www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

MODELING OF WORK ENVELOPE REQUIREMENTS IN THE PIPING AND STEEL TRADES AND THE INFLUENCE OF GLOBAL ANTHROPOMORPHIC CHARACTERISTICS

SUBMITTED: 2016
REVISED: July 2016
PUBLISHED: October 2016 at http://www.itcon.org/2016/19
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SUMMARY: *Limited and unavailable workspace for crews on the jobsite results in losses of productivity. With the increased usage of Building Information Modeling (BIM) in the construction industry, four dimensional animation that brings together the three dimensional model of a building and its construction schedule to visualize construction process is emerging. To support space planning in the preconstruction management, this research provides a framework to integrate the knowledge of work envelope requirements among piping and steel trades. Typical work envelope requirements were defined through in-depth interviews with superintendents on U.S. industrial projects. Therefore, the rules and semantic information extracted from the interviews were summarized in seven decision trees, describing the geometric parameters relative to the body parts (e.g. chest and eye height). To compare the level of work envelope overlaps among global populations, anthropomorphic data was used to assess the absolute dimensions of the work envelopes. The results show that some work envelope requirements have a limited tolerance and are more sensitive to different body dimensions across global populations. It was found that in such situations the population anthropomorphic characteristics significantly impact the work envelope requirements. Therefore, this paper presents a decision supporting tool of work envelope requirements in compliment to space planning, which can improve the productivity, accuracy and efficiency of workspace management in the piping and steel trades.*

KEYWORDS: *work envelope, workspace management, productivity, anthropomorphic characteristics, BIM.*

REFERENCE: *Pierre Bannier, Haifeng Jin, Paul M. Goodrum (2016). Modeling of work envelope requirements in the piping and steel trades and the influence of global anthropomorphic characteristics. Journal of Information Technology in Construction (ITcon), Vol. 21, pg. 292-314, http://www.itcon.org/2016/19*

1. INTRODUCTION

The required workspace among individual craft workers is a limited resource which needs to be planned and allocated effectively in advance among multiple trades in the preconstruction phase. It is a challenging issue in space planning because of the unique workspace of a specific activity and the complex parameters of occupied work space among multiple trades (Dawood and Mallasi, 2006). The productivity of the U.S. construction industry has decreased or at least stagnated since 1964 (Dyer et al., 2012), which means construction projects are under increasing pressure to optimize their available resources. The executions of activities in a limited workspace lead to the loss of productivity (Moon et al., 2014), jobsite congestion (Kamat et al., 2005; Mallasi, 2006), schedule delay (Guo, 2002), and safety hazards (Zhang et al., 2006; Riley and Sanvido, 1995). Therefore, it is important for superintendents and space planners to identify the space requirements of activities throughout a construction schedule in order to provide work crews available workspace and a productive environment.

Workspace representation is the initial step in space planning management. While other industries have been focusing for a long time on the workspace requirement for the workers, the most notable is the case in aerospace industry (Merlet, 1995; Yang et al., 2008). But in the construction industry, this remains a secondary matter dealt with on the worksite. Individuals tasked with space planning, which may fall onto an assistant superintendent or field engineer, may not have the experience to determine the accurate geometric parameters of work space required by the activities. In these cases, the individual has to consult the superintendents, which is time consuming and inefficient. Moreover, the space planners assign the work space, but they are unable to identify the optimal height of the execution position for crews. It is impractical for the space planners to generate workspace requirements and assignment by themselves. Especially in industrial projects, there is a lack of academia efforts on the work space representation and identification for complex piping activities.

Temporary facilities have a direct spatial relationship with executed workspace of activities. Prior research (CII, 2012) highlighted that temporary facilities form one of the top four primary cost categories which belongs to indirect construction costs. Scaffolding systems as one of the temporary facilities to support construction operations has an impact on construction safety, quality and profitability (Ratay, 1987). A number of recent research studies focused on planning and management of temporary facilities, such as computer-assisted generation of temporary structure plans (Kim et al., 1987), optimization of scaffolding design (Kim and Ahn, 2011), and automation of planning in BIM (Kim and Teizer, 2014). Therefore, considering space planning, research efforts towards workspace requirements have a significant impact on temporary facilities planning.

