

**Work Envelope Requirements Among Piping and Steel
Trades and the Influence of Anthropomorphic
Characteristics of Global Populations**

by

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Work Envelope Requirements Among Piping and Steel Trades and the Influence of Anthropomorphic Characteristics of Global Populations

Thesis directed by Prof. Paul M. Goodrum

With the increased usage of Building Information Modeling (BIM) in the construction industry, new preconstruction processes are emerging. This is the case of 4D animation that brings together the 3D model of a building and its construction schedule to visualize construction process in a virtual manner. This technologically advanced approach in the preconstruction phase contrasts with the unanticipated overstaffing on the worksite, which results in losses of productivity. This research provides a framework to help bridge this gap, by integrating the knowledge of work envelope requirements on piping and steel construction to prevent overstaffing and reduce productivity losses. Initial efforts to identify the way that work envelope requirements were defined in the literature revealed that if many possible usages are considered, very little was found on how to automatically assess the exact work envelope requirement. Thus the work envelope was first defined through five in-depth interviews with experienced superintendents on steel and piping projects. Their thought process, when presented with common situations, was recorded and general rules were extracted. Those rules were then summarized in 16 decision trees, describing the required work envelope in specific steel and piping construction situations. Most of those work envelope definitions include dimensions relative to the body parts. This led to assess the absolute dimensions of the work envelope, using anthropomorphic data, to compare the level of work envelope overlap between worldwide populations. The results show that some work envelope requirements, identified through the interviews, have a limited tolerance and are more sensitive to body dimension changes. It was found that in such situation the population anthropomorphic characteristics significantly impact the work envelope requirements. This research contributes to the body of knowledge by defining the characteristics of the work envelope on construction projects. Specifically it stresses

the independence horizontal and vertical components of the work envelope; identifies the specific factors impacting those two components; and describe how not considering the anthropomorphic data would impact the space planning on site.

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Chapter 1

Introduction

While construction projects are becoming more and more complex, they remain by nature prototypes where inherent risks exist whether systems will work correctly the first time. Concurrently, pressure for timely delivery is increasing. As an answer, the construction industry has experienced a growing use of technologies. Yet the productivity of this industry has decreased or at least stagnated since 1964 (Dyer et al., 2012), which means that construction projects do not take full advantage of their resources. The classical resources considered by construction planner are work hours, materials and equipment. But, the space available to execute the scheduled activities is also one of the main resources and constraints that affect the productivity of a project. The overstaffing, when too many craft worker are sharing the same workspace, has been recognized as a factor contributing to the before mentioned decrease in construction productivity.(Hanna et al., 2007)

In recent years the Architecture, Engineering and Construction (AEC) industry experienced a paradigm shift from traditional Computer Aided Design (CAD) to Building Information Modeling (BIM). This new technology is defined as a “set of interacting policies, processes and technologies generating a methodology to manage the essential building design and project data in digital format throughout the building’s life-cycle” (Succar, 2009) and transforms the way design, construction and maintenance of building is performed. The core advance of BIM is to link a set of 2D and 3D representations of a project to a database, so that every visual element has a corresponding entry in the database with its physical and functional characteristics.

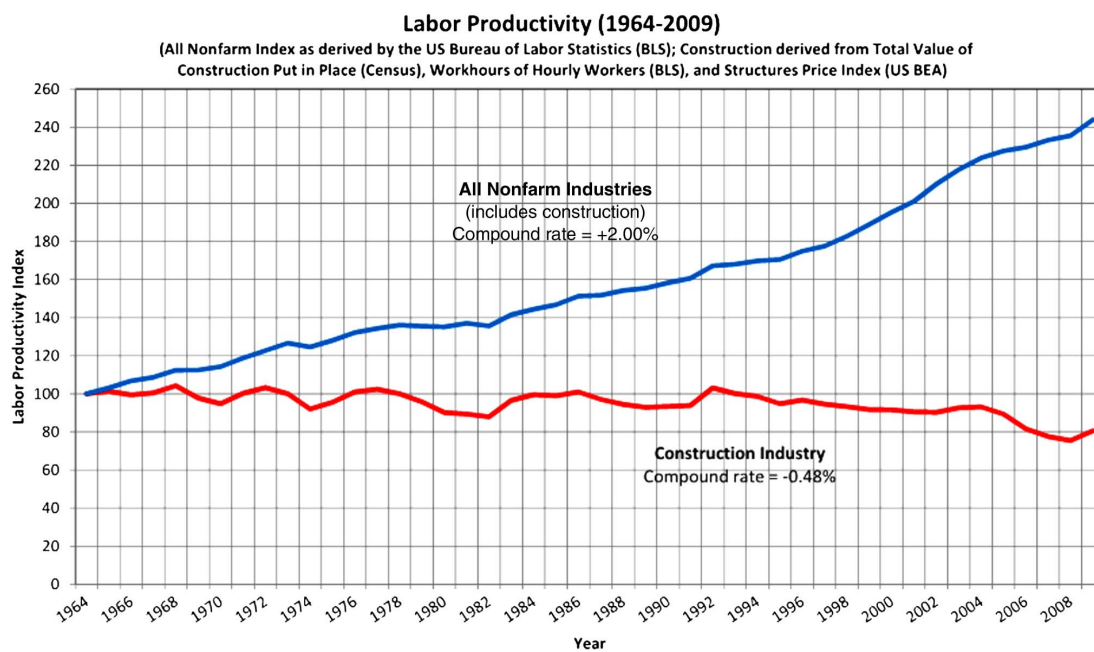


Figure 1.1: Comparison of Productivity Index Construction Industry and All Non- Farm Manufacturing Industry. From (Dyer et al., 2012)

The most extensive use of BIM is currently observed during the preconstruction phase. Designers are now proficient with its usage and construction companies are using it more widely. Among the most advanced usages of BIM seen on the field, there is the 4D animation tool. It consists in linking the 3D model of a building to the project schedule to visualize the construction process before it actually occurs on site. This is a first attempt to better communicate to the construction team the construction challenges, but the information it brings them remains limited.

The construction phase remains very traditional in its methods with limited usage of the latest technologies. Traditional planning techniques involve Gantt charts, network diagrams and CPM. But if these methods are adequate to communicate the time dimension of a task they do not enable the project managers to grasp the space constraints involved (Mawdesley et al., 1996). There is actually a lack of tools to analyze, detect, control and monitor workspace conflicts, which leads to losses in productivity (Dawood and Mallasi, 2006). With such tools the project managers could analyze their schedule and quickly identify “hot spots” at some point in time and space in their schedule. They could later optimize it by reducing overstaffing without lengthening the construction duration. An enhanced 4D animation showing the work envelope required for each activities and their conflicts could be such a tool.

Chapter 2

Background and justification

2.1 Space requirement is a key planning constrain

With the increasing pressure for timely delivery, the first reaction to increase the production rate is to increase the resources allocated to construction activities and the number of concurrent activities. The workspace resource cannot be increased, but only shared between trades. This results in conflicts when work envelopes of more than one activity are overlapping. Since the late 90s, the workspace was recognized as a key resources on a construction site (Thabet and Beliveau, 1994) and the lack of proper tools to include space in the project planning acknowledged (Mawdesley et al., 1996). Traditional planning tools such as Gantt charts do not enable the project planners to grasp the interaction between construction activities (Dawood and Mallasi, 2006). Sometimes, planners rely on sketches or 2D drawings to allocate the workspace between trades. But the work is performed in a 3D environment, and some projects with constrained space such as tunnels (J et al., 2007) or bridges are taking advantage of all the dimensions.

With the ever-increasing complexity of buildings geometries the project planners are unable to fully understand the time-space relationship of construction tasks. It leads to a large number of unexpected workspace interactions between trades. Riley and Sanvido (1997b) conducted a case study on a construction project and recorded the spatial conflicts occurring on a two-month period. While the observations were limited to the mechanical, electrical, plumbing and fire protection trades, 71 examples of such conflicts were recorded. Although this work does not provide quantified productivity losses due to those space-time conflicts, there is many supporting evidence. Mallasi

and Dawood (2001) concluded that such interferences contributed to decrease the productivity of the workforce by 30% and Sanders and Thomas (1991) found productivity losses up to 65%. This is confirmed by many other research studies that lists the work envelope conflicts among the major causes of productivity losses [for example, (Rad, 1980; Oglesby et al., 1989; Howell and Ballard, 1997)]. The main source of spatial conflicts is overcrowding, when too many craft worker have to share the same working area. Instead of focusing on individual workspaces U.S. Army Corps of Engineers (1979) focused on the link between overall overcrowding in an area and the loss of productivity. The Figure 2.1 shows that this relationship is not perfectly linear. With the link between space usage and productivity losses now established, great benefits can be expected from using enhanced planning tools that manage both time and space as critical resources, which is sometime called Critical Space Analysis (CSA) in the literature (Dawood and Mallasi, 2006).

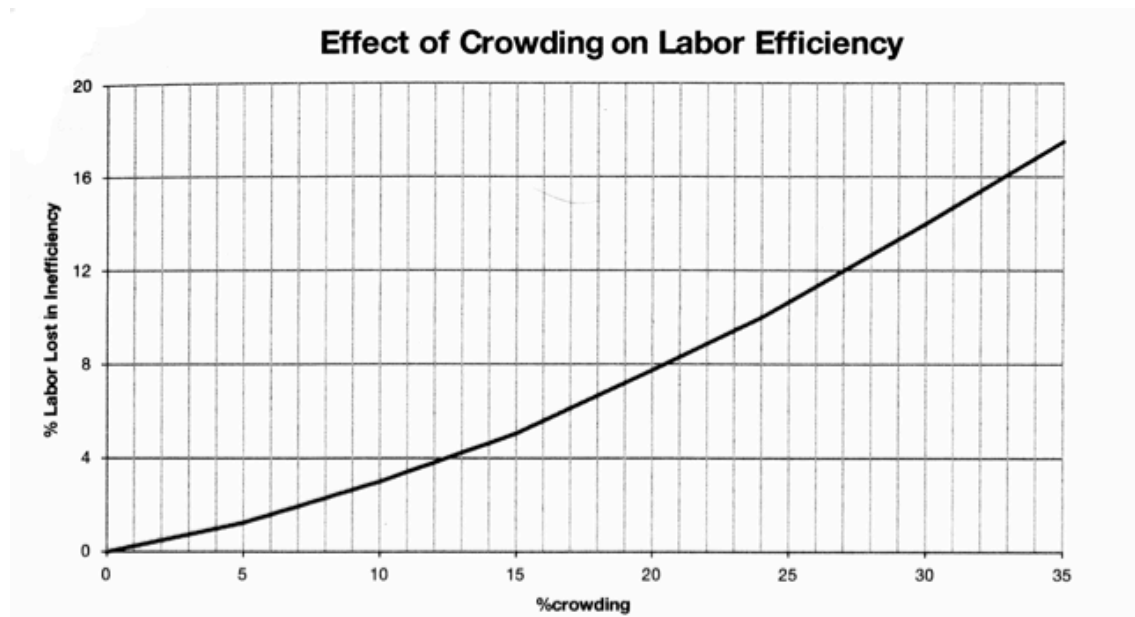


Figure 2.1: There is a non Relationship between overcrowding and loss of labor efficiency. From (U.S. Army Corps of Engineers, 1979)

2.2 Recognition of the work envelope ontology

Once the impact of space usage on productivity and project planning is acknowledged, better understanding of how space is allocated is required. While early classifications only relied on the amount of overlap between work envelopes (Thabet and Beliveau, 1997), it became important to also classify the nature of the workspace and their conflicts. This is needed to provide project planners with the nature of the conflict and its priority. According to Mallasi (2006) it enabled them to answer the questions “which space-type is expected to interfere during that week?” and “what is the severity of such interference?”. Then the clash can be assessed, and the right scheduling decision made in full knowledge.

