular to the rotating axis must be determined. The distance parallel to the rotating axis can be found by calculating a Z value (Equation 3.2) for both points defining the line segment \( z_1 \) and \( z_2 \). To find the distance each defining point is away from the axis \( P_1 \) and \( P_2 \), Equation 3.3 must be used. Using these values for each point defining the line, Equation 3.4 finds the distance the volume will extend horizontally past the centerline representation \( H \) (See Figure 3.16).

\[
p_n = \sqrt{\left( x_j + x_u \cdot Z_n - x_n \right)^2 + \left( y_j + y_u \cdot Z_n - y_n \right)^2 + \left( z_j + z_u \cdot Z_n - z_n \right)^2} \quad (3.3)
\]

\( P_n = \text{distance from the rotating axis to point } n \)

\( u = \text{Unit Vector of rotating axis} \)

\( n = \text{point being evaluated} \)

\( j = \text{location of the joint being welded} \)

\( Z_n = \text{Distance from the joint being welded to point } n \text{ parallel to the rotating axis} \)
\[ H = \frac{1}{2} \cdot \sin \left( \tan^{-1} \left( \frac{|P_2 - P_1|}{|Z_2 - Z_1|} \right) \right) \cdot D \]  

(3.4)

\( D = \text{Diameter of the part} \)

\( P_x = \text{Distance from the rotating axis to point } x \)

\( Z_x = \text{Distance from the joint being welded to point } x \text{ parallel to the rotating axis} \)

Finally, looking through each point’s location relative to the joint being welded (Z) combined with the impact of each point’s parent part diameter (H), we can determine if any points extend beyond the horizontal location found for the fixturing part, and thus if there is a potential collision.

![Diagram](image.png)

Figure 3.16: Finding Furthest Horizontal Distance from Weld Joint for a Line Segment
**Find Maximum Height and Length of Assembly**

The maximum height and length a machine can accommodate will be unique to each machine. However, the height and length of the assembly will be the same regardless of the machine evaluated. Thus, if the maximum height and length of a pipe assembly are calculated and stored once, they can be used repetitively when analyzing each machine.

The height of an assembly is the furthest distance of its geometry from the rotating axis. The distance of each point from the rotating axis is defined in Equation 3.3. Similar to finding the furthest horizontal location for base collision, finding furthest vertical distance must also consider the effect of each part’s diameter. Using the horizontal and vertical (Z and P) values for each line segment’s defining points (point 1 and 2), an orientation can be found. Equation 3.5 finds how far the line segment’s volume extends past the line segment in the vertical direction (V) using the line segment’s orientation and the parent part’s diameter (See Figure 3.17). The combined distance of the line segments largest vertical distance (greatest P value) and it’s V yields it’s maximum distance from the axis of rotation. Performing this analysis for each line segment in the geometry and storing the greatest will yield the assembly’s maximum height.

\[ V = \frac{1}{2} \cdot \cos \left( \tan^{-1} \left( \frac{P_2 - P_1}{Z_2 - Z_1} \right) \right) \cdot D \]  

(3.5)

\[ D = \text{Diameter of the part} \]

\[ P_x = \text{Distance from the rotating axis to point } x \]

\[ Z_x = \text{Distance from the joint being welded to point } x \text{ parallel to the rotating axis} \]
Finding the overall length involves a similar process to finding the maximum height. However, the maximum height was reflective of the distance from the rotating axis, thus the minimum value was always zero (P=0). The horizontal length is the distance between a minimum and maximum value which must be found independently. Figure 3.18 illustrates the components of length between two line segments (A and B). In this example, $Z_{\text{LineSegment,Max}}$ is the furthest Z of the line segment and $H_{\text{LineSegment}}$ is the distance the volume extends horizontally past the line segment. Thus, the length of the geometry shown is equal to $|Z_A| + H_A + |Z_B| + H_B$.

The geometry’s minimum horizontal location is the lowest Z–H value of any point in the geometry (Equation 3.2 and Equation 3.4). The maximum horizontal location will be the greatest $Z+H$ value of all the points in the geometry (Equation 3.2 and Equation 3.4). The difference between the minimum and maximum horizontal locations is geometry’s length.
Evaluating Each Horizontal Welding Machine

To find particular Horizontal Welding Machines able to complete a weld requires the machines to also be analyzed individually. Each machine has unique capabilities for weld diameter, height and length, as well as a distinctive weld head shape.

According to Figure 3.7, the first item to be evaluated for each HWM is the weld diameter. If the weld diameter is not satisfied by the machine, it fails and stops evaluating the current HWM. Likewise, if the assembly’s calculated height and length are not satisfied by a specific HWM, the logic will stop evaluating the machine and exit without storing the machine as a suitable option.

The final step in evaluating a HWM is to perform a collision detection for the welding head. The welding head must be able to reach the joint it is welding continuously as the assembly...
is rotated. The clearance requirement for the welding head is the previously mentioned “V” shape (Figure 3.10). The top portion of the triangle shape is not bounded and stretches to infinity (see Figure 3.19). If any of the assembly crosses the estimated shape of the welding head, the HWM fails the collision detection.

Two parametric lines (Equations 3.6 and 3.7) represent the bounding shape for the weld head.

\[
WH_1(t) = \begin{bmatrix} t \\ \tan(\theta)t + \frac{1}{2} \text{IntDiameter} \end{bmatrix} \quad t \geq 0 \quad (3.6)
\]

\[
WH_1 = \text{Right side boundary of the weld head}
\]

\[
\theta = \text{Angle from the weld head representation to part surface (See Figure 3.19)}
\]

\[
\text{IntDiameter} = \text{Diameter of the joint’s parent part}
\]

\[
WH_2(t) = \begin{bmatrix} -t \\ \tan(\theta)t + \frac{1}{2} \text{IntDiameter} \end{bmatrix} \quad t \geq 0 \quad (3.7)
\]

\[
WH_2 = \text{Left side boundary of the weld head}
\]

\[
\theta = \text{Angle from the weld head representation to part surface (See Figure 3.19)}
\]

\[
\text{IntDiameter} = \text{Diameter of the joint’s parent part}
\]
To determine if any of the parts cross into this area, each one must be analyzed individually. Since the assembly will be fully rotated around an axis passing through the joint, the procedure must only consider the location of each line segment relative to the joint being welded in two dimensions; horizontal distance \(Z\) along the rotating axis from the joint and vertical distance \(P\) from the axis. Calculating the horizontal and vertical distance (Equations 3.2 and 3.3) for each of the two defining points of a 3-D line segment yields two new points. These points define a new parametric line segment (LS) in 2-D (Equation 3.8).

\[
LS(t) = \left[\frac{Z_1 + (Z_2 - Z_1)t}{P_1 + (P_2 - P_1)t}\right] 0 \leq t \leq 1
\]

\(P_x = Distance\ from\ the\ rotating\ axis\ to\ point\ x\)

\(Z_x = Distance\ from\ the\ joint\ being\ welded\ to\ point\ x\ parallel\ to\ the\ rotating\ axis\)