A work envelope describes a volume of three-dimensional space around a building component in which it is assumed that a worker, a facility or a piece of equipment, must be physically present in order to execute a construction activity on that component. Workspace required for a specific executed activity is 3D (x, y, z) space around or outside the executed component in the construction. The Architecture, Engineering and Construction (AEC) industry has experienced a paradigm shift from traditional Computer Aided Design (CAD) to 3D/4D Building Information Modeling (BIM). Since activities in the construction industry are executed by multiple crews, traditional 2D/3D techniques with schedule information are inadequate for managing workspaces due to their lack of spatial representation (Chau et al., 2004; Dawood, 2010; Koo and Fischer, 2000; Zhang and Hu, 2011; Kassem et al., 2015). Adopting BIM approaches for workspace planning as 3D/4D visualization tools improves workspace management capabilities.

2. BACKGROUND AND JUSTIFICATION

2.1 Space planning practices of activity execution workspace management

The activity execution workspace management involves the physical constraints of space on the jobsite, workspace planning, integration with construction planning, mathematical algorithms used to detect conflicts, visualization and advanced techniques to optimize workspace planning. Successful workspace planning for industrial projects should depend on the geometric parameters and accurate semantic interpretation of construction information, which includes correct geometrical representation and requirements of work space and properties of components, information of spatial relationships.

Previous research has focused on the modeling of activity space requirements. Thabet and Beliveau (1994) identified the demand workspace and available workspace and quantified them to estimate space required in multi-storey buildings. Riley and Sanvido (1995) analyzed the specific spaces needed for activities on site and related the sequence of activities to define the order of spaces occupied, which was also focused on multi-storey projects. Akinci (2002, 2002) developed an automated workspace planning generator to represent the generic requirements of activity workspace and provide detection of the spatial conflicts. Dawood and Mallasi (2006) proposed a construction activity execution space analysis using a critical space-time analysis (CSA), which enabled the project managers to assign and detect the workspace interferences. In order to utilize the workspace planning techniques into application of construction management, integration of traditional planning process (Critical Path Method) and Building Information Modeling was applied in 4D/5D environment providing managers with real-time management (Chavada et al., 2012). Moon et al. (2014) simulated a genetic algorithm (GA) based system incorporating with BIM to minimize the interference level of workspace conflicts. A framework for a workspace planning process was proposed by Choi et al. (2014), which contains five phases: 4D BIM generation, workspace requirement identification, workspace occupation representation, workspace problem identification and workspace problem resolution. Although the existing research have some valuable attempts in representation and integration planning of work space management, these techniques still have several limitations in application on industrial projects, including the following

- Current methods and techniques of workspace planning are based on the definition of activity execution space but require the planners to manually input the geometric parameters of workspace models into the respective automated space planning system. However, there is a lack of research studies focusing on the accurate geometric information of workspace requirements and the interpretation method from semantic information acquired from superintendents into absolute dimensions.

- Superintendents are not typically involved in the preconstruction phase of the project, but space planners may not have the experience to estimate the accurate workspace and as a result, have to consult the superintendents or the crews to acquire the workspace requirements. Even if superintendents are involved, the task of engaging their input on workspace requirement during a model's development is time-consuming and costly.

2.2 Problem Statement

Our research addresses the need to efficiently and accurately describe the spatial workspace requirements in the space planning management of the piping and steel trades. Current workspace management lacks the specific workspace information from the perspective of superintendents, which makes the space planning impractical and over simplified. In order to address this challenge effectively, we proposed a better approach, which is based on the following hypotheses: 1) the spatial workspace requirements and the parameters of three dimensional work envelope vary depending on the type of activities; 2) different postures of work crews executing an activity significantly influence the workspace requirements; and, 3) differences among the anthropomorphic characteristics of global populations have a great impact on space planning of temporary facilities. We will test these hypotheses in a two-phase research method described in Section 3, and the results from Section 4 will provide useful information for our research objectives.