The workspace conflict taxonomy was mainly developed by Akinci et al. (2002) which formulated both a workspace classification and corresponding clashes classification to compliment the overlap quantification. In this work, the overlap quantification is performed through a so-called conflict ratio, which is the ratio of the conflicting volume over the total object volume. It classifies the workspaces under six categories: Building Components, Labor Crew Space, Equipment Space, Hazard Space, Protected Space and Temporary Structure. Two conflicting spaces are not necessary of the same category so Akinci et al. (2002) developed another set of categories for the conflict type. The link between the conflicting spaces types and the resulting conflict type is performed through a two-way matrix. For instance an “Equipment Space” conflicting with a “Labor Crew Space” is called “Congestion”. For each of the seven conflict types there is a corresponding priority. Based on the conflict ratio and conflict priority an overall conflicts ranking can be fulfilled. Many other research work focused on classifying workspaces (Riley and Sanvido, 1997a; Guo, 2002; Dawood and Mallasi, 2006; Moon et al., 2009; Wu and Chiu, 2010; Chua et al., 2010) finding a number of categories ranging from 4 to 12. Chavada et al. (2012) found that there are many similarities in those classifications and summarized them in 4 categories: (1) Main Workspace, (2) Support Workspace, (3) Object Workspace, (4) Safety Workspace.

In most of the literature reviewed, the workspace is linked to the objects. As noted by

Chavada et al. (2012) this is impractical and does not account for a multiple objects sharing the same workspace. Not linking workspace to activities makes these studies unable to consider some workspaces types such as “Safety Workspace” which might is not specific to an object.

2.3 Usages of work envelope

The primary usage of the work envelope, as described previously, is to detect and analyze the time-space conflicts in the project schedule. Some attempt to use on-the-shelf software has been mentioned (J et al., 2007; Haque and Rahman, 2009).

Some more advanced usage, involving various optimization algorithms for the project schedule, such as Genetic algorithm or fuzzy logic, have also been mentioned in the literature but there is little evidence that they have been utilized on actual projects.

In compliment to the work schedule optimization, the knowledge of the work envelope can have many application, some of them unforeseen. The research team was approached and partnered with Bentley Systems who had interest in assessing the work envelope for construction methods purpose. Indeed, knowing the workspace requirement in an automated fashion can help to determine the scaffolding requirements for the “at-height” tasks and eventually optimize the scaffolding plan. This show that the work envelope definition framework presented may lead to many applications in the industry.

2.4 But a lengthy process to input the work envelope

All those groundbreaking usage are still requiring the basic knowledge of the work envelope for each individual task. However, off-site planners do not have on the field experienced to draw an accurate estimate. Most of the literature refers to the involvement of project superintendents to manually input the required work envelope. Sadly, superintendents are rarely involved in the preconstruction phase of the project. Even if that would be possible the process would still remain lengthy and extremely costly.

A first attempt to automate the work envelope assessment was made by Akinici et al. (2002)

with the development of the proof of concept software 4DWorkPlanner. But the automation is limited to the 3D drawing of the workspace. The user still has to manually enter the dimensions of the work envelope and its position relative to the component to be installed. Then the software would draw it on top of the building model, in a virtual 3D environment. This solution facilitates the input process for the user, but does not help him in making an accurate estimate of the workspace requirement. The involvement of a professional who has a field experience would still be required to make that estimate.

Chapter 3

Research Structure

In order to achieve the previously mentioned objectives, the present research was divided in two phases. The first phase focused on defining the work envelope by involving expert superintendents in in-depth interviews. These interviews helped capture their thought process when making workspace requirement decisions and also record the influencing parameters of those decisions. The results obtained from this first phase were mainly dimensions relative to the body parts. For instance in some situations the ideal working height is “between chest and waist” which lead to the following question: “What is the average chest and waist height?” To answer that question the phase 2 focused on tabulated and calculated anthropomorphic data to translate those relative dimensions into absolute measures. In addition we calculated the probability to have significant work envelope overlap between two populations. This gives an insight on how global companies would have to adapt their workspace from one country to another. This phased process allows a better understanding of the mechanic behind the work envelope assessment, before getting into more detailed physical constrains.

3.1 Phase 1: Work envelope structure

The initial phase of the study involved understanding the reasoning process behind the work envelope assessment. The work envelope, also referred as craft workspace in the literature, is the three-dimensional shape that encompass the craft worker and the volume surrounding him which is required to perform safely and comfortably a specific activity. The superintendents are

widely recognized as retaining this knowledge since they manage the construction process at the task level (Akinci et al., 2002). Thus, in-depth interviews were conducted with five experienced superintendents. This sample size, which might appear relatively small is the consequence of a limited overall population. The unique technical qualification required to provide useful information for the purpose of this project limits number of suitable candidates. This is compensated by the high level qualifications of the interviewees as described as follows:

- **Superintendent 1:** Former superintendents on oil & gas project in the U.S. Gulf Coast with about 10 years of experience on the field. Now working as subject matter expert at Bentley Systems.
- **Superintendent 2:** Former superintendents on oil & gas project in the U.S. Gulf Coast with about 8 years of experience on the field. Now working as subject matter expert at Bentley Systems.
- **Superintendent 3:** Scaffolding superintendent in the U.S. Gulf Coast for one of 50 biggest U.S. contractor. He has about 12 years of experience on the field.
- **Superintendent 4:** Scaffolding superintendent for as scaffolding contractor in western Canada on oil sand refineries projects. He has many years of experience as pipe and steel superintendent and 3 on scaffolding.
- **Superintendent 5:** Piping superintendent on oil & gas project in the U.S. Gulf Coast for one of the Major U.S. contractor. He has about 15 years of experience, 6 as a superintendent.

The superintendents were selected for their high level of experience in the industry, in particular on oil & gas projects in the U.S. Gulf Coast. This area is notably interesting for the purpose of this project with the recent shale gas boom. Indeed the current facilities in the U.S. Gulf Coast that were designed to import Liquefied Natural Gas (LNG) are now retrofitted to export it.

Given the large number and diversity of task involved in a construction project the research team developed a framework describing the work envelope requirements, out of a selected number of tasks. Other industries have been focusing for a long time on the workspace requirement for their workers notable is the case of the aerospace industry. But in the construction industry this remains a secondary matter dealt on the worksite. This framework intends to bring a rational consideration on the work envelope requirements by answering the question: “Why do we need such space?” Yet, the visual representation ensure that the concept can be understood by a broad audience.

At this point the research team partnered with Bentley Systems, and it was decided that the focus would be on work envelope requirement involved in scaffolding operations. More precisely the focus was on piping and steel operations, common on oil & gas project that involve scaffolding. The interviews consisted in presenting situations commonly found on oil & gas project through sample worksheets (Figure 3.1 and Appendix A). To ensure accuracy the selected situation were extracted from a 3D model of an actual carbonation plant provided by Bentley System. The specific area were selected in collaboration with our first interviewee to cover a broad spectrum of site configurations. The worksheets present both 2D and 3D views, textual data about the component installed (size, weight, installation method), callouts on the connection points and a virtual mannequin to give a sense of scale. A total of nine sample worksheets were developed. Once the situation was introduced to the superintendents, they were asked what would be the optimal workspace requirement and to detail their decision process.

The superintendents thought process was recorded in a spreadsheet (Table 4.1a). This spreadsheet records the raw interviews with for each interviewee the rules that were given for each worksheet. The rules were analyzed and summarized into 16 decision trees. Four of those decision trees are displayed in Chapter 4. The remaining ones differs only by the 3D representation. These decision trees articulated themselves around “break point” that were identified in the interviews. Such breakpoints are parameters which are recognized to have a significant impact on the work envelope requirement. For instance, it was determined that the optimal working height for bolting two beams is different than for welding. The purpose of the decision trees is to describe the

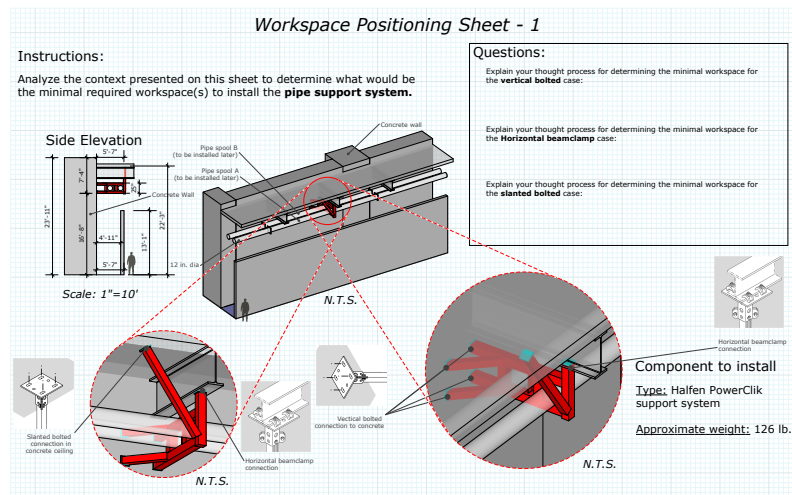


Figure 3.1: One of the worksheets describing a pipe support system bolted to a beam and to a concrete wall. The connection points are highlighted in cyan.

workspace assessment process, in a way similar to “IF-THEN” statements so that it can be easily implemented in software algorithm. To compliment the decision trees, 3D drawing were included to directly visualize the situation described.

3.2 Phase 2: Work envelope dimensioning

The work envelope definition obtained in phase 1 includes many dimensions relative to the body parts, such as “at face height”. This is interesting because it does not limit the definition to a specific population but in practice planners need real physical dimensions for the various applications previously mentioned. The relative definitions need to be translated into absolute dimensions using anthropomorphic data. The Figure 3.2 presents the process used. The body-relative dimensions obtained at the phase 1 are used as input for this second phase. Two types of supporting data are used to convert the body-relative work envelope into an absolute one with real physical dimensions. Eventually, the work envelopes from different populations are compared to each other.