\(LS = 2-D\ line\ segment\ representing\ the\ pipe\ segment’s\ centerline\)
Yet, the line segment LS is only a representation of a volume’s centerline location. To find a representation of the external volume, the 2-D line segment will be shifted by its radius in both directions perpendicular to its orientation to create lines \(A(r)\) and \(B(r)\) (Equation 3.9 and Equation 3.10).

\[
A(r) = \left[ \left( Z_1 - \frac{1}{2} \text{Diameter} \cdot \sin(\phi) \right) + \left( Z_2 - Z_1 \right) r \right] \quad \left[ \left( P_1 + \frac{1}{2} \text{Diameter} \cdot \cos(\phi) \right) + \left( P_2 - P_1 \right) r \right] \\
0 \leq r \leq 1
\]

\(A(r) = 2\)-D line segment representing an external surface

\[P_x = \text{Distance from the rotating axis to point x}\]

\[Z_x = \text{Distance from the joint being welded to point x parallel to the rotating axis}\]

\[\theta = \text{Angle from the weld head representation to part surface (See Figure 3.10)}\]

\[
B(r) = \left[ \left( Z_1 + \frac{1}{2} \text{Diameter} \cdot \sin(\phi) \right) + \left( Z_2 - Z_1 \right) r \right] \quad \left[ \left( P_1 - \frac{1}{2} \text{Diameter} \cdot \cos(\phi) \right) + \left( P_2 - P_1 \right) r \right] \\
0 \leq r \leq 1
\]

\(B(r) = 2\)-D line segment representing a second external surface

\[P_x = \text{Distance from the rotating axis to point x}\]

\[Z_x = \text{Distance from the joint being welded to point x parallel to the rotating axis}\]

\[\theta = \text{Angle from the weld head representation to part surface (See Figure 3.10)}\]

To determine where each vector of a pipe’s external line segments (\(A(r)\) and \(B(r)\)) intersect the right side vector of the weld head \((\text{WH}_1(t))\), \(A(r)\) and \(B(r)\) are set equal in to \(\text{WH}_1(t)\) in Equation 3.11 and Equation 3.12. Solving Equation 3.11 and 3.12 individually for \(r\) and \(t\) determines where along the parametric equations the vectors intersect. If the intersection occurs within the line segments \((t \geq 0 \text{ and } 0 \leq r \leq l)\), there will be a collision between the two objects. Additionally, the process must be repeated for the left side of the weld head by using \(\text{WH}_2\) in
place of WH$_1$.

\[ WH_1(t) = A(r) \quad 0 \leq r \leq 1 \quad t \geq 0 \]  \hspace{1cm} (3.10)

WH$_1 = \text{Right side boundary of the weld head}$

\[ A(r) = \text{Representation of exterior surface} \]

\[ WH_1(t) = B(r) \quad 0 \leq r \leq 1 \quad t \geq 0 \]  \hspace{1cm} (3.11)

WH$_1 = \text{Right side boundary of the weld head}$

\[ B(r) = \text{Second representation of exterior surface} \]

### 3.4.5 Evaluating Orbital Welding Equipment

When selecting an orbital welder (or welders) for a particular application, all available orbital welders are analyzed individually. Decisions are based on a number of criteria (Figure 3.20). The first item is the outer diameter. The weld diameter of the joint is compared to the orbital welder’s capability. Next, the logic will evaluate the assembly to determine if it provides a location which the orbital welder can secure (fix) itself to. Since the welder can be placed on either side of the weld, both locations are checked. Lastly, a collision detection is performed to ensure that the orbital welder can be placed in the location or locations permitting fixing without any interference from the assembly. If a welder fails any of the aforementioned criteria, the logic will exit evaluating the welder. Otherwise it will be recorded as a suitable option.
Figure 3.20: Evaluate Orbital Welders
Representing Orbital Welding Machines

Before selecting orbital welders for an application, general criteria for each orbital welder must be established. These unique machine parameters will be used when determining if the welder suits the application. The first parameter that must be known is the weld diameters the orbital welder is suitable to perform. The rest of the parameters are basic geometric dimensions commonly published by the manufacturer (See Figure 3.21). These dimensions are used for the fixing and collision detection processes.

![Figure 3.21: Orbital Clearance Requirements (Image Source: Magnatech, 2006)](image)

Fixturing for Orbital Welding Machines

Orbital welders require being fixed to only one of the two parts being welded together. Thus, two potential locations are evaluated to find if the current welder can be used to create the weld. Decisions are made using the immediately connected parts’ types and the previously mentioned dimensions (Figure 3.21).
Any orbital welder must have a straight section of pipe to secure itself to. There is not adequate room for fixing on elbows, tees or flanges. Thus, the only type of part an orbital welder can secure itself to is a straight tube with a minimum length of dimension A (Figure 3.21).

**Collision Detection for Orbital Weld Head**

The last test for an orbital welder is if the assembly is expected to interfere with the welder. A collision detection will be performed using the assembly’s geometry and the known welder dimension to determine if the parts are likely to collide.

Similar to the collision detection for the weld head of the Horizontal Welding Machine, the shape of the orbital welder will be simplified and tested against the assembly geometry. As discussed within this section, a representation of each pipe section’s external surface is created using the known centerline equation and part radius. The machine representation is then compared to the external surface of each segment of geometry.

The orbital welding head is approximated by a rectangular shape. In fact, the orbital welder is represented by using two shapes, one for each position of the welder. As illustrated in Figure 3.20, each possible position of the orbital welder (Figure 3.22 or Figure 3.23) is evaluated for collision detection individually as needed. The dimensions of the shapes (Figure 3.22 and 3.23) are based on the orbital welder’s dimensions (Figure 3.21). The line segments bounding the rectangular shape in Figure 3.22 are Equations 3.13 through 3.15. The second rectangular shape (Figure 3.23) is characterized by the line segments in Equations 3.16 through 3.18.
\[ L_1(l) = \left[ \frac{-B}{\frac{1}{2}(\text{IntDiameter} + l(C - \text{IntDiameter}))} \right] \quad 0 \leq l \leq 1 \]  
\[ T_1(t) = \left[ \frac{-B + t(A + B)}{\frac{1}{2}(\text{IntDiameter} + C - \text{IntDiameter})} \right] \quad 0 \leq t \leq 1 \]  
\[ R_1(f) = \left[ \frac{A}{\frac{1}{2}(\text{IntDiameter} + r(C - \text{IntDiameter}))} \right] \quad 0 \leq f \leq 1 \]
If any of the assembly’s geometry crosses any of the line segments being considered, a collision will be expected. Since the welding process requires the assembly to be fully rotated about the axis passing through the weld, the procedure must only consider the location of the assembly’s line segments relative to the joint being welded. This can be expressed as a distance from the rotating axis (P) and distance to the joint parallel to the axis (Z) (Equations 3.2 and 3.3). Each 3-D line segment will be therefore expressed as a 2-D line segment (See Equation 3.8). However, this line segment only represents the centerline equation. To represent the exterior surface, two new line segments (A(r) and B(r); Equations 3.9 and 3.10) are created. These two bounding line segments are created by shifting the centerline perpendicularly in each direction by the part’s radius.