The paper's primary contribution to the overall body of knowledge is the specific recognition of activity-based workspace requirements in the piping and steel trades, which can be directly utilized by space planners, designers and researchers to improve the efficiency of workspace management. This paper also presents an insight on how workspace requirements could influence the space planning of temporary facilities that support the work crews through the execution of multiple activities. Furthermore, the mathematical assessment of workspace requirements based on the anthropomorphic characteristics shows not only the differences of workspace demand among global populations at different locations, but also help construction managers to plan temporary facilities more efficiently to meet the workspace requirements. It can be practical to differ space plans for multiple activities and temporary facilities.

2.3 Recognition of the work envelope ontology and its spatial relationship with temporary facilities planning

The work envelope, also referred to as main workspace in the literature, is the three-dimensional shape that encompasses the craft worker that is required to perform a specific activity safely and comfortably. The shape and type of a work envelope depend on the nature of the activity, the type of component, and the construction technology (Navon, 2005). Some efforts using work envelope has been applied in the detection and analysis of time-space conflicts in the project schedule (Kim and Fischer, 2007; Haque and Rahman, 2009). More advanced usage, involving various optimization algorithms such as Genetic algorithms and fuzzy logic, have also been mentioned in the literature, but there is little evidence that they have been utilized on actual industry practices.

Work envelope is related to the minimum physical space and arrangement in the execution of a specific activity. Many research studies focused on the classification of workspaces (Dawood and Mallsi, 2006; Guo, 2002; Moon et al., 2009; Wu and Chiu, 2010; Chua et al., 2010). The number of categories assigned in previous research ranged from 4 to 12. However, Chavada et al. (1995) found that there were many similarities in those classifications and summarized them in four categories: main workspace, supporting workspace, object workspace and safety workspace. The optimal height or posture for crews to execute an activity, determines the most comfortable position for a worker. However, very few past research efforts have taken the optimal height of activity execution into account space planning among construction process. For instance, among pipefitters and ironworkers, welding and bolting are the most common and critical activities involved in the piping and steel trades, which typically dominate most project's critical path. Therefore, if the optimal height for execution is identified, space planners are able to provide the crews with the most productive height of temporary facilities.

Previous studies have stressed that temporary facilities planning, such as scaffolding systems that belong to supporting workspace, have a spatial relationship with the main object workspaces (Kim and Teizer, 2014). So if factors and parameters of workspace for work crews have a great influence on the allocation and position of scaffolding space, the knowledge of specific activity-based relationship between workspace and linked activities should be obtained in a more accurate and efficient way. If this general knowledge is proven to be critical in space planning, there are certain influential factors such as anthropomorphic data that can affect the application and adaptation of this knowledge to different projects worldwide. As a result, we associated the space planning of scaffolding platforms with the workspace of the linked single activity and analysed how the anthropomorphic characteristics affect the work envelopes' geometries and scaffolding space among multiple populations in a mathematical model. The association of location-to-activity is processed through a two-phase methodology, including (1) workspace structure, and (2) workspace dimensioning, with the identification of work envelopes. In order to shift the work space knowledge in piping and steel construction activities, we propose an activity-based decision making tool for the determination of work envelopes' physical parameters and set up a mathematical model to assess the anthropomorphic impact on space planning among multiple global populations.

3. RESEARCH METHODOLOGY

As illustrated in Figure 1, the research structure of the proposed decision supporting tool for work space requirements in space planning of piping and steel trades was based on an input and output framework. Considering the large number and diverse tasks involved in a construction project, the authors developed a framework describing the work envelope requirements among the piping and steel trades, out of a selected number of tasks. 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 ensures that the concept can be understood by a broad audience. In order to achieve the previously mentioned objectives, the proposed method was composed of two phases.

The first phase focused on the definition of the work envelopes by involving piping and steel superintendents, which are subject matter experts in this domain, through in-depth interviews. These interviews helped capture their thought process when determining workspace requirement, aiming at recording the semantic information and geometric parameters provided by superintendents. The workspace requirements are summarized in decision trees that describe geometric information such as orientation of work envelopes' outlines, shapes and dimensions related to specific construction activities. This phase developed seven decision trees as output (A).

The second phase focused on comparisons of anthropomorphic data of global populations and their impact on the interpretation from relative body dimensions into absolute measures. For instance, phase one assists the space planners to determine the ideal working height in certain situations as "between chest and waist", which leads to the following question: "What is the average height of between waist and chest?" Therefore, considering global populations during phase two provided insights on how global construction companies would have to adapt their workspaces from one country to another.