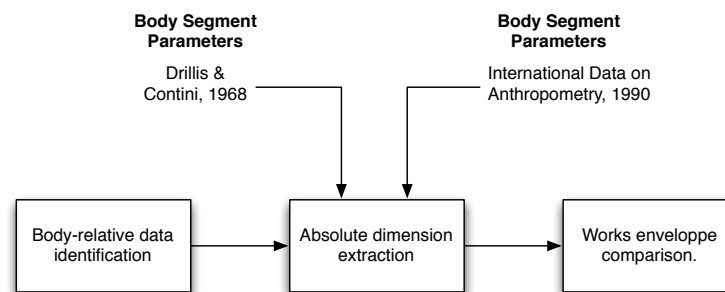


Figure 3.2: Absolute work envelope dimensioning process.

Jürgens et al. (1990) is the primary source for anthropomorphic measurements. It gathers data from multiple worldwide studies conducted from the sixties to the late eighties. This meta-analysis, published by the International Labor Office, breaks down the world into twenty populations. From those the present research only retains the seven most important for the construction industry that are still representative of the world population. They cover developed

countries where the major global companies are doing business, but also BRIC countries where a growing number of opportunities for those companies are emerging: (1) International; (2) North American; (3) Latin American (Rest); (4) North Europe; (5) Eastern Europe; (6) North India; (7) South India. The pitfall of this data sources is that some populations only have a limited number of body dimensions available. The only information consistently available across every population is the stature, or overall body height, from the bottom of the feet to the top of the head.

| Population | Stature | |
|----------------|-----------|---------------|
| | Mean (mm) | Std Deviation |
| International | 1780 | 79 |
| North America | 1790 | 70 |
| Latin America | 1750 | 61 |
| North Europe | 1810 | 61 |
| Eastern Europe | 1750 | 58 |
| North India | 1670 | 58 |
| South China | 1660 | 30 |

Table 3.1: Stature mean and standard deviation for the selected populations

To compensate this lack of consistent data across every population, the present study relies solely on, the Stature, with its mean and standard deviation, but the remaining body segment parameters (ie. Size of the other body parts) are calculated using data from Drillis and Contini (1968). Indeed, this study provides ratios between the stature and many body segments size. By combining the two sources of data it is possible to know the dimension of many body parts for the selected populations. Then the work envelope dimension can be deduced, including its mean and standard deviation.

Once the work envelope is perfectly defined, it raises the question to know how similar or different the populations are. The usual statistical analysis methods cannot be used since there is no sample but rather statistical metrics extracted from the population itself. Thus, the analysis relies on common probability methods. Knowing how similar two populations are relative to their work envelope, translates in knowing the level of overlap between the populations. Since every

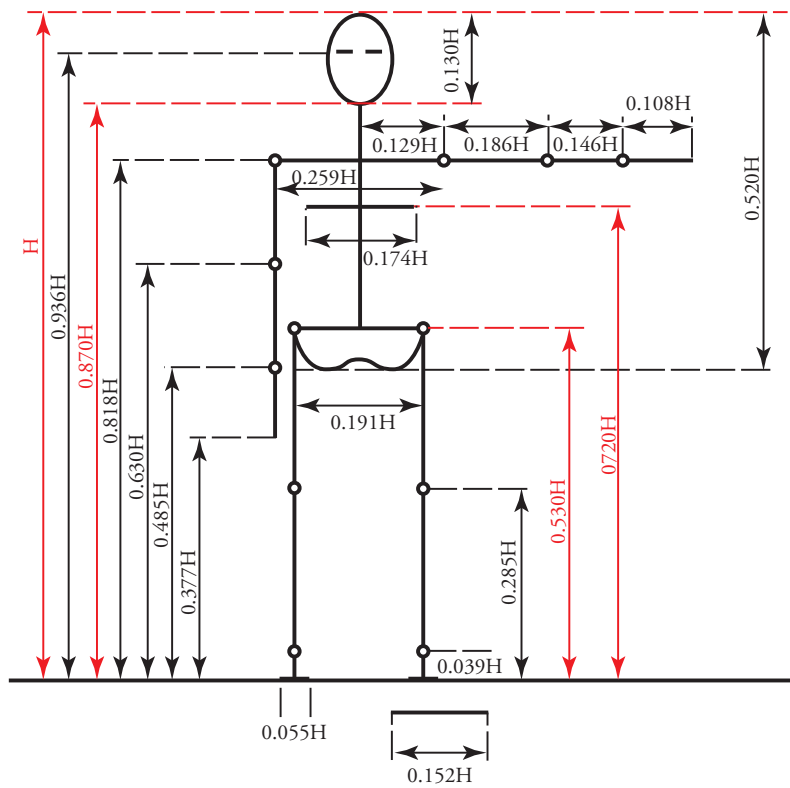


Figure 3.3: Body segment parameters, From (Drillis and Contini, 1968). The parameters used in this study are highlighted in red.

individual in each population is unique, the probability to reach a required level of overlap is used. In other terms, when choosing randomly one individual in each of the two compared populations, what is the probability to reach the required work envelope overlap? It is now a random variable problem that can be easily solved.

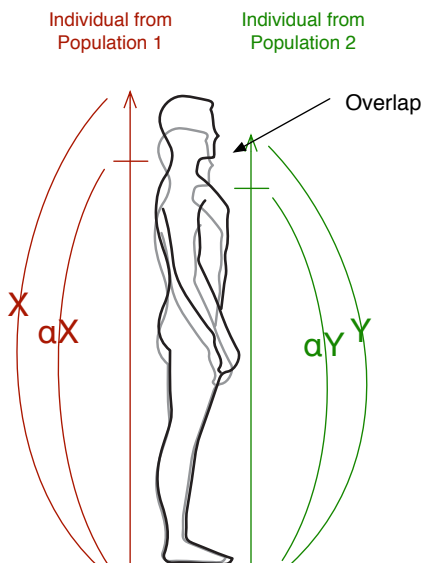


Figure 3.4: Comparison of two individuals from different populations.

The following shows how the method can be applied to the “face height” overlap. X is the stature of an individual randomly picked from the population 1 and Y for the individual from population 2. The α represent the stature to chin ratio as found in (Drillis and Contini, 1968). Then the probability to reach the level of required overlap, R , translates into:

$$\begin{aligned}
 Y - \alpha X \geq (X - \alpha X) &\iff Y \geq (X - \alpha X)R + \alpha X \\
 &\iff Y \geq X(R - \alpha R + \alpha) \\
 &\iff Y - X(R - \alpha R + \alpha) \geq 0
 \end{aligned}$$

The International Data on Anthropometry (Jürgens et al., 1990) assumes that the population stature follows a normal distribution. In this case it means that if both X and Y follow a normal

distribution, a linear combination of them also does:

$$X \sim N(\mu_X, \sigma_X)$$

$$Y \sim N(\mu_Y, \sigma_Y)$$

so:

$$Y - X(R - \alpha R + \alpha) \sim N(\mu_Y - (R - \alpha R + \alpha)\mu_X, \sigma_Y + (R - \alpha R + \alpha)^2\sigma_X)$$

It means that $P(Y - X(R - \alpha R + \alpha) \geq 0)$ can be easily calculated using common statistical analysis software. Visually, it translates into the area under the normal curve.

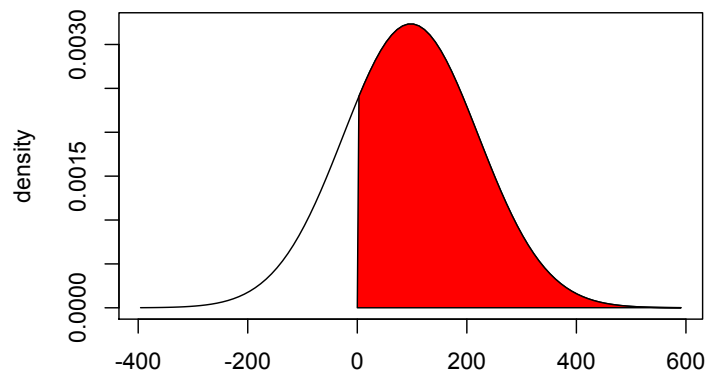


Figure 3.5: Normal curve showing the density distribution of the overlap. The area under the curve is the overlap probability.

Chapter 4

Results

The research effort, initiated a way to optimize craft workers productivity by defining more accurately the work envelope, also provided information to enhance the ergonomics of the craft worker's environment. Applying the work envelope concept to scaffold planning could both, increase the cost efficiency of the equipment, and enhance the safety of the workers.

4.1 Phase 1

Following the aforementioned method, interviews with five experienced superintendents were conducted. Their raw input is gathered in table 4.1a where the names of the interviewees have been removed to ensure privacy. Although the sample size is limited, the high level of agreement between the answers gives sufficient confidence in the results. An initial analysis revealed that an unsafe practice, consisting on standing on a bucket was mentioned. It was of course discarded from future analysis. Some other aspect more focused toward optimization or good practices not directly relevant to the work envelope requirement are also mentioned in table 4.1a and have been discarded.

| Interviewee | Drawing sheet | Rules mentioned | Comment |
|-------------------------|---|---|---------|
| Superintendent 1 | Sheet 1 – Bolted support system | <p>The railing height on a scaffold is 3ft. Nothing should hit this threshold.</p> <p>The height of the platform is set using the highest elevated connection</p> <p>The optimal height for bolting is above waist and below chest (3-4ft above the platform)</p> <p>The number of levels of platform needed will be set given the vertical distance between the connections</p> <p>For a bolted connection to a wall there should be 3ft 6in of space from the wall</p> <p>3ft 6in space around the outside of the object is optimal (in any situation)</p> <p>The comfortable welding position is just below the chest to above the waist</p> <p>For vertical welds with sufficient head clearance: The right position is just above the waist. (ie. 3ft from the platform for a 5'10" worker)</p> <p>Horizontal weld with sufficient head clearance: At face height (5'5")</p> <p>Horizontal weld with insufficient head clearance: comfortable reaching arm extension above the head</p> | |
| | Sheet 2 – Welded support system | <p>For the vertical connection the width of the workspace can be 4ft. 4ft is the standard width of a scaffold and is about what is required to bolt/weld</p> <p>The bigger the pipe, the bigger the scaffold</p> | |
| | Sheet 3 – Vertical pipe weld | <p>The worker needs to see the top of the flange connection. Sometime he can "feel" the hole but it's not advisable for safety reasons</p> | |
| | Sheet 4 – Other pipe weld | <p>The larger the component the higher the number of workers.</p> | |
| | Sheet 5 – Other pipe weld (alternate phasing) | <p>8"-12" Bolted valve: 2 workers</p> <p>14"-24" Bolted valve: 3 to 4 workers</p> | |
| | Sheet 6 – Flange connection | <p>Don't necessarily require a bigger workspace around. Stick with the 3ft 6in around.</p> | |
| | Sheet 7 – Butterfly valves | <p>You will need to add another level of scaffold if the connection(s) are in a range bigger than between the "sweet spot" (between waist and chest) and the eyes (Applicable to all pipe connections)</p> <p>The "workable range for a worker is from 4-5in from the ground up to the eye level. (Applicable broadly)</p> <p>The worker should be able to work on the actuator</p> <p>The actuator won't always fit in the 3ft 6in range so you have make sure that this space is still available even with the actuator</p> | |
| | Sheet 8 – Small Butterfly valves | <p>Avoid having people working below someone else for safety reasons. Try to stagger scaffolds</p> | |
| | Sheet 9 – Pipe Rack | | |