Next, each line segment representing the exterior volume (A(r) and B(r)) will be set equal to each of the line segments bounding the orbital welding head. If the orbital is in the first position, the vectors of A and B will be set equal to each vector of the line segments L1(l), T1(t) and R1(f) (Equations 3.19 through 3.24).

\[
L2(l) = \left[ \frac{-A}{1} \left( \text{IntDiameter} + 1(C - \text{IntDiameter}) \right) \right] \quad 0 \leq l \leq 1 \quad (3.16)
\]

\[
T2(t) = \left[ \frac{-A + t(A + B)}{1} \left( \text{IntDiameter} + C - \text{IntDiameter} \right) \right] \quad 0 \leq t \leq 1 \quad (3.17)
\]

\[
R2(f) = \left[ \frac{B}{1} \left( \text{IntDiameter} + r(C - \text{IntDiameter}) \right) \right] \quad 0 \leq f \leq 1 \quad (3.18)
\]
If the orbital welder is in the second position, the vectors of the line segments L2, T2 and R2 will be set equal shown to the vector of A and B as in Equations 3.2 through 3.30.

\[ T1(t) = A(r) \quad 0 \leq r \leq 1 \quad 0 \leq t \leq 1 \]  \hspace{1cm} (3.21)
\[ T1(t) = B(r) \quad 0 \leq r \leq 1 \quad 0 \leq t \leq 1 \]  \hspace{1cm} (3.22)
\[ R1(f) = A(r) \quad 0 \leq r \leq 1 \quad 0 \leq f \leq 1 \]  \hspace{1cm} (3.23)
\[ R1(f) = B(r) \quad 0 \leq r \leq 1 \quad 0 \leq f \leq 1 \]  \hspace{1cm} (3.24)

Next, each equation is solved for the two unknown parametric values. If both of the parametric values are within the limits shown in the respective equation (the equation is true), the line segments will intersect. If there are any intersections, a collision is expected, and indicates the current position is a failure.
3.5 Summary of Methodology

This chapter presented an approach for a Computer Aided Process Planning system to evaluate the sequence of operations, grouping of setups, and machine selection for a pipe assembly. The primary objective of the system is to produce the most automated plan (or plans) possible, with a secondary objective of minimizing the number of setups at the tacking station. The methodology presented for machine selection compares assembly geometry to individual machine capabilities, choosing the most automated machine (or machines) able to complete the weld. It uses the results of the machine selection function to guide the logic for operations sequencing and setups. The end result will satisfy the objectives for the provided assembly geometry and machine parameters.
Chapter 4

Experimentation

To examine the methodology proposed for the Computer Aided Process Planning (CAPP) system for pipe welding, several pipe assemblies were created and processes planned. They were process planned using realistic machines for the application of low quantity high variability pipe welding.

This chapter will first present the machine parameters. Next, an assembly will be presented and the methodology will be examined in detail for all sequences. The resulting process plans for that example will then be assessed on the basis of their validity and usefulness. Finally, 4 more example assemblies and their recommended process plans will be presented and discussed.

4.1 Equipment

A single orbital welder has been chosen, the REDHEAD by Magna-Tech, shown in Figure 2.5. It is designed with a built-in 200A (continuous) water cooled torch for Gas Tungsten Arc Welding (GTAW). Its exact clearance requirements are illustrated in Figure 4.1. The orbital head has an adjustable diameter, capable of accommodating an outer diameter of 3.5 to 6.625 inches.
Two HWM’s have been chosen with different pipe diameter capability (See Table 4.1 and Figure 4.2). A Horizontal Welding Machine (HWM) is composed of several elements, key of which is the rotating base. The rotating base chosen for both HWM’s was the Pipe Bully, manufactured by All-Fab Corp. The clearance between the table center-line (Rotational Axis) to the top of the base support is 28.25 inches and the clearance between the center-line and floor is 32.00 inches. Since the base support is the lesser of the two, it will be used as the vertical clearance. The horizontal clearance will depend on the facility layout and location of other objects. However, to test the system it was assumed to be 5 feet in length. The last parameter is the shape of the weld head as illustrated in Figure 3.10. The lines defining the head are assumed to be 60 degrees from horizontal (See Figure 3.10).
4.2 Example 1

The first example assembly features 4 parts and 3 joints. Two are straight pipes, one is a tee and one is an elbow. The assembly is comprised entirely of nominally sized 4 inch pipe with a true outer diameter of 4.5 inches.

The assembly has been illustrated using two types of drawings. The first is a shop drawing featuring general dimensions for the final “as built” assembly (Figure 4.3). The second drawing contains key dimensions specifically for pipe process planning (Figure 4.4). The latter will frequently be referred to during the process planning methodology (Section 4.2.5).
Figure 4.3: Example 1 – Shop Drawing
Figure 4.4: Example 1 – Key Dimensions
The part identifiers (such as “Part A” or “Part C”) shown in Figure 4.3 and Figure 4.4 are specific to each part in the assembly. Each part also has a unique part number, regardless of its application. For example, in Figure 4.3 and 4.4, “Part A” and “Part B” are both identical pipe sections with the Part Number “Tube_001” because they have the same diameter and length. Individual part drawings are located in Appendix A. The Part Numbers for each item in Example 1 (Figure 4.3 and Figure 4.4) are located in Table 4.2.

Table 4.2: Part Numbers for Each Item in Example 1

<table>
<thead>
<tr>
<th>Assembly Part</th>
<th>Part Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part A</td>
<td>Tube_001</td>
</tr>
<tr>
<td>Part B</td>
<td>Tube_001</td>
</tr>
<tr>
<td>Part C</td>
<td>E90_001</td>
</tr>
<tr>
<td>Part D</td>
<td>Tee_001</td>
</tr>
</tbody>
</table>

The geometry for Example 1 is shown in Figure 4.5. It includes a part name for each item in the assembly, a part type, an outer diameter, and at least 1 line segment representing the centerline of the part. The straight pipe sections are represented by one line segment. The elbow and tee are represented by two line segments.

--- Parts ---

"Part C", Elbow (90 deg.), 4.5
0.4,0 - 0.0,0
0.0,0 - 4.0,0

"Part A", Tube, 4.5
4.0,0 - 39.0,0

"Part D", Tee, 4.5
39.0,0 - 47.25,0,0
43.225,0,0 - 43.225,4.225,0

"Part B", Tube, 4.5
43.225,4.125,0 - 43.125,39.125

Figure 4.5: Data Representation for Example 1

The two HWM’s used in this chapter differ only in the diameter of pipe that they can accommodate. The assembly in Example 1 can be welded using either of the two machines. Therefore, detailed results are shown for one of the HWM’s. The analysis is performed on the joints between pipe sections. Example 1 has 3 joints, as shown in Table 4.3.
Based on the number of joints in the assembly, there are 6 possible sequences. Each sequence will be evaluated individually to find the lowest automation score. This evaluation is shown in Figures 4.6 through 4.11. Each figure represents one sequence.

The first sequence evaluated is ordered \{J1, J2, J3\}. As indicated in Figure 3.4, the evaluation will begin with the first joint in the sequence (j=1), which is J1. J1 connects the Elbow (Part C) to the adjacent tube (Part A). The joint number (j=1) is sent to the Machine Selection function, along with the sequence. Since this is the “Find Sequences with Lowest Automation” logic, it will not specify a setup.