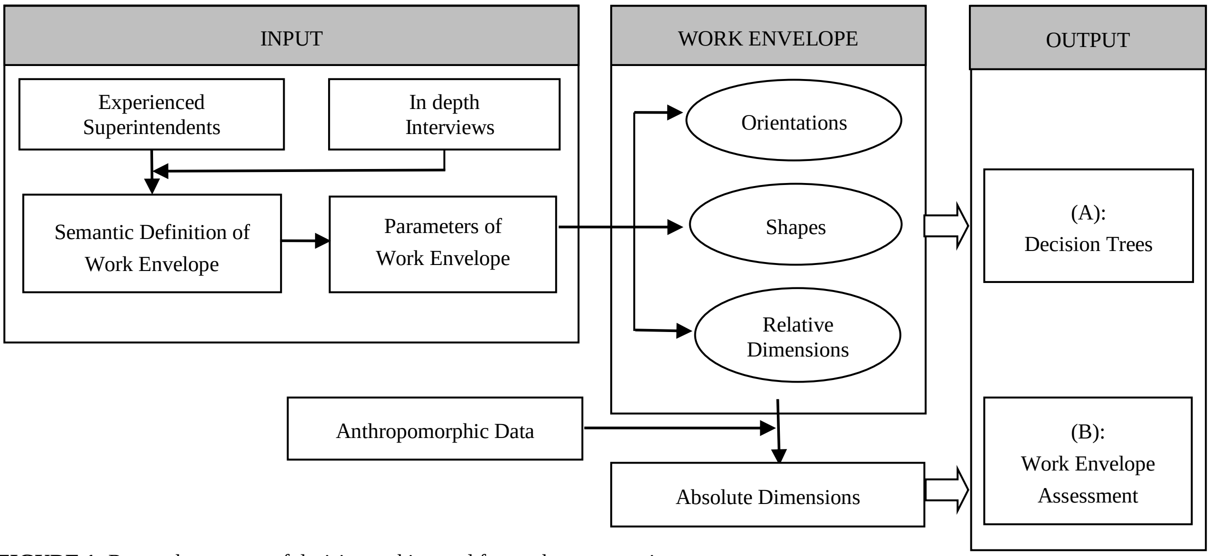

FIGURE 1: Research structure of decision making tool for work space requirements

As a result, different probabilities with significant work envelope overlaps of either two of the global populations are checked using physical body dimensions. This phase exports work envelope assessment of comparisons among multiple populations, which is the output (B) of this study, aiming at a better understanding of the mechanics 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 the reasoning approach behind the physical requirements for work envelopes. Currently, the superintendents are widely recognized as retaining this knowledge, since they manage the construction process at the task level (Akinci 2002).

A structured interview, which is still the most widely used technique for knowledge acquisition (Cullen and Bryman, 1988; Gebus and Leiviska 2009), was conducted with the superintendents to validate the final interviews. The superintendents were selected based on the following criteria:

(1) he/she is currently employed at time of the interview as a piping or scaffolding superintendent;

(2) he/she is experienced in working in the U.S. or Canada oil and gas industry;

(3) he/she has minimum experience of 5 years as a piping or scaffolding superintendent.

This step addresses the workspace and scaffolding requirements for work crews. In particular, construction superintendents were interviewed to describe the work envelopes in welding and bolting activities between piping and steel components.

To gain detailed information, selected superintendent who had rich experience and knowledge in industrial construction and scaffolding requirements were interviewed (Table 1). Considering that the sample size is relatively small, the results should be validated to improve the accuracy, completeness, and reliability of the interview results with further review (Hoffman, 1987; Crandall et al., 2006; O’ Brien et al., 2011). While the unique technical qualification required to provide useful information for the purpose of this project limits the number of suitable candidates, the interviews involved five experienced superintendents, and their independent responses were compared to validate the results.