Table 4.1: Raw interview transcription

| | | | |
|-------------------------|---|--|---|
| Superintendent 2 | Sheet 1 – Bolted support system | When bolting above head platform should be 5ft below connection | |
| | Sheet 2 – Welded support system | When welding overhead from below the platform should be 5ft below connection | |
| | Sheet 3 – Vertical pipe weld | For a pipe welding the worker should be able to see the top of the weld | |
| | Sheet 4 – Other pipe weld | Ideal height for welding is at chest, i.e., 4ft from the platform level | |
| | Sheet 5 – Other pipe weld (alternate phasing) | | |
| | Sheet 6 – Flange connection | | |
| | Sheet 7 – Butterfly valves | | |
| Superintendent 3 | Sheet 1 – Bolted support system | The platform should be 7 by 4ft (ie. 3ft 6in outside the element) | |
| | Sheet 2 – Welded support system | The height of the platform should be 16ft to comfortably reach each components | |
| | Sheet 3 – Vertical pipe weld | The welding process requires more space here since the welder needs to be at the weld face | |
| | Sheet 4 – Other pipe weld | The platform should be 3-4ft below the weld position | |
| | Sheet 5 – Other pipe weld (alternate phasing) | If the pipe is bigger than 4ft in diameter two levels of scaffold are needed | |
| | Sheet 6 – Flange connection | There is no real impact of the phasing since using the crane vs the chain fall will require the same amount of welding workspace | |
| | Sheet 7 – Butterfly valves | The platform should be 10 by 10 ft (around the pipe) | Equivalent to 3ft 6in. From the pipe |
| | Sheet 8 – Small Butterfly valves | To be able to reach each flange the platform should be 6-8in below the lower flange | |
| | Sheet 9 – Pipe Rack | Also a 10 by 10 ft platform to go around the valve | |
| | | 10 by 10 ft platform to be able to reach the other side of the tank and | |
| | | Floor of the platform is just above the tank (room limitations) | |
| | | Comfortable working height is 3-4 feet above the ground but workers can use a bucket | Unsafe practice not considered in the process |

| | | | |
|-------------------------|---|--|--|
| Superintendent 4 | Sheet 1 – Bolted support system | Above head bolting should be done in a way that the connection point is at face height | |
| | Sheet 2 – Welded support system | Increased complexity required that the weld appends at face height | |
| | Sheet 3 – Vertical pipe weld | Ideal welding position is between waist and chest A welder can work as high as his face height And down to his knee height | |
| | Sheet 4 – Other pipe weld | There should be between 3 and 4ft of space out of the pipe | |
| | Sheet 5 – Other pipe weld (alternate phasing) | | |
| | Sheet 6 – Flange connection | There is less restriction on flanged connections but the optimal work height is between waist and chest | |
| | Sheet 7 – Butterfly valves | The worker should be to turn around the actuators (3-4ft) | |
| | Sheet 8 – Small Butterfly valves | | |
| | Sheet 9 – Pipe Rack | Try to avoid having people working on top of each other at the same time. The connection points on a pipe rack should be treated as the other connections There should be 3ft outside the element to allow enough space The optimal bolting height is at waist height | |
| Superintendent 5 | Sheet 1 – Bolted support system | For a vertical weld the ideal position is between waist and chest | |
| | Sheet 2 – Welded support system | For an horizontal welding it is better to be at face height | |
| | Sheet 3 – Vertical pipe weld | Welding pipes is similar to welding beams it just requires more attention (quality assurance) There should be 3ft from the outside of the pipe to allow enough space for the welder | |
| | Sheet 4 – Other pipe weld | | |
| | Sheet 5 – Other pipe weld (alternate phasing) | There will be some space needed for the handling of components but there is no real impact on the worker's space | |
| | Sheet 6 – Flange connection | Workers should be able to reach the top and bottom of the flange | |
| | Sheet 7 – Butterfly valves | The workers need to be able to go around the valve Workers can work on elements as low as mid-shin | |
| | Sheet 8 – Small Butterfly valves | | |
| | Sheet 9 – Pipe Rack | Welding on pipe racks requires the same amount of space as usual welding | |

The analysis of the interviews first stressed that the work envelope had two components: vertical and horizontal. The horizontal component, or work envelope footprint, is well understood since it refers to the traditional, 2D way of planning space allocation. The interviewees overwhelmingly agree that the work envelope horizontal component should be 3ft 6in from the connection point. The vertical component is more complex since it relies not only on the human body size but also on the movement of the craft workers.

Vertical positioning raises ergonomics and job safety issues. The interview analysis revealed that there is an ideal working position but also a wider range of acceptable positions. This is due to the nature of the construction work where there is limited control on the environment, as opposed to factory work. Given that the scaffolding planning usage was targeted, this aspect has been particularly investigated. Indeed, proper vertical positioning of a scaffold system is critical for the workers but it is highly impractical to have a scaffold system specifically tailored for each work envelope. Later on, in the scaffold planning process it is expected there will be some optimization and a single scaffold system would have to accommodate multiple work envelope. Thus it is required to provide not only the “sweet spot” of work but wider range that would accommodate optimization while ensure that the work could be performed.

The focus of this research was steel and piping on oil & gas projects and connection points have been chosen as the reference for the work envelope definition. So the nature of the connected parts defined a first classification level to describe the work envelope. The nine interview worksheets represented four connection types:

- Beam-to-Beam
- Beam-to-Concrete
- Pipe-to-Valve
- Pipe-to-Pipe

Decision Tree for Vertical Position of the workspace requirement (Beam-to-Beam connection)