The Machine Selection function will begin by evaluating the HWM for J1. It will conclude based on the geometry that the outer diameter, height, length, and collision detection can be satisfied by HWM_1. The function also determined that the assembly can be fixed by either of two locations (Part A or Part C). Since a HWM was found successful, orbital welders will not be evaluated.

The machine selection will then be called for each of the remaining joints (J2 and J3). The function will determine that J2 can also be completed with HWM_1. However, the logic finds that J3 can not be completed by a HWM machine, due to the height requirement exceeding the machines capabilities. An orbital was determined to be successful as it can position itself on the connecting tube (Part B).

Once each of the welds has been evaluated, the joint will be saved in a setup, and the score for that joint will be recorded. Once the sequence is complete, the BestScore has been determined from the machine selections made for the sequence. Since it was the first sequence

<table>
<thead>
<tr>
<th>Joint</th>
<th>Part</th>
<th>Part</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td>Part C</td>
<td>Part A</td>
</tr>
<tr>
<td>J2</td>
<td>Part A</td>
<td>Part D</td>
</tr>
<tr>
<td>J3</td>
<td>Part D</td>
<td>Part B</td>
</tr>
</tbody>
</table>

Table 4.3: Joints Names for Example 1
evaluated, the score was stored. The same process was then repeated for each of the 5 remaining sequences.
S=1

For j = 1 (J1), Setup = 0:
  • Machine Selection is called:
    o Can Fix HWM by Elbow (Part C) or Tube (Part A)
    o No Base Collision Expected
    o Height = 4.125”, Length = 41.25”
    o HWM_1
      ▪ OD is satisfied
      ▪ Height is satisfied
      ▪ Length is satisfied
      ▪ Collision detection for weld head passes
      ▪ HWM_1 is successful
    o Return: HWM_1
  • \(A_{1,1}=1\)
  • \(\text{Setup}_1=[J1]\)

For j = 2 (J2), Setup = 0:
  • Machine Selection is called:
    o Can Fix HWM by Elbow (Part C) or Tee (Part D)
    o No Base Collision Expected
    o Height = 4.125”, Length = 49.5”
    o HWM_1
      ▪ OD is satisfied
      ▪ Height is satisfied
      ▪ Length is satisfied
      ▪ Collision detection for weld head passes
      ▪ HWM_1 is successful
    o Return: HWM_1
  • \(A_{1,2}=1\)
  • \(\text{Setup}_2=[J2]\)

For j = 3 (J3), Setup = 0:
  • Machine Selection is called:
    o Can Fix HWM by Tube (Part B)
    o No Base Collision Expected
    o Height = 45.375”, Length = 41.375”
    o HWM_1
      ▪ OD is satisfied
      ▪ Height Fails
      ▪ HWM_1 Fails
    o Orbital Welder
      ▪ OD is Satisfied
      ▪ Can Fix to Tube (Part B)
      ▪ Passes Collision Detection
    o Return: Orbital welder
  • \(A_{1,3}=2.3\)
  • \(\text{Setup}_3=[J3]\)

BestTotalScore=4.4

Store Sequence

Figure 4.6: Lowest Automation Score for Sequence 1 (J1-J2-J3)
S = 2
For j = 1 (J1), Setup = 0:
  • Machine Selection is called:
    o Can Fix HWM by Elbow (Part C) or Tube (Part A)
    o No Base Collision Expected
    o Height = 4.125", Length = 41.25"
    o HWM_1
      • OD is satisfied
      • Height is satisfied
      • Length is satisfied
      • Collision detection for weld head passes
      • HWM_1 is successful
    o Return: HWM_1
  • $A_{2,1}=1$
  • Setup$_1$={$J1$}
For j = 2 (J3), Setup = 0:
  • Machine Selection is called:
    o Can Fix HWM by Tube (Part B)
    o No Base Collision Expected
    o Height = 4.125", Length = 41.375"
    o HWM_1
      • OD is satisfied
      • Height is satisfied
      • Length is satisfied
      • Collision detection for weld head passes
      • HWM_1 is successful
    o Return: HWM_1
  • $A_{2,2}=1$
  • Setup$_2$={$J3$}
For j = 3 (J2), Setup = 0:
  • Machine Selection is called:
    o Can Fix HWM by Elbow (Part C) or Tee (Part D)
    o No Base Collision Expected
    o Height = 39.125", Length = 49.5"
    o HWM_1
      • OD is satisfied
      • Height Fails
      • HWM_1 Fails
      • Orbital Welder
        • OD is Satisfied
        • Can Fix to Tube (Part A)
        • Passes Collision Detection
      o Return: Orbital welder
  • $A_{2,3}=2.3$
  • Setup$_3$={$J2$}

BestTotalScore=4.4

Store Sequence

Figure 4.7: Lowest Automation Score for Sequence 2 (J1-J3-J2)
S = 3
For j = 1 (J2), Setup = 0:
  • Machine Selection is called:
    o Can Fix HWM by Tee (Part D) or Tube (Part A)
    o No Base Collision Expected
    o Height = 4.125", Length = 43.25"
    o HWM_1
      ▪ OD is satisfied
      ▪ Height is satisfied
      ▪ Length is satisfied
      ▪ Collision detection for weld head passes
      ▪ HWM_1 is successful
      o Return: HWM_1
    • A_3,1=1
    • Setup_1={J2}
For j = 2 (J1), Setup = 0:
  • Machine Selection is called:
    o Can Fix HWM by Elbow (Part C) or Tee (Part D)
    o No Base Collision Expected
    o Height = 4.125", Length = 49.5"
    o HWM_1
      ▪ OD is satisfied
      ▪ Height is satisfied
      ▪ Length is satisfied
      ▪ Collision detection for weld head passes
      ▪ HWM_1 is successful
      o Return: HWM_1
    • A_3,2=1
    • Setup_2={J1}
For j = 3 (J3), Setup = 0:
  • Machine Selection is called:
    o Can Fix HWM by Tube (Part B)
    o No Base Collision Expected
    o Height = 45.375", Length = 41.375"
    o HWM_1
      ▪ OD is satisfied
      ▪ Height Fails
      ▪ HWM_1 Fails
      o Orbital Welder
        ▪ OD is Satisfied
        ▪ Can Fix to Tube (Part B)
        ▪ Passes Collision Detection
        o Return: Orbital welder
    • A_3,3=2.3
    • Setup_3={J3}

BestTotalScore=4.4

Store Sequence

Figure 4.8: Lowest Automation Score for Sequence 3 (J2-J1-J3)
S = 4

For j = 1 (J2), Setup = 0:

- Machine Selection is called:
  - Can Fix HWM by Tee (Part D) or Tube (Part A)
  - No Base Collision Expected
  - Height = 4.125”, Length = 43.25”
    - OD is satisfied
    - Height is satisfied
    - Length is satisfied
    - Collision detection for weld head passes
      - HWM_1 is successful
  - Return: HWM_1

- A_{4,1}=1
- Setup_1={J2}

For j = 2 (J3), Setup = 0:

- Machine Selection is called:
  - Can Fix HWM Tube (Part B)
  - No Base Collision Expected
  - Height = 39.125”, Length = 41.375”
    - OD is satisfied
    - Height Fails
    - HWM_1 Fails
  - Orbital Welder
    - OD is Satisfied
    - Can Fix to Tube (Part B)
    - Passes Collision Detection
  - Return: Orbital welder

- A_{4,2}=2.3
- Setup_2={J3}

For j = 3 (J1), Setup = 0:

- Machine Selection is called:
  - Can Fix HWM by Tube (Part B)
  - No Base Collision Expected
  - Height = 45.375”, Length = 41.375”
    - OD is satisfied
    - Height Fails
    - HWM_1 Fails
  - Orbital Welder
    - OD is Satisfied
    - Can Fix to Tube (Part A)
    - Passes Collision Detection
  - Return: Orbital welder

- A_{4,3}=2.3
- Setup_3={J1}

BestTotalScore=5.8

Do NOT Store Sequence

Figure 4.9: Lowest Automation Score for Sequence 4 (J2-J3-J1)
For $j = 1$ (J3), $Setup = 0$:
- Machine Selection is called:
  - Can Fix HWM by Tube (Part B)
  - No Base Collision Expected
  - Height = 4.125”, Length = 41.375”
  - HWM_1
    - OD is satisfied
    - Height is satisfied
    - Length is satisfied
    - Collision detection for weld head passes
    - HWM_1 is successful
  - Return: HWM_1
- $A_{5,1}=1$
- $Setup_1=\{J3\}$

For $j = 2$ (J1), $Setup = 0$:
- Machine Selection is called:
  - Can Fix HWM by Elbow (Part C) or Tube (Part A)
  - No Base Collision Expected
  - Height = 4.125”, Length = 41.25”
  - HWM_1
    - OD is satisfied
    - Height is satisfied
    - Length is satisfied
    - Collision detection for weld head passes
    - HWM_1 is successful
  - Return: HWM_1
- $A_{5,2}=1$
- $Setup_2=\{J1\}$

For $j = 3$ (J2), $Setup = 0$:
- Machine Selection is called:
  - Can Fix HWM by Tee (Part D) or Elbow (Part C)
  - No Base Collision Expected
  - Height = 41.375”, Length = 49.5”
  - HWM_1
    - OD is satisfied
    - Height Fails
    - HWM_1 Fails
  - Orbital Welder
    - OD is Satisfied
    - Can Fix to Tube (Part A)
    - Passes Collision Detection
  - Return: Orbital welder
- $A_{5,3}=2.3$
- $Setup_3=\{J2\}$

Best Total Score = 4.4
Store Sequence

Figure 4.10: Lowest Automation Score for Sequence 5 (J3-J1-J2)
S = 6
For j = 1 (J3), Setup = 0:
  - Machine Selection is called:
    o Can Fix HWM by Tube (Part B)
    o No Base Collision Expected
    o Height = 4.125”, Length = 41.375”
    o HWM_1
      - OD is satisfied
      - Height is satisfied
      - Length is satisfied
      - Collision detection for weld head passes
      - HWM_1 is successful
    o Return: HWM_1
  - $A_{6,1}=1$
  - Setup_1:={J3}
For j = 2 (J2), Setup = 0:
  - Machine Selection is called:
    o Can Fix HWM by Tube (Part A) or Tee (Part D)
    o No Base Collision Expected
    o Height = 39.125”, Length = 43.25”
    o HWM_1
      - OD is satisfied
      - Height Fails
      - HWM_1 Fails
    o Orbital Welder
      - OD is Satisfied
      - Can Fix to Tube (Part A)
      - Passes Collision Detection
    o Return: Orbital welder
  - $A_{6,2}=2.3$
  - Setup_2:={J2}
For j = 3 (J1), Setup = 0:
  - Machine Selection is called:
    o Can Fix HWM by Elbow (Part C) or Tee (Part D)
    o No Base Collision Expected
    o Height = 39.125”, Length = 49.5”
    o HWM_1
      - OD is satisfied
      - Height Fails
      - HWM_1 Fails
    o Orbital Welder
      - OD is Satisfied
      - Can Fix to Tube (Part A)
      - Passes Collision Detection
    o Return: Orbital welder
  - $A_{6,3}=5.6$
  - Setup_3:={J1}

**BestTotalScore=5.8**

Do NOT Store Sequence

Figure **4.11**: Lowest Automation Score for Sequence 6 (J3-J2-J1)
After evaluating all 6 sequences, two were eliminated due to the automation scores. The remaining 4 sequences will be evaluated to find the minimum number of setups. The procedure will attempt to tack several joints in sequence, then weld all of them.

This process of minimizing setups for Sequence 1 ([J1, J2, J3]) is illustrated in Figure 4.12. The first step is to create the initial setup, presently with only the first joint (J1). The evaluation first begins by checking to see that the next joint (j=2) is attached. Following which, the machine selection will be called using Setup1+J2 as the present setup. The Machine Selection function returns the same process score for the assembly with both joints in a single setup. Thus, the additional joint is a success.

The logic then attempts to add the next joint, j=3 (J3) to the setup. First, it is found to be connected to the previous joint. Next, the machine selection is called for each of the joints in setup1. The score found for the first joint j=1 is inferior to that found during the “Find Sequences with the Lowest Automation Score” logic. Thus, the sum of the automation score will be worse than before. The logic then creates a second setup and adds the third joint (J3) to it. With all the joints completed, it can successfully exit the logic, recording the number of setups as the best found at this time. The same logic will then be applied to all of the remaining stored sequences, as shown in Figure 4.12 through 4.15.
s = 1. j = 1, i=1 
Setup₁ = {J₁} 
J₁ (J1) is connected to J₂ (J2) 
For j=1 (J1), setup = {Setup₁ + J₂} 
  • Machine Selection is called:
    o Can Fix HWM by Elbow (Part C) or Tube (Part A)
    o No Base Collision Expected 
    o Height = 4.125”, Length = 49.5” 
    o HWM₁ 
      ▪ OD is satisfied 
      ▪ Height is satisfied 
      ▪ Length is satisfied 
      ▪ Collision detection for weld head passes 
      ▪ HWM₁ is successful 
    o Return: HWM₁ 
  • Score = A₁₁ 
Setup₁ + J₂ = {J₁, J₂} 
j = j+1 = 2 
J₂ (J2) is connected to J₃ (J3) 
For joint = 1 (J1), setup = {Setup₁ + J₃} 
  • Machine Selection is called:
    o Can Fix HWM by Elbow (Part C) or Tube (Part A)
    o No Base Collision Expected 
    o Height = 39.125”, Length = 49.5” 
    o HWM₁ 
      ▪ OD is satisfied 
      ▪ Height Fails 
      ▪ HWM₁ Fails 
    o Orbital Welder 
      ▪ OD is Satisfied 
      ▪ Can Fix to Tube (Part A) 
      ▪ Passes Collision Detection 
    o Return: Orbital welder 
  • Score ≠ A₁₂ 

j=j+1=3 
i=i+1=2 
Setup₂={J₃} 
MinSetups=i=2 

Store Sequence

Figure 4.12: Minimum Number of Setups for Sequence 1 (J1-J2-J3)
S = 2, j = 1, i=1
Setup_1 = \{J1\}
J_1 (J1) is NOT connected to J_2 (J3)
j=j+1=2
i=i+1=2
Setup_2 = \{J3\}
J_2 (J3) is connected to J_3 (J2)