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

TABLE 1: Experience description of the five interviewed superintendents

Superintendent	Experience Description
1	Former piping superintendent on oil & gas projects along the U.S. Golf Coast with approximately 10 years of experience on the field.
2	Former piping superintendent on oil & gas projects along the U.S. Golf Coast with approximately 8 years of experience on the field.
3	Scaffolding superintendent along the U.S. Golf Coast for one of the 50 largest U.S. contractors. He has approximately 12 years of experience in the field.
4	Scaffolding superintendent for a scaffolding contractor in the Western Canadian oil sand refineries projects. He has approximately 10 years of experience as a piping and steel superintendent and 3 years supervising scaffolding crews.
5	Piping superintendent on oil & gas project in the U.S. Gulf Coast for a major U.S. contractor. He has approximately 15 years of construction experience, including 6 years as a superintendent.

Temporary facilities, especially scaffolding, are typically involved in the execution of tasks in oil and gas projects. Furthermore, scaffolding space planning is directly related to work envelope requirements in piping and steel operations. Therefore, the structured interviews consisted of presenting construction tasks commonly found on oil and gas project through sample worksheets (Figure 2). To ensure the technical accuracy and context of each construction task, the selected situations were extracted from a 3D model of an actual carbonation plant. The specific area was 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 regarding the physical parameters. 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.

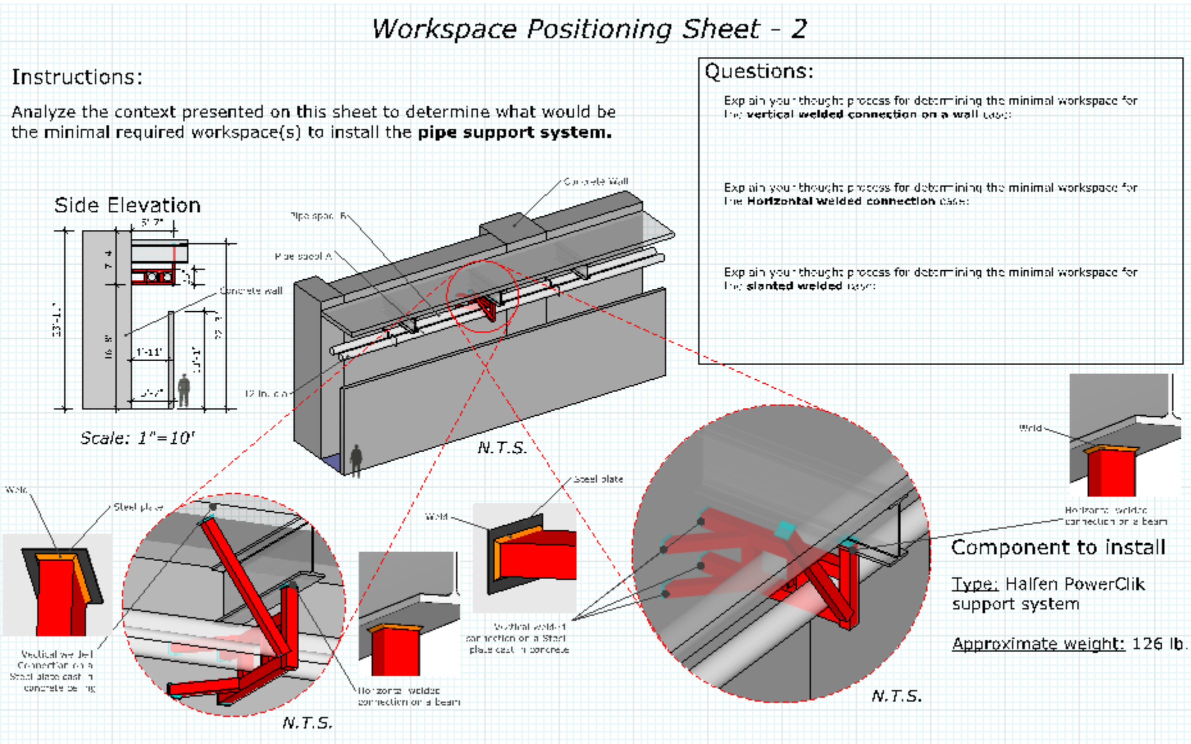

FIGURE 2: A sample worksheet describing a piping support system welded to a beam and to a concrete wall. (Note, the connection points are highlighted in cyan.).