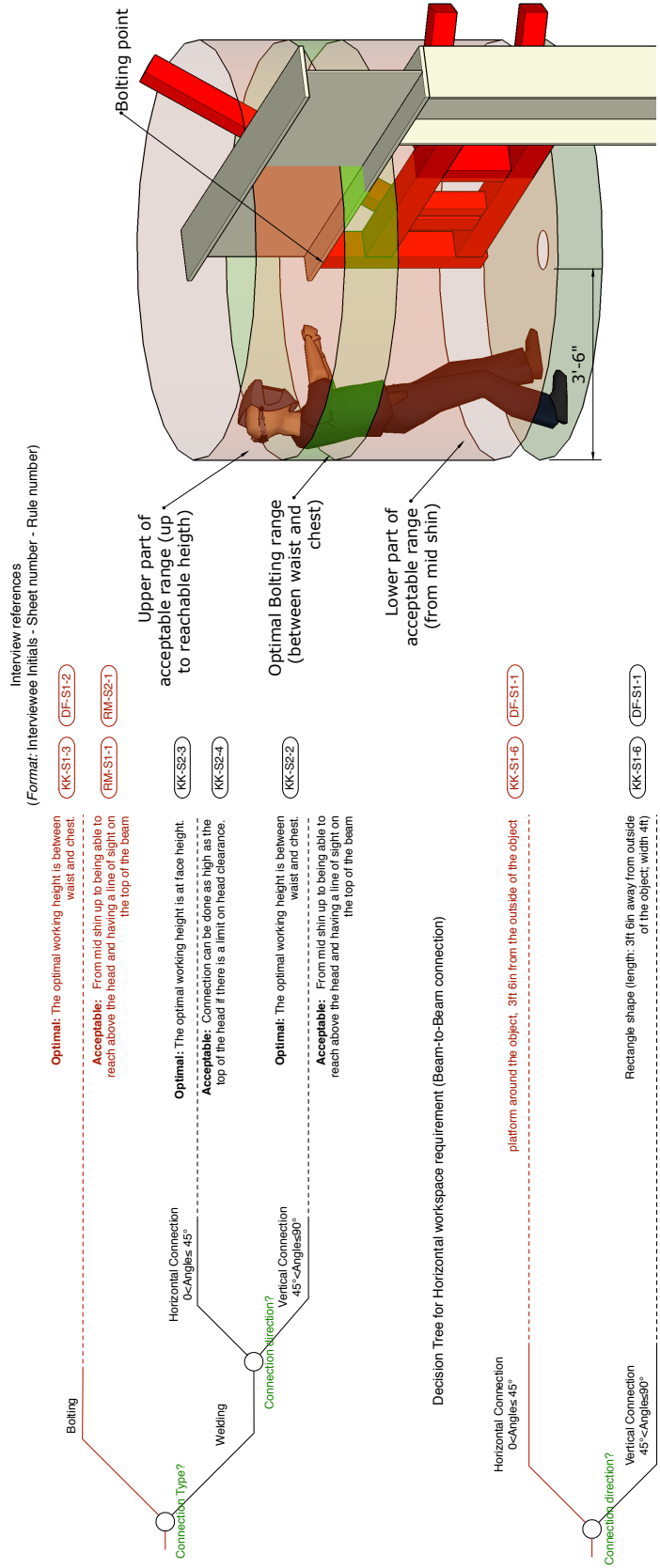


Figure 4.1: Decision tree for a Beam-to-Beam connection

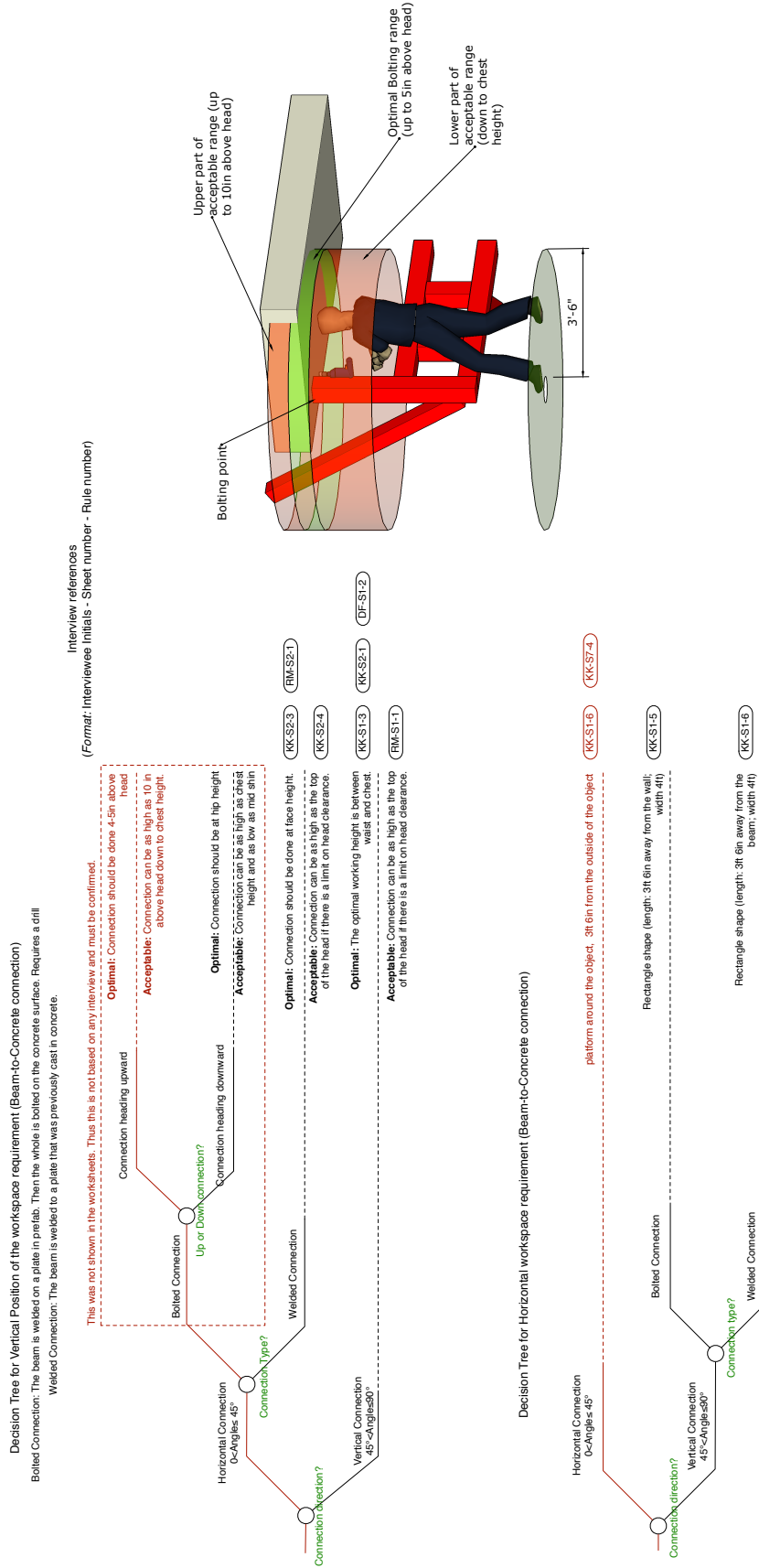


Figure 4.2: Decision tree for a Beam-to-Concrete connection

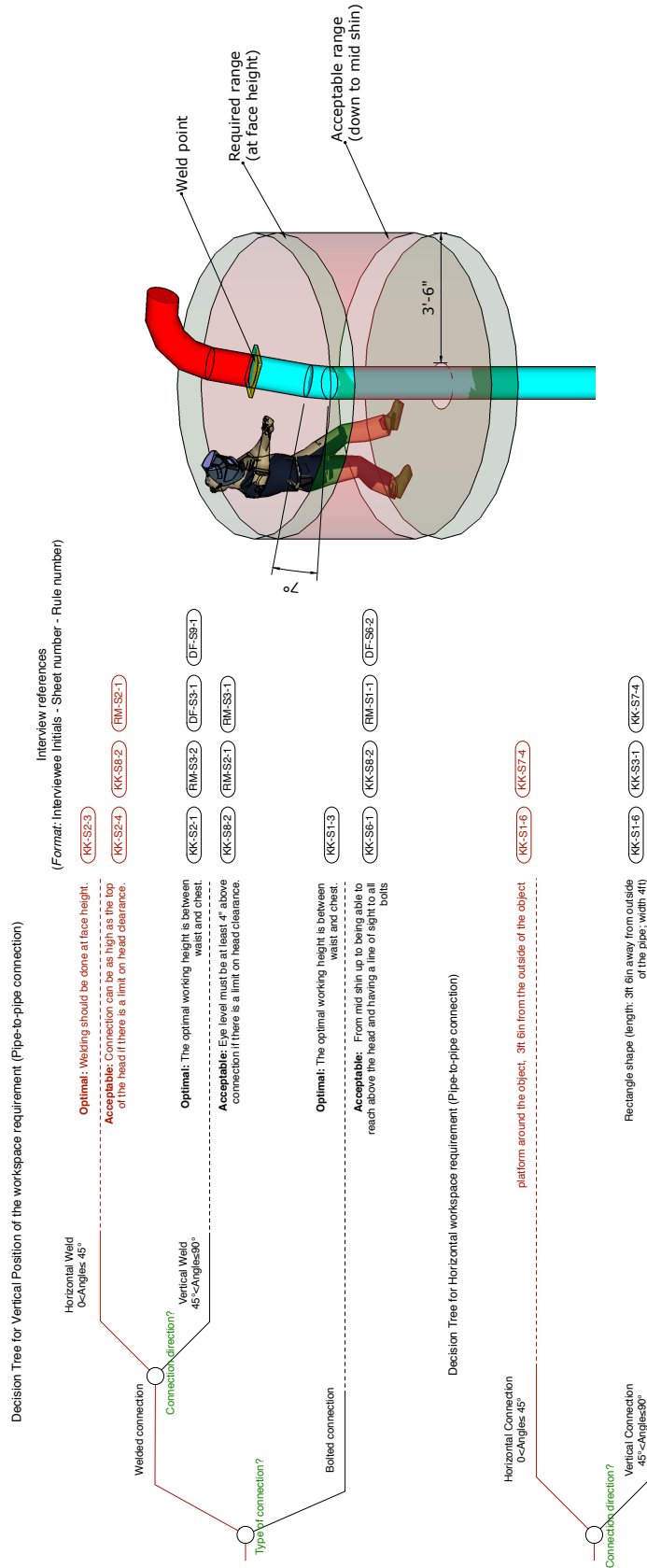


Figure 4.3: Decision tree for a Pipe-to-Pipe connection

Decision Tree for Vertical Position of the workspace requirement (Pipe-to-Valve connection)

Interview references
(Format: Interviewee Initials - Sheet number - Rule number)

KK-ST-3

Optimal: The optimal working height is between waist and chest.

KK-SB-1

Acceptable: Eye level must be at least 4" above connection if there is a limit on head clearance.

KK-SB-2

HM-ST-1

Optimal bolting range (between waist and chest)

DF-SB-2

Upper part of the acceptable range (up to the reachable height)

Lower part of the acceptable range (down to shin height)

3'-6"

Optimal bolting range (between waist and chest)

Decision Tree for Horizontal workspace requirement (Pipe-to-Valve connection)

KK-SB-4

platform around the object, 3ft 6in from the outside of the pipe + 3ft6 in from the outside of the actuator

KK-SB-4

Rectangle shape (length: 3ft 6in away from outside of the pipe; width: 4ft + length of the valve)

KK-SB-4

Rectangle shape (length: 3ft 6in away from outside of the pipe + 3ft 6in from the actuator; width: 4ft + length of the valve)

Vertical Pipe

Pipe direction?

Vertical actuator

Horizontal Pipe

Horizontal actuator

Actuator direction?

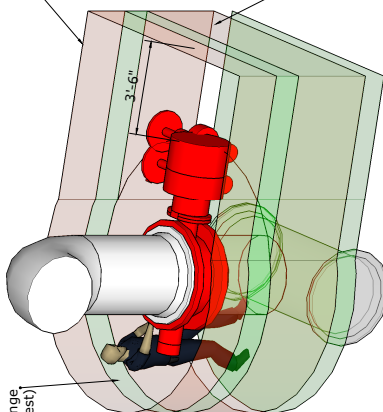


Figure 4.4: Decision tree for a Pipe-to-Valve connection

Starting from this initial classification the interviewees revealed there were significant differences on how the work envelope was defined. So for each of those four categories two decision trees were developed to describe both the vertical and horizontal component of the work envelope. These decision trees presented from figure 4.1 to 4.4 are using “break points” or nodes that drives the work envelope shape and dimensions. These break points are: the connection type, bolted or welded; the connection orientation, horizontal or vertical; and sometime the connection direction, upward or downward.

Each of the individual decision tree have specificities but the break points bear similar impacts that can be analyzed. As stated previously, the work envelope has a horizontal component which has been broadly defined a 3ft 6in from the connection point. Additional discussions with the interviewed superintendents were needed to refine this statement, which remains vague in a 3D environment. It was found that in a case of a vertical connection the work envelope footprint had to take a rectangular shape as opposed to a circular shape for a horizontal connection. This has been justified by the fact that for a vertical connection the worker has to be able to reach either side of the connection. In the case of a horizontal one, the worker needs to be able to turn around the connection point.

The type of connection method also plays an important role in the vertical component of the work envelope as is represented by nodes on the decision trees. A welded connection, especially on pipes, must meet higher quality standards, which requires more visual attention. This translates into an optimal working height at the eye level for a weld as opposed to “between waist and chest” for a bolted connection where there is higher usage of the arms.

Eventually, the connection direction has a significant impact on the vertical component of the workspace in the case of a horizontal bolted connection of a beam to a concrete element. This specific situation typical of pipe support system requires specific tooling such as a drill, which will change the ideal working height. In this situation an upward connection would be ideally located above head to ensure comfortable arms position. When the connection is downward, the ideal connection position is located at hip height.

4.2 Phase 2

As mentioned previously, the work envelope is mainly defined relative to body parts. This is the case of the vertical component of the work envelope. The horizontal component has been unanimously described in the interviews as an absolute, fixed dimension, of 3ft 6in. There are no reasons to reconsider this statement and believe that there could be significant impact of the population on the horizontal component of the workspace. This section will indeed focus on the vertical component and show what impacts could be expected on the scaffolding application.

The analysis was carried on the two body-relative dimensions mentioned in the interviews: “at face height” and “between chest and waist”. The method described on chapter 2 was used with a required overlap of 25%, 50 and 75%. The corresponding joint probabilities are displayed on tables 4.0 and 4.1.

Face height - ratio=0.87
Required overlap 25%

| | International | North American | Latin American (Rest) | North Europe | Eastern Europe | North India | South China |
|-----------------------|---------------|----------------|-----------------------|--------------|----------------|-------------|-------------|
| International | | 0,887 | 0,874 | 0,872 | 0,880 | 0,698 | 0,715 |
| North American | | | 0,873 | 0,904 | 0,879 | 0,682 | 0,696 |
| Latin American (Rest) | | | | 0,854 | 0,943 | 0,800 | 0,844 |
| North Europe | | | | | 0,860 | 0,633 | 0,630 |
| Eastern Europe | | | | | | 0,805 | 0,852 |
| North India | | | | | | | 0,976 |
| South China | | | | | | | |

Required overlap 50%

| | International | North American | Latin American (Rest) | North Europe | Eastern Europe | North India | South China |
|-----------------------|---------------|----------------|-----------------------|--------------|----------------|-------------|-------------|
| International | | 0,776 | 0,745 | 0,746 | 0,750 | 0,510 | 0,483 |
| North American | | | 0,734 | 0,786 | 0,740 | 0,488 | 0,440 |
| Latin American (Rest) | | | | 0,693 | 0,846 | 0,619 | 0,612 |
| North Europe | | | | | 0,698 | 0,420 | 0,349 |
| Eastern Europe | | | | | | 0,622 | 0,616 |
| North India | | | | | | | 0,889 |
| South China | | | | | | | |

Required overlap 75%

| | International | North American | Latin American (Rest) | North Europe | Eastern Europe | North India | South China |
|-----------------------|---------------|----------------|-----------------------|--------------|----------------|-------------|-------------|
| International | | 0,631 | 0,582 | 0,584 | 0,584 | 0,346 | 0,275 |
| North American | | | 0,557 | 0,620 | 0,558 | 0,308 | 0,226 |
| Latin American (Rest) | | | | 0,496 | 0,689 | 0,420 | 0,352 |
| North Europe | | | | | 0,496 | 0,240 | 0,148 |
| Eastern Europe | | | | | | 0,418 | 0,347 |
| North India | | | | | | | 0,700 |
| South China | | | | | | | |

Table 4.0: Joint probability of meeting the required overlap for the “face height”

The required overlap measures the tolerance on vertical component of the work envelope that

is allowed. This can be translated in the level on comfort is required. Regarding the “face height” area it can be distinguished two groups of populations. A first one including International, North American, Latin American (Rest), North Europe and Eastern Europe. A second one including North India, South China. There is a high level of agreement within these two groups, which means that the work envelope can be considered as identical for the population within each of the groups. Applying this to scaffolding, it means that from a project located in North America to another one located in North India the scaffold planning should be adapted to account for the population specificities on some task involving the “face height” dimensions. This is the case of most the welded connections for instance.