For joint=2 (J3), setup = \{Setup_2 + J2\}
- Machine Selection is called:
  - Can Fix HWM by Tube (Part B)
  - No Base Collision Expected
  - Height = 45.375”, Length = 41.375”
    - HWM_1
      - OD is satisfied
      - Height Fails
      - HWM_1 Fails
  - Orbital Welder
    - OD is Satisfied
    - Can Fix to Tube (Part B)
    - Passes Collision Detection
  - Return: Orbital welder
- Score ≠ A_{2,2}

j=j+1=3
i=i+1=2
Setup_3={J2}
i ≠ 3 ≠ MinSetups
Do NOT Store Sequence

Figure 4.13: Minimum Number of Setups for Sequence 2 (J1-J3-J2)
S = 3, j = 1, i=1
Setup_1 = {J2}
J_1 (J2) is connected to J_2 (J1)
For j=1 (J2), setup = {Setup_1 + J1}
  • Machine Selection is called:
    o Can Fix HWM by Tee (Part D) or Tube (Part A)
    o No Base Collision Expected
    o Height = 4.125", Length = 49.5"
    o HWM_1
      ▪ OD is satisfied
      ▪ Height is satisfied
      ▪ Length is satisfied
      ▪ Collision detection for weld head passes
      ▪ HWM_1 is successful
    o Return: HWM_1
  • Score = A_{3,1}
    Setup_1 + J2 = {J1, J2}
j = j+1 = 2
J_2 (J1) is connected to J_3 (J3)

For joint = 1 (J2), setup = {Setup_1 + J3}
  • Machine Selection is called:
    o Can Fix HWM by Elbow (Part C) or Tee (Part D)
    o No Base Collision Expected
    o Height = 39.125", Length = 49.5"
    o HWM_1
      ▪ OD is satisfied
      ▪ Height Fails
      ▪ HWM_1 Fails
    o Orbital Welder
      ▪ OD is Satisfied
      ▪ Can Fix to Tube (Part A)
      ▪ Passes Collision Detection
    o Return: Orbital welder
  • Score ≠ A_{3,2}

j=j+1=3
i=i+1=2
Setup_2={J3}
MinSetups=i=2
Store Sequence

Figure 4.14: Minimum Number of Setups for Sequence 3 (J2-J1-J3)
S = 5, j = 1, i=1
Setup_1 = {J3}
J_1 (J3) is NOT connected to J_2 (J2)
j=j+1=2
i=i+1=2
Setup_2 = {J1}
J_2 (J1) is connected to J_3 (J2)

For joint=2 (J1), setup = {Setup_2 + J2}
- Machine Selection is called:
  - Can Fix HWM by Tube (Part A)
  - No Base Collision Expected
  - Height = 39.125”, Length = 49.5”
    - HWM_1
      - OD is satisfied
      - Height Fails
      - HWM_1 Fails
  - Orbital Welder
    - OD is Satisfied
    - Can Fix to Tube (Part A)
    - Passes Collision Detection
  - Return: Orbital welder
- Score ≠ A_{5,2}

j=j+1=3
i=i+1=2
Setup_3 = {J2}
i = 3 ≠ MinSetups

Do NOT Store Sequence

Figure 4.15: Minimum Number of Setups for Sequence 5 (J3-J1-J2)
Figures 4.1 through 4.15 have illustrated the logic details for Example 1. The two sequences with the best automation score and the minimum number of setups are shown in Figures 4.12 and 4.14. The logic was implemented also in Microsoft Visual Basic. The program’s procedure instructions for the welder are shown in Figure 4.16.

---

**Figure 4.16: Process Plans for Example 1**

The decision logic returned two equal process plans. They both feature the same amount of automation and can be accomplished in 2 setups. Both solutions indicate that parts A, C and D should be tacked first, as part of a single setup. Then a HWM process can be done in either order using HWM_1 or HWM_2 for both joints. Following this, D and B can be tacked then welded using an orbital welder.

The difference between the two process plans is the sequence of welding (1-2-3 versus 2-1-3). Since the two first joints were grouped into a single setup for both sequences, the geometry when welding joints 1 and 2 will be the same in either process plan. Therefore, these two plans are effectively 1 process plan.
4.3 Example 2

For this and the following examples a brief summary will be presented. This example assembly features 5 parts and 4 connecting joints. All parts have an external diameter of 4.5 inches. A shop drawing (Figure 4.17) and a list of assembly parts (Table 4.4) are provided and discussed. The drawings containing key dimensions for process planning and each assembly’s data representation are located in Appendix B. The methodology was applied and the results returned are shown in Figure 4.18. Each of the four process plans feature an automation score of 11.8 and 2 setups.

One observation of the logic worth noting is the system’s inability to suggest an HWM weld for the connection of Part C to Part D in any of the procedures, which may be surprising since it provides sufficient access. However, the weld between Part C and Part D could only be performed using a horizontal welding machine if it were performed prior to welding the joints on either side of Part C. Otherwise a collision of the welding head is expected when welding C to D. Tacking part C to D prevents mechanized welding of Part B and Part E to Part C due to an expected welding head collision with Part D. The system identified the automation score to be superior when having two HWM welds as opposed to just one (11.8 versus 18.2). Additionally, an orbital welder was found to be unable to complete the weld between Part C and Part D because it did not have a sufficient location to secure itself to (a straight tube of 5 inches or more is required on at least one side of the weld).

Each solution provided has the same setups; the only difference between process plans is the sequence of joints welded within each setup. Similar to the first example, the sequence of welding within each setup is irrelevant, as the geometry will be the same for the joint regardless of the order of welds performed within the joint. Therefore, these four alternatives are effectively one single process plan.
Table 4.4: Part Numbers for Each Item in Example 2

<table>
<thead>
<tr>
<th>Assembly Part</th>
<th>Part Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part A</td>
<td>Tube_002</td>
</tr>
<tr>
<td>Part B</td>
<td>E90_001</td>
</tr>
<tr>
<td>Part C</td>
<td>Tee_001</td>
</tr>
<tr>
<td>Part D</td>
<td>E90_001</td>
</tr>
<tr>
<td>Part E</td>
<td>Tee_001</td>
</tr>
</tbody>
</table>

Figure 4.18: Process Plans for Example 2
4.4 Example 3

The third example (Figure 4.9) system is composed of nominally 6 inch pipe (6.625 inch actual outer diameter) (Figure 4.9 and B.3). There are 5 parts in the system and 4 connecting joints. The assembly’s part numbers are listed in Table 4.5. The exact data representation used and a drawing containing key dimensions for process planning are provided in Appendix B.

When the process planning methodology is applied, the CAPP system returns two process plans (Figure 4.10) each with an automation score of 5.4 and 3 setups. Each process plan begins by tacking Part B to Part C and welding the joint using HWM_2, the only HWM able to accommodate the 6.625” diameter pipe. The next tack and weld is performed on Part B to Part A using HWM_2 also. Parts A, B and C could not be performed at the same level of automation in a single setup because of an expected base collision when welding Part B to Part C from Part A. However, separating the tacking operations into two setups permits a HWM to be used for both joints.