The raw interviews with each superintendent were recorded in a spreadsheet and specific rules for defining the work envelope requirement for each specific task was derived. The rules were analyzed and summarized into seven decision trees, displayed in Figures 6, 7, 8, and 9. The remaining trees differ only by the 3D representation. These decision trees articulated themselves around “breakpoints” that were identified in the interviews. Such breakpoints are parameters that are recognized to have a significant impact on the work envelope requirement. For instance, it was determined that the optimal working height for welding two vertical pipes together is different from bolting the same pipes. The purpose of the decision trees is to describe the workspace assessment process, in a way similar to “IF-THEN” statements so that they could be easily implemented into software algorithms. To complement the decision trees, 3D drawings were included to directly visualize the situation described.

3.2 Phase 2: Work envelope dimensioning

The work envelope definition obtained in phase 1 included many dimensions relative to individual body parts, such as “at face height”. This is interesting as it does not limit the definition to a specific population, but space planners need more specific physical dimensions for the various applications previously mentioned. The relative definitions need to be interpreted into absolute dimensions using anthropomorphic data. Figure 3 presents the process used to extend the phase 1 interview data into definitive physical requirements. The body-relative dimensions obtained during phase 1 of the study were used as input for the 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 were compared to each other.

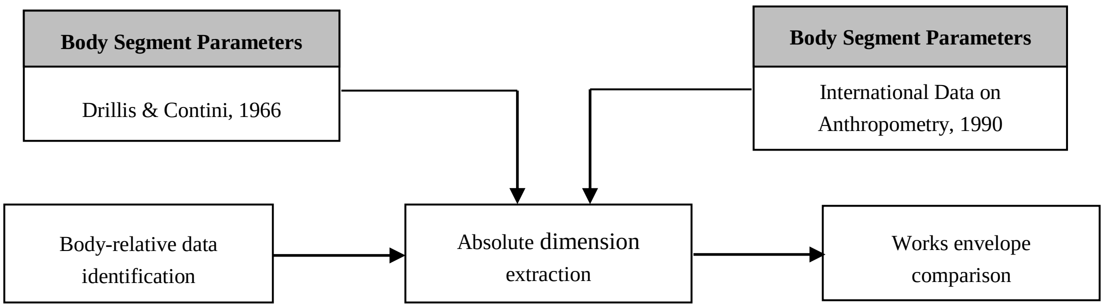

FIGURE 3: Absolute work envelope dimensioning process.

The primary source for anthropomorphic measurements was obtained from Jurgens et al. (1990). Their studies gathered data from multiple worldwide studies conducted from the sixties to the late eighties. This meta-analysis, published by the United Nations International Labor Office, breaks down the world into twenty populations. From these populations, the authors retained data for seven global populations including: (1) International (A meta-region that encompass all populations and represent the”mean” of the world population); (2) North American; (3) Latin American; (4) North Europe; (5) Eastern Europe; (6) North India; and (7) South China. The pitfall of this data source is that some populations only have a limited number of body dimensions available. The only information consistently available across every population was their stature, or overall body height, from the bottom of the feet to the top of the head.

TABLE 2: Stature mean and standard deviation for the selected populations

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

To compensate for this lack of consistent data across every population, the authors relied solely on stature, with its mean and standard deviation, shown in Table 2, but the remaining body segment parameters (ie. Size of the other body parts) (Figure 4) are calculated using data from Drillis and Contini (1966). Indeed, this data source 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 was defined, it raises the question how similar or different populations influence the physical work envelope requirements for piping and steel construction activities. 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.