Waist and Chest - ratio=0.720 & 0.350

| Required overlap 25% | | | | | | | |
|-----------------------|---------------|----------------|-----------------------|--------------|----------------|-------------|-------------|
| | International | North American | Latin American (Rest) | North Europe | Eastern Europe | North India | South China |
| International | | 0,988 | 0,977 | 0,992 | 0,978 | 0,935 | 0,941 |
| North American | | | 0,985 | 0,994 | 0,985 | 0,948 | 0,954 |
| Latin American (Rest) | | | | 0,989 | 0,996 | 0,981 | 0,985 |
| North Europe | | | | | 0,990 | 0,955 | 0,962 |
| Eastern Europe | | | | | | 0,985 | 0,989 |
| North India | | | | | | | 0,998 |
| South China | | | | | | | |

| Required overlap 50% | | | | | | | |
|-----------------------|---------------|----------------|-----------------------|--------------|----------------|-------------|-------------|
| | International | North American | Latin American (Rest) | North Europe | Eastern Europe | North India | South China |
| International | | 0,965 | 0,942 | 0,968 | 0,944 | 0,833 | 0,834 |
| North American | | | 0,952 | 0,977 | 0,953 | 0,840 | 0,842 |
| Latin American (Rest) | | | | 0,954 | 0,986 | 0,925 | 0,933 |
| North Europe | | | | | 0,956 | 0,827 | 0,828 |
| Eastern Europe | | | | | | 0,933 | 0,942 |
| North India | | | | | | | 0,990 |
| South China | | | | | | | |

| Required overlap 75% | | | | | | | |
|-----------------------|---------------|----------------|-----------------------|--------------|----------------|-------------|-------------|
| | International | North American | Latin American (Rest) | North Europe | Eastern Europe | North India | South China |
| International | | 0,857 | 0,801 | 0,833 | 0,803 | 0,529 | 0,489 |
| North American | | | 0,796 | 0,868 | 0,799 | 0,492 | 0,443 |
| Latin American (Rest) | | | | 0,757 | 0,915 | 0,663 | 0,636 |
| North Europe | | | | | 0,760 | 0,403 | 0,338 |
| Eastern Europe | | | | | | 0,669 | 0,641 |
| North India | | | | | | | 0,923 |
| South China | | | | | | | |

Table 4.1: Joint probability of meeting the required overlap for the “between chest and waist”

Regarding the “between chest and waist” dimension no such disagreement can be found across the population selected. It means that no adaptation would be required for the tasks involving the “between waist and chest” dimension. Most of the bolted connections are in this case.

Chapter 5

Conclusion & contribution to the body of knowledge

The present research presented a new process to assess the work envelope requirement without involving heavy user input, which is highly impractical and costly. The workspace cannot be fully considered as a resource and new space-constrained scheduling streamlined. Also a framework describing how to assess the work envelope has been provided and could be expended to other trades.

One of the main contributions of this research is the recognition that the work envelope is a tri-dimensional object with two components, one vertical and one horizontal. The horizontal one is the most critical component in an overcrowding management perspective. Although most construction projects occur in a 3D environment it is often a compilation of 2D planes such as floors. Confined projects, such as tunnel are a notable exception where space is used at its fullest and requires of the work envelope in all directions. The vertical component can have many applications, most of them currently unforeseen. This research introduced one of them, the scaffold planning and optimization. The vertical component is vital for such usage to ensure good ergonomics and safety to the workers.

The main drivers of the driver of the work envelope shape and dimension have been identified. The connection type, welded or bolted, which impact the optimal work height; The connection orientation, horizontal or vertical, which determines the footprint of the work envelope; And the connection direction, upward or downward, which also impacts the optimal work height in some specific situations. Those drivers and their impacts were summarized in decision trees to automate the work envelope decision process.

Eventually, the influence of the population was analyzed using anthropomorphic data from multiples world populations. It was concluded that there was no impact on the horizontal component of the work envelope, which means that not considering the work anthropomorphic data has little impact on the space planning aiming to reduce overcrowding. At the opposite, for some application such as the scaffold planning it needs to be considered to ensure good ergonomics and safety for the craft workers.

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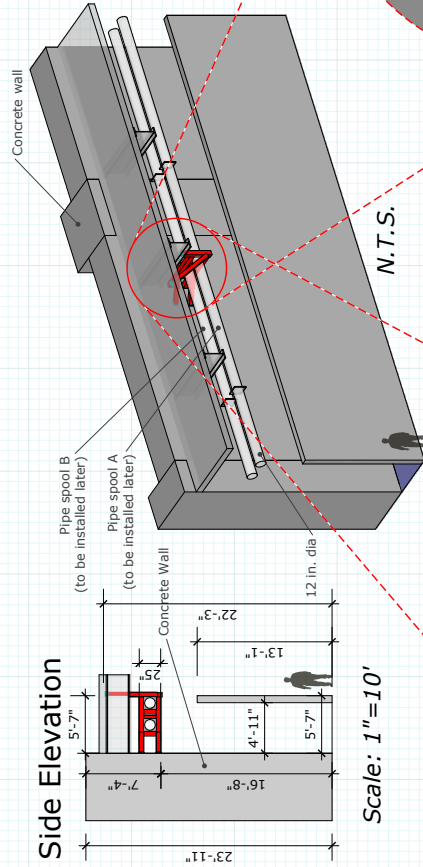
Appendix A

Interview worksheets

Workspace Positioning Sheet - 1

Instructions:

Analyze the context presented on this sheet to determine what would be the minimal required workspace(s) to install the **pipe support system**.



N. T. S.

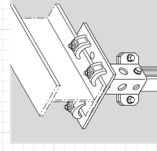
N. T. S.

Questions:

Explain your thought process for determining the minimal workspace for the **vertical bolted** case:

Explain your thought process for determining the minimal workspace for the **Horizontal beamclamp** case:

Explain your thought process for determining the minimal workspace for the **slanted bolted** case:

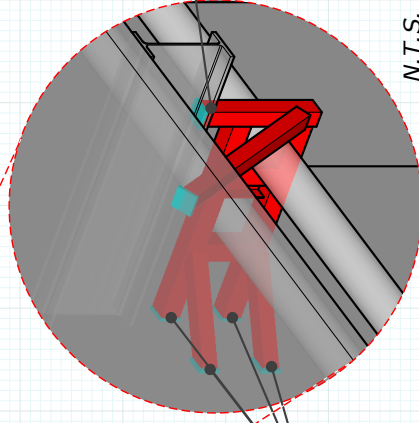


Horizontal beamclamp connection

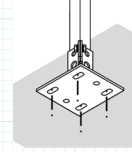
Component to install

Type: Halfen PowerClik support system

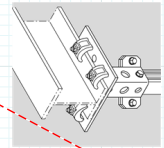
Approximate weight: 126 lb.



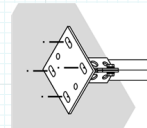
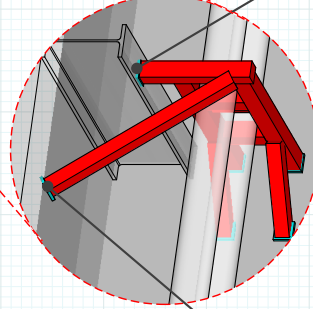
N. T. S.



Vertical bolted connection to concrete



Horizontal beamclamp connection

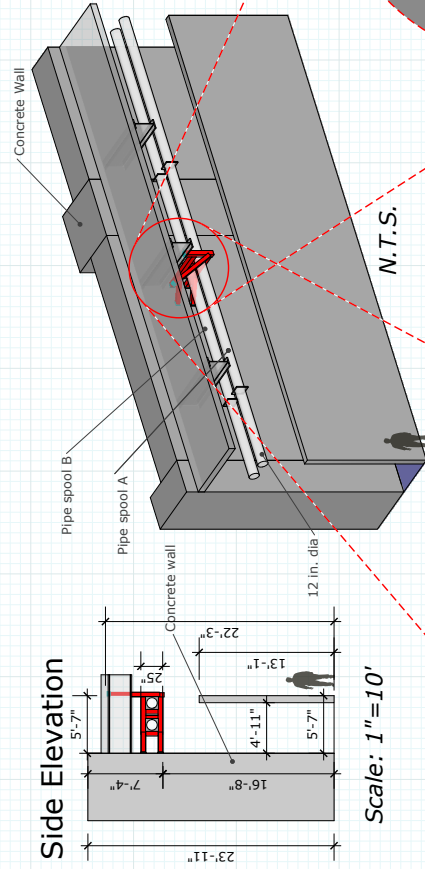


Slanted bolted connection in concrete ceiling

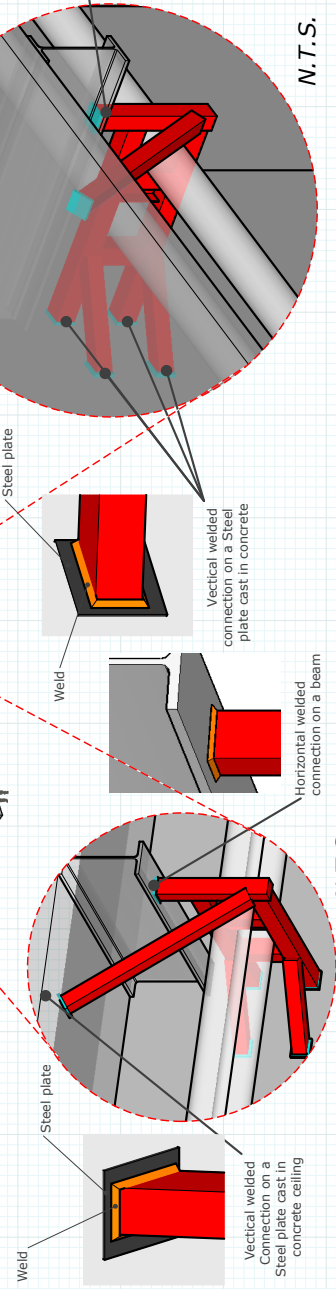
Workspace Positioning Sheet - 2

Instructions:

Analyze the context presented on this sheet to determine what would be the minimal required workspace(s) to install the **pipe support system**.