With Part A, Part B and Part C connected, Part D can not be done as a HWM due to the expected head collision with Part B, yet an orbital welder can be secured to Part D. Additionally, Part E can be done with a HWM at any time and is not influenced by Parts C, B or A. Once again, the solutions represent a single process plan.
Figure 4.19: Example 3 – Shop Drawing
Table 4.5: Part Numbers for Each Item in Example 3

<table>
<thead>
<tr>
<th>Assembly Part</th>
<th>Part Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part A</td>
<td>Tee_002</td>
</tr>
<tr>
<td>Part B</td>
<td>E45_001</td>
</tr>
<tr>
<td>Part C</td>
<td>Tee_002</td>
</tr>
<tr>
<td>Part D</td>
<td>Tube_003</td>
</tr>
<tr>
<td>Part E</td>
<td>Flange_001</td>
</tr>
</tbody>
</table>

---

-- Process Plan 1 --
1) Fit and Tack: Part B to Part C
2) Fixture by Part B in machine HWM_2
   Weld Part B to Part C

3) Fit and Tack: Part A to Part C
4) Fixture by Part A in machine HWM_2
   Weld Part A to Part B

5) Fit and Tack: Part C to Part D
6) Fit and Tack: Part D to Part E
7) Weld Part C to Part D using Orbital
8) Fixture by Part C in machine HWM_2
   Weld Part D to Part E

---

-- Process Plan 2 --
1) Fit and Tack: Part B to Part 
2) Fixture by Part B in machine HWM_2
   Weld Part B to Part C

3) Fit and Tack: Part A to Part C
4) Fixture by Part A in machine HWM_2
   Weld Part A to Part B

5) Fit and Tack: Part D to Part E
6) Fit and Tack: Part C to Part D
7) Fixture by Part C in machine HWM_2
   Weld Part D to Part E
8) Weld Part C to Part D using Orbital

Figure 4.20: Process Plans for Example 3
4.5 Example 4

The fourth example assembly shown in Figure 4.21 is comprised of 5 parts and 4 joints as well. The most interesting portion of the design is the inclusion of two 45 degree angles attached to each other. The part numbers for all parts in the assembly are listed in Table 4.6. The parts are all 4.5 inches in true outer diameter. The assembly’s geometry data and a drawing containing key dimensions for process planning are included in Appendix B.

The methodology was applied and returned 3 equal process plans in Figure 4.22. Each process plan has an automation score of 5.4 and 3 setups. The first two process plans appear to show similarity to what was noticed in the first 3 examples; they are essentially identical plans a different sequence of welds within the first setup. They both have the joint from Part A to Part C and from Part C to Part D as the first setup, and the joint from D to E as the second. The third process plan is different than the first two. It keeps a single joint as the first setup, the joint from Part C to Part D. The second setup features two joints, from Part D to Part E and from Part A to Part C. While the third process plan is significantly different from the first two, it is an equivalent option since it has the same automation score and number of setups.
Table 4.6: Part Numbers for Each Item in Example 4

<table>
<thead>
<tr>
<th>Assembly Part</th>
<th>Part Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part A</td>
<td>Tee_001</td>
</tr>
<tr>
<td>Part B</td>
<td>Tube_002</td>
</tr>
<tr>
<td>Part C</td>
<td>E45_002</td>
</tr>
<tr>
<td>Part D</td>
<td>E45_002</td>
</tr>
<tr>
<td>Part E</td>
<td>Tee_001</td>
</tr>
</tbody>
</table>

----------: Process Plan 1 :-----------
1) Fit and Tack: Part A to Part C
2) Fit and Tack: Part C to Part D
3) Fixture by Part A in machine HWm_1 or HWm_2
   Weld Part A to Part C
4) Fixture by Part D in machine HWm_1 or HWm_2
   Weld Part C to Part D
5) Fit and Tack: Part D to Part E
6) Fixture by Part E in machine HWm_1 or HWm_2
   Weld Part D to Part E
7) Fit and Tack: Part A to Part B
8) Weld Part A to Part B using Orbital

----------: Process Plan 2 :-----------
1) Fit and Tack: Part C to Part D
2) Fit and Tack: Part A to Part C
3) Fixture by Part D in machine HWm_1 or HWm_2
   Weld Part C to Part D
4) Fixture by Part A in machine HWm_1 or HWm_2
   Weld Part A to Part C
5) Fit and Tack: Part D to Part E
6) Fixture by Part E in machine HWm_1 or HWm_2
   Weld Part D to Part E
7) Fit and Tack: Part A to Part B
8) Weld Part A to Part B using Orbital

----------: Process Plan 3 :-----------
1) Fit and Tack: Part C to Part D
2) Fixture by Part C or Part D in machine HWm_1 or HWm_2
   Weld Part C to Part D
3) Fit and Tack: Part D to Part E
4) Fit and Tack: Part A to Part C
5) Fixture by Part E in machine HWm_1 or HWm_2
   Weld Part D to Part E
6) Fixture by Part A in machine HWm_1 or HWm_2
   Weld Part A to Part C
7) Fit and Tack: Part A to Part B
8) Weld Part A to Part B using Orbital

Figure 4.22: Process Plans for Example 4
4.6 Example 5

The final example assembly shown in Figure 4.23 features 6 parts and 5 joints. The assembly is made from all 6 inch nominal pipe with a real outer diameter of 6.625 inches. The individual part numbers are listed in Table 4.7. The assembly’s geometric data representation and a drawing containing the key dimensions for process planning are included in Appendix B.

The process planning methodology found that there were 4 equal process plans (as shown in Figure 4.24). The process plans each had an automation score of 7.8 and 3 setups. The system found in each plan that the best joint to tack first is the connection between Part D and Part C. It then found that Part E and Part F can be added in a single setup and can both be completed using HWM 2. It then found that Part B and Part A can be attached to Part C using orbital welders. The system was forced to chose an orbital welder due to an expected collision between the welding head and Part D, E and F.
Figure 4.23: Example 5 - Shop Drawing
Table 4.7: Part Numbers for Each Item in Example 5

<table>
<thead>
<tr>
<th>Assembly Part</th>
<th>Part Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part A</td>
<td>Tube_004</td>
</tr>
<tr>
<td>Part B</td>
<td>Tube_004</td>
</tr>
<tr>
<td>Part C</td>
<td>Tee_002</td>
</tr>
<tr>
<td>Part D</td>
<td>E45_001</td>
</tr>
<tr>
<td>Part E</td>
<td>Tube_003</td>
</tr>
<tr>
<td>Part F</td>
<td>Tee_002</td>
</tr>
</tbody>
</table>

1. **Process Plan 1**: Fit and Tack: Part C to Part D  
   Weld Part D to Part D
2. **Process Plan 2**:  
   Fixture by Part D in machine HWM_2  
   Weld Part D to Part E
3. **Process Plan 3**:  
   Fixture by Part F in machine HWM_2  
   Weld Part E to Part F  
   Fit and Tack: Part E to Part F  
   Weld Part E to Part D
4. **Process Plan 4**:  
   Fixture by Part F in machine HWM_2  
   Weld Part E to Part F  
   Weld Part D to Part E  
   Fit and Tack: Part E to Part F  
   Weld Part E to Part D  
   Weld Part D to Part E  
   Weld Part E to Part D

Figure 4.24: Process Plans for Example 5
Chapter 5
Conclusions and Future Research

5.1 Conclusions

The proposed system for Computer Aided Process Planning (CAPP) is designed to create instructions (process plans) for welding pipe assemblies. The system is intended for assemblies which contain up to 6 parts, are to be produced in low quantity, and are each unique in form.