Scale: 1"=10'

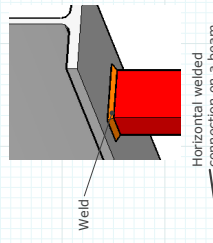


Questions:

Explain your thought process for determining the minimal workspace for the **vertical welded connection on a wall** case:

Explain your thought process for determining the minimal workspace for the **Horizontal welded connection** case:

Explain your thought process for determining the minimal workspace for the **slanted welded** case:



Component to install

Type: Halfen PowerClik support system

Approximate weight: 126 lb.

N.T.S.

N.T.S.

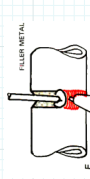
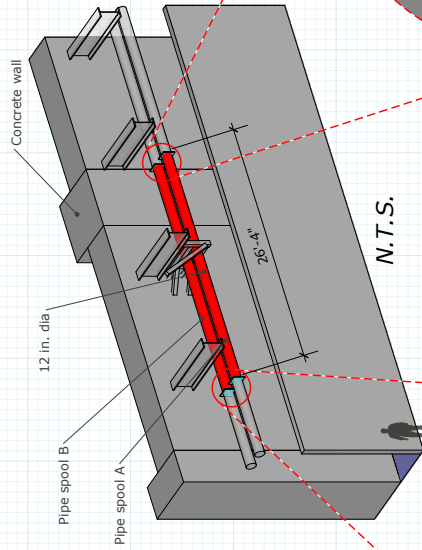
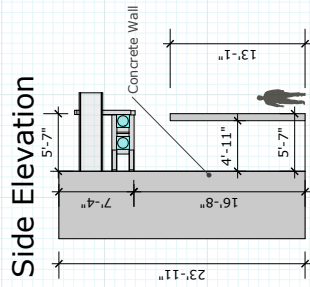
Workspace Positioning Sheet - 3

Instructions:

Analyze the context presented on this sheet to determine what would be the minimal required workspace(s) to install the **pipe spools "A" & "B"**.

Questions:

Explain your thought process for determining the minimal workspace for the **vertical welded connection between pipes** case:



Vertical welded connection between pipes

Component to install

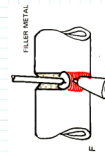
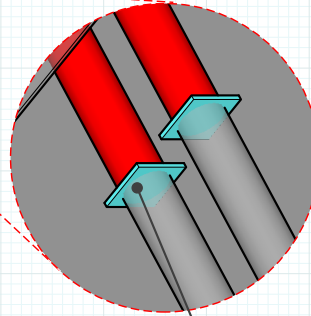
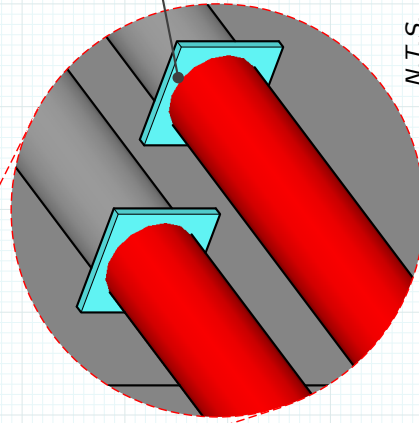
Type: Carbon Steel Pipe

Diameter: 12 in.

Wall Thickness: 0.375 in.

Weight: 1'300 lb. each

N.T.S.

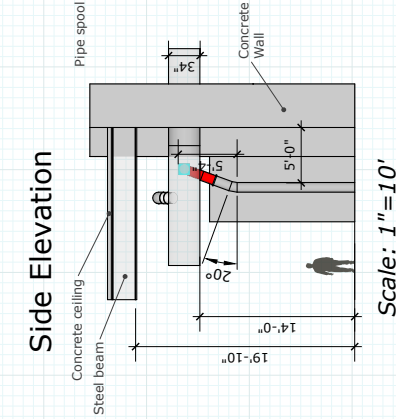


Vertical welded connection between pipes

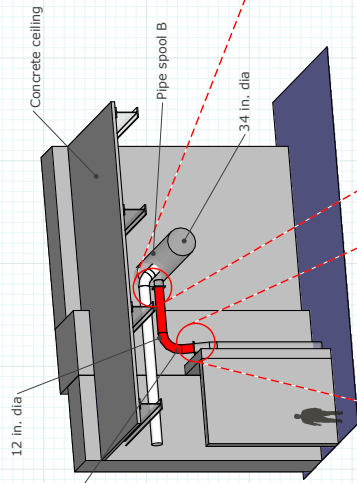
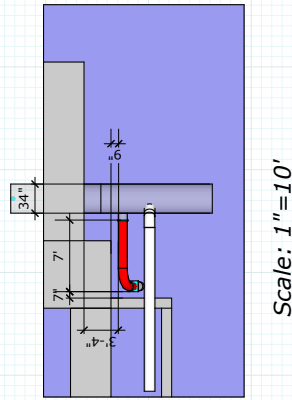
Workspace Positioning Sheet - 4

Instructions:

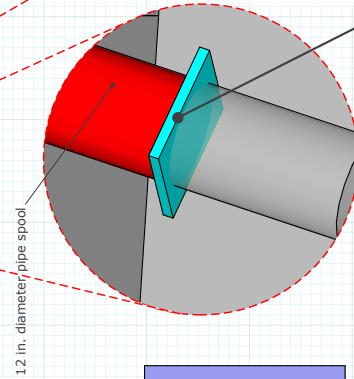
Analyze the context presented on this sheet to determine what would be the minimal required workspace(s) to install the **pipe spool "A"**.



Top View



N.T.S.

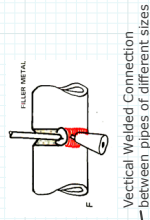


N.T.S.

Questions:

Explain your thought process for determining the minimal workspace for the **vertical welded connection between pipes of different sizes** case:

Explain your thought process for determining the minimal workspace for the **slanted welded connection between pipes** case:



Component to install

Type: Carbon Steel pipe

Diameter: 12 in.

Wall Thickness: 0.375 in.

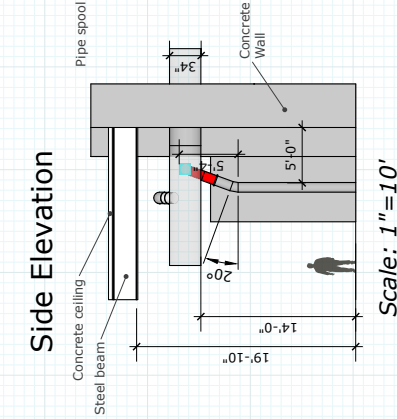
Weight: 400 lb.

N.T.S.

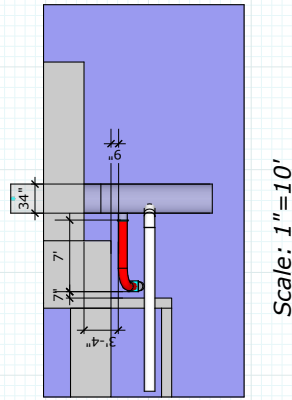
Workspace Positioning Sheet - 5

Instructions:

Analyse the context presented on this sheet to determine what would be the minimal required workspace(s) to install the **pipe spool "A"**.



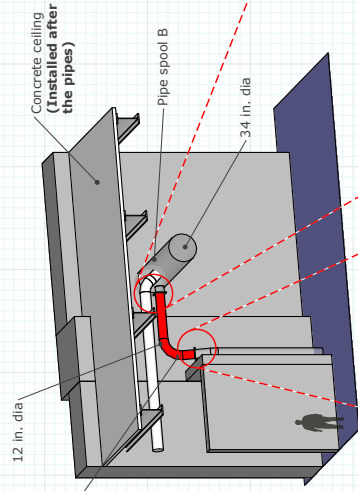
Top View



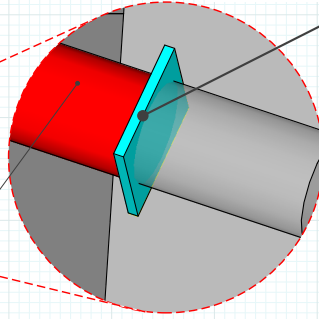
Questions:

Explain your thought process for determining the minimal workspace for the **vertical welded connection between pipes of different sizes** case:

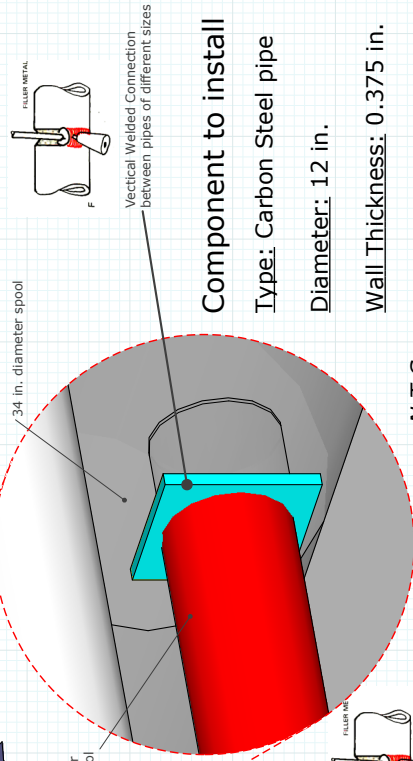
Explain your thought process for determining the minimal workspace for the **slanted welded connection between pipes** case:



N.T.S.



N.T.S.



Component to install

Type: Carbon Steel pipe

Diameter: 12 in.

Wall Thickness: 0.375 in.

Weight: 400 lb.

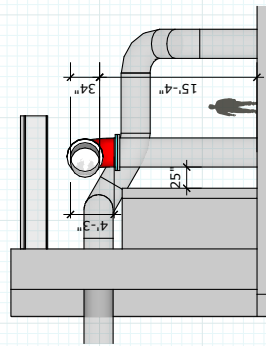
N.T.S.

Workspace Positioning Sheet - 6

Instructions:

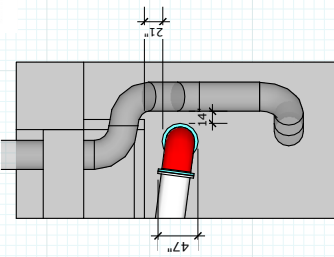
Analyze the context presented on this sheet to determine what would be the minimal required workspace(s) to install the **pipe angle**.

Front Elevation

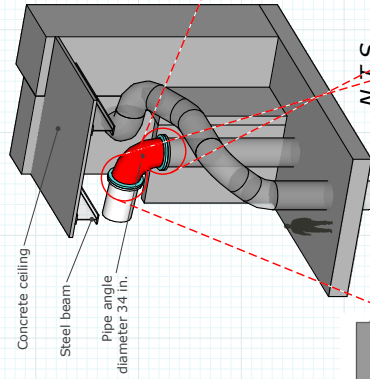


Scale: 1"=10'

Top View

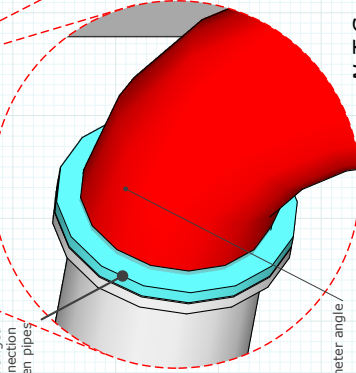


Scale: 1"=10'



N.T.S.