With a lower initial setup time than robotic equipment, and improved speed and reliability over manual methods, mechanized welding equipment is most suited for the manufacturing system. The types of mechanized equipment considered in the CAPP system are Horizontal Welding Machines (also known as roll welders) and orbital welders. However, not all welds can be completed using mechanized equipment. Thus, the system still maintains the ability to choose a manual welder when appropriate.

The CAPP system considers machine selection, sequencing of operations and fitting setups. Decisions are made to meet two objectives. The primary objective is to choose the most automated equipment possible. Automation is gauged by the type of machinery selected for each weld. Horizontal Welding Machines are the most automated of the two forms of mechanized equipment. Manual welding is less automated than either of the mechanized methods. The second objective is to minimize the number of setups at the tacking station without reducing the use of automated equipment.

The Computer Aided Process Planning System presented for the welding of pipe assemblies has demonstrated an ability to complete the objectives. The examples show that the
CAPP system consistently completes the primary goal of creating process plans that maximize the use of automated machinery. The process plans also appear to satisfy the second goal, minimizing the number of setups while maintaining the maximum use of automated welding equipment.

### 5.2 Future Research

One way the process planning system could be improved is by eliminating process plans that are deemed identical. Two or more process plans are considered identical when their solutions contain the same setups and machine selections. The sequence of welds within a setup bears no influence on the welding processes.

Additionally, there are several improvements that can be made concerning weld quality. When designed, the CAPP for pipe welding made several significant assumptions worth revisiting. The first was that distortion was negligible, and therefore wasn’t considered. A potential area for future work is to use the sequence of operations to steer away from a sequence where distortion is likely, such as performing two welds located near each other. Several key factors should be considered to quantify the risk of distortion, such as welding process, pipe diameter, wall thickness, material and distance between welds.

Another area of potential future work would be to consider welding processes. Due to material, joint design, wall thickness, and other factors, certain welds are often better suited for some processes (such as GTAW or SAW) than others. This may influence the machines that are considered during the machine evaluation. Additionally, some processes are capable of producing higher quality welds than others. If critical joints could be identified they could be paired with higher quality welding processes.

A third quality related improvement would be to consider performing challenging joints first. A joint may be deemed challenging if there are stringent quality standards or the geometry
prevents easy access. The added level of difficulty may increase the likelihood of a weld failing; failed welds result in wasted time and material. One possible solution would be to identify these joints and perform the welding operation earlier in the sequence. Therefore, if a weld does fail, it would result in fewer parts discarded and less time wasted.
Bibliography


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Wang, Lihui and Weiming Shen. Process Planning and Scheduling for Distributed
Appendix A: Part Geometry

Figure A.1: Part Drawing for Tube_001
Figure A.2: Part Drawing for Tube_002
Figure A.3: Part Drawing for Tube_003
Figure A.4: Part Drawing for E90_001
Figure A.5: Part Drawing for E45_001

- Dimensions:
  - Ø6.065
  - Ø6.625

- Annotations:
  - 45°
  - R9.000

- Title:
  - Part Drawing for E45_001

- Scale:
  - 1:1
Figure A.6: Part Drawing for E45_002
Figure A.9: Part Drawing for Flange_001
Appendix B: Assembly Geometry

Figure B.1: Example 2 – Key Dimensions
"Part A", Tube, 4.5
0, 0.20 - 0, 0.4

"Part B", Elbow (90 deg.), 4.5
0, 0.4 - 0, 0.0
0, 0.0 - 4, 0.0

"Part C", Tee, 4.5
4, 0, 0 - 12.25, 0, 0
8.125, 0, 0 - 8.125, 0, 4.125

"Part D", Elbow (90 deg.), 4.5
8.125, 0, 4.125 - 8.125, 0, 8.125
8.125, 8.125 - 8.125, 4, 8.125

"Part E", Tee, 4.5
12.25, 0, 0 - 16.375, 0, 0
16.375, 4.125, 0 - 16.375, -4.125, 0

Figure B.2: Data Representation for Example 2
Figure B.3: Example 3 – Key Dimensions
"Part A", Tee, 6.625
0.0, 0 - 0.0, 11.25
0.0, 5.625 - 3.625, 0.625

"Part B", Elbow (45 deg.), 6.625
0.0, 11.25 - 0.0, 15
0.0, 15 - 2.632, 0.17632

"Part C", Tee, 6.625
2.632, 0.17632 - 6.629, 0.21629
6.629, -5.625, 21.629 - 6.629, 5.625, 21.629

"Part D", Tube, 6.625
6.629, 1.025, 21.629 - 6.629, 17.625, 21.629

"Part E", Flange, 6.625

Figure B.4: Data Representation for Example 3
Figure B.5: Example 4 – Key Dimensions
"Part A", Tee, 4.5
   0,0,0 - 8.25,0,0
   4.125,0,0 - 4.125,4.125,0

"Part B", Tube, 4.5
   4.125,4.125,0 - 4.125,20.125,0

"Part C", Elbow (45 deg.), 4.5
   8.25,0,0 - 10.735,0,0
   10.735,0,0 - 12.492,-1.757,0

"Part D", Elbow (45 deg.), 4.5
   12.492,-1.757,0 - 14.249,-3.514,0
   14.249,-3.514,0 - 16.734,-3.514,0

"Part E", Tee, 4.5
   16.734,-3.514,0 - 24.984,-3.514,0
   20.859,-3.514,0 - 20.859,0.611,0

Figure B.6: Data Representation for Example 4
Figure B.7: Example 5 – Key Dimensions
"Part A", Tube, 6.625  
-45.625, 0, 0 - 5.625, 0, 0 <1, 0, 0>

"Part B", Tube, 6.625  
5.625, 0, 0 - 45.625, 0, 0 <1, 0, 0>

"Part C", Tee, 6.625  
-5.625, 0, 0 - 5.625, 0, 0 <1, 0, 0>  
0, 0, 0 - 0.5, 625 <0, 1, 0>

"Part D", Elbow (45 deg.), 6.625  
0, 5.625, 0 - 0, 0.375, 0 <0, 1, 0>  
0, 0.375, 0 - 0.12027, 2.652 <0, 0.707, 0.707>

"Part E", Tube, 6.625  
0.12027, 2.652 - 0.20512, 11.137 <0, 0.707, 0.707>

"Part F", Tee, 6.625  
0.20512, 11.137 - 0, 28.466, 19.091 <0, 0.707, 0.707>  
0, 24.489, 15.114 - 0, 28.466, 11.137 <0, 0.707, -0.707>

Figure B.8: Data Representation for Example 5