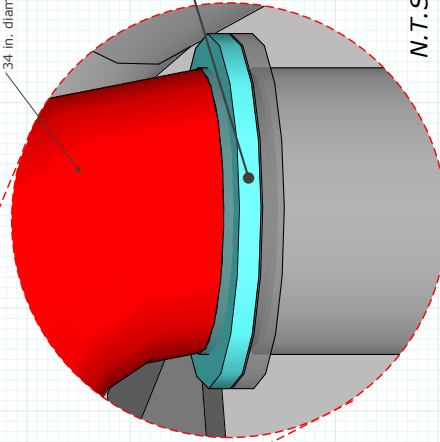
Vertical flanged connection between pipes



34 in. diameter angle

N.T.S.

34 in. diameter angle



Horizontal flanged connection between pipes

Component to install

Type: Carbon Steel pipe angle

Diameter: 34 in.

Wall Thickness: 0.375 in.

Weight: 800 lb.

N.T.S.

Questions:

Explain your thought process for determining the minimal workspace for the **vertical flange connection between pipes** case:

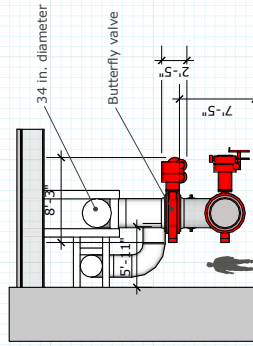
Explain your thought process for determining the minimal workspace for the **horizontal flange connection between pipes** case:

Workspace Positioning Sheet - 7

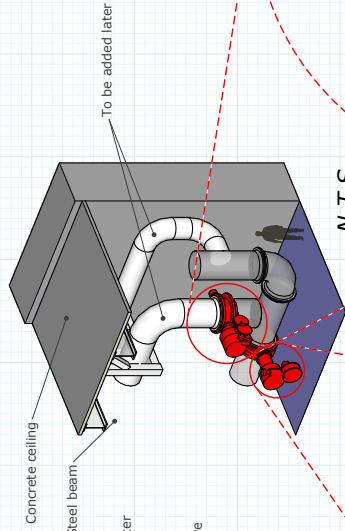
Instructions:

Analyze the context presented on this sheet to determine what would be the minimal required workspace(s) to install the **butterfly valve with large accuator**.

Side Elevation



Scale: 1"=10'

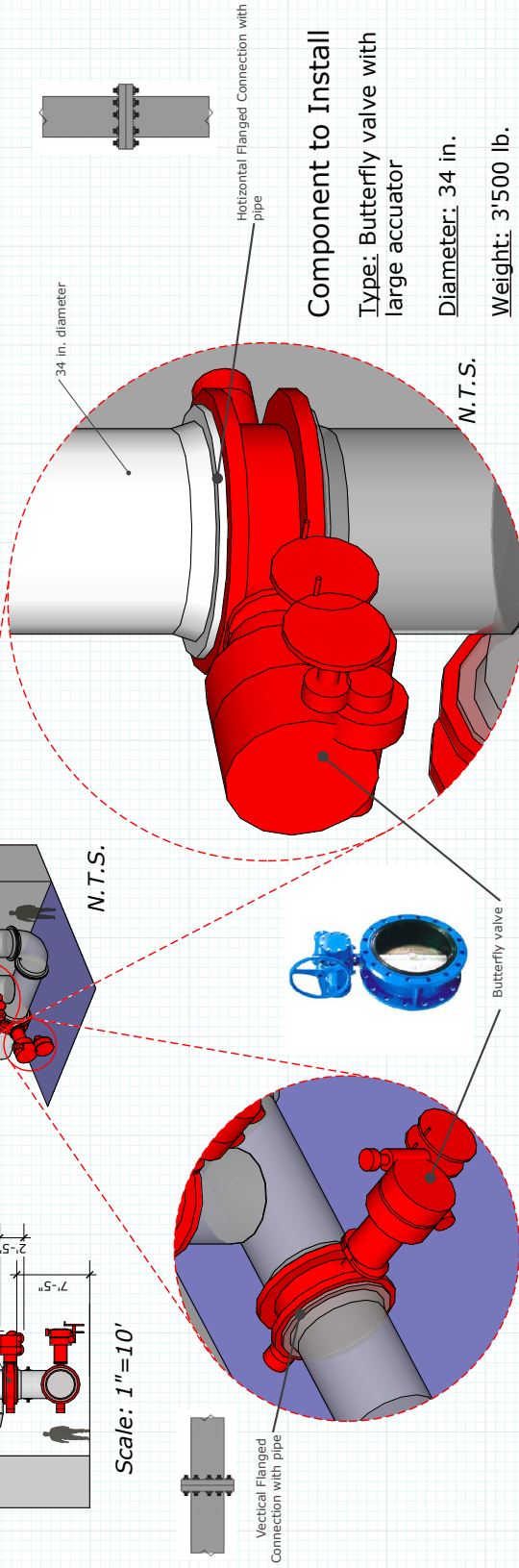


N.T.S.

Questions:

Explain your thought process for determining the minimal workspace for the **vertical butterfly valve** case:

Explain your thought process for determining the minimal workspace for the **horizontal butterfly valve** case:



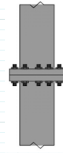
Component to Install

Type: Butterfly valve with large accuator

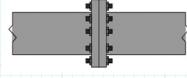
Diameter: 34 in.

Weight: 3'500 lb.

N.T.S.



Vertical Flanged Connection with pipe



Horizontal Flanged Connection with pipe



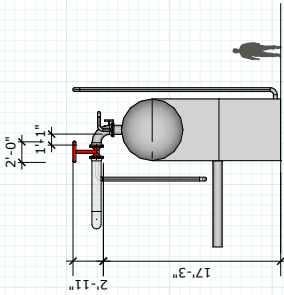
Butterfly valve

Workspace Positioning Sheet - 8

Instructions:

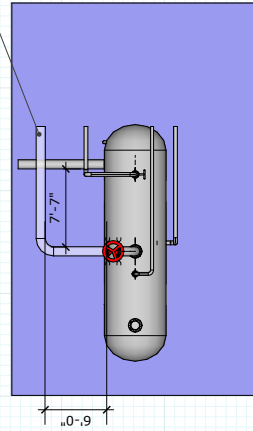
Analyze the context presented on this sheet to determine what would be the minimal required workspace(s) to install the **butterfly valve with small actuator**.

Side Elevation



Scale: 1"=10'

Top Elevation

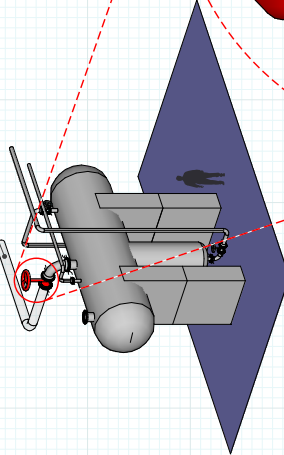


Scale: 1"=10'

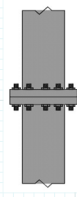
Questions:

Explain your thought process for determining the minimal workspace for the **horizontal butterfly valve** case:

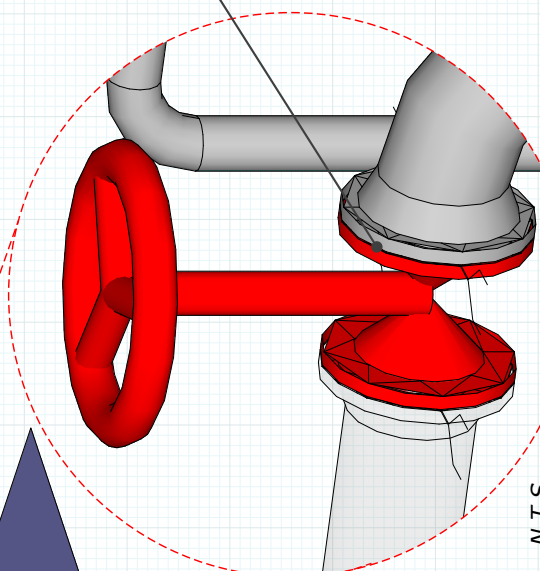
To be added later



N.T.S.



Vertical Flanged Connection with pipe



N.T.S.

Component to Install

Type: Butterfly valve with small actuator

Diameter: 11 in.

Weight: 700 lb.

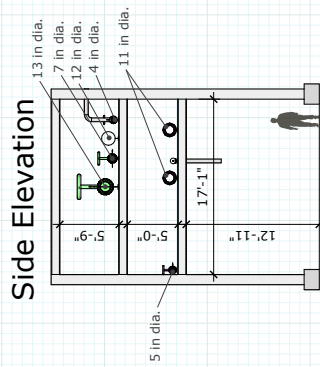
Workspace Positioning Sheet - 9

Instructions:

Analyze the context presented on this sheet to determine what would be the minimal required workspace(s) to connect the **pipes on the rack together**

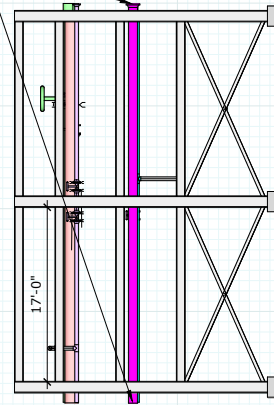
Questions:

Explain your thought process for determining the minimal workspace for the **pipes**:

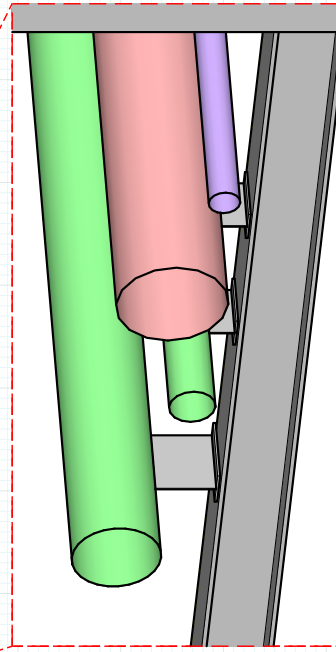
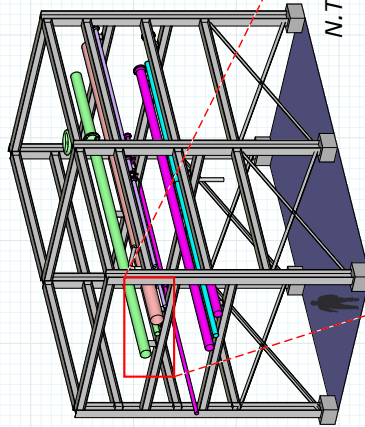


Scale: 1"=10'

Top Elevation



Scale: 1"=10'



Component to Install

Type: Pipes on a rack

Diameter: many

Weight: many