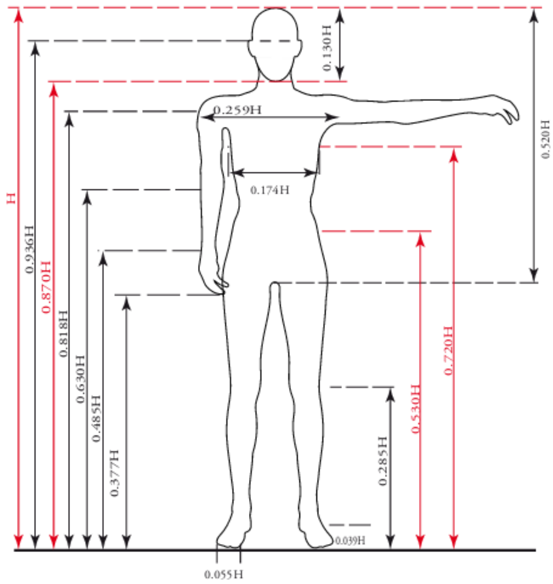

FIGURE 4: Body segment parameters, from (Drillis and Contini, 1966) (The parameters used in this study are highlighted in red.).

Knowing how similar two populations are relative to their work envelope, translates into knowing the level of overlap between the populations. Since every 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 in Figure 5? The scenario now involves a random variable problem that can be solved.

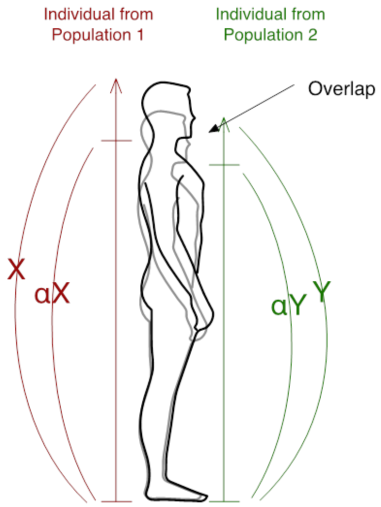

FIGURE 5: Comparison of two individuals from different populations.

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 [32]. Then, the probability to reach the level of required overlap, R, translates into:

$$Y-\alpha X \geq (X-\alpha X)R \Leftrightarrow Y \geq (X-\alpha X)R+\alpha X \quad \ldots (1)$$

$$\Leftrightarrow Y \geq X(R-\alpha R+\alpha) \quad \ldots (2)$$

$$\Leftrightarrow Y - X(R-\alpha R+\alpha) \geq 0 \quad \ldots (3)$$

The International Data on Anthropometry [31] 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:

$$X \sim N(\mu_X, \sigma_X) \quad \ldots (4)$$

$$Y \sim N(\mu_Y, \sigma_Y) \quad \ldots (5)$$

So:

$$Y - X(R-\alpha R+\alpha) \sim N(\mu_Y - (R-\alpha R+\alpha)\mu_X, \sigma_Y + (R-\alpha R+\alpha)^2 \sigma_X) \quad \ldots (6)$$

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

4. RESULTS

The research effort, initiated a way to optimize craft workers' productivity by defining more accurately the work envelope, also the effort 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: The Definition of Working Envelopes

In order to enable the reasoning of work envelope requirements in a systematic way, we summarized and compared the results of the interviews. According to the level of agreements and difference among the results, the geometric space requirements have been described as semantic and qualitative spatial requirements.

4.1.1 Results of in-depth interviews and the validation

Following the aforementioned method, in-depth interviews with five experienced superintendents were conducted. The results and comparisons are illustrated in Table 3, where the names of the interviewees have been removed to ensure privacy, an initial analysis revealed that an unsafe practice, consisting on standing on a bucket was mentioned. It was of course discarded from future analysis. Other aspects more focused toward optimization or good practices not directly relevant to the work envelope requirement are also mentioned and have been discarded.

The first interview providing the most detailed spatial workspace requirements was set as the primary interview. In order to verify the results of the first interview, the results of the other four interviews were compared to examine if their results were compatible to the space requirements and scaffolding demand described by superintendent. Each interview is comprised of nine categories according to the connection types of the activities, which respectively are bolted support systems, welded support systems, vertical pipe welding, other pipe welding, other pipe welding (alternate phasing), flange connection, butterfly valves, small butterfly valves, and pipe rack. The bolted support system and welded support system are parts of the steel trade, and the remaining seven systems belong to the piping trade. Therefore, the comparisons are consisted of nine parts as presented in Table 3.

The results of interviews are compared to determine the spatial requirements for multiple activities. The analysis of the interviews stressed the work envelope had two components: a horizontal and a vertical component. The horizontal component, or work envelope footprint, is well understood, since it refers to the traditional 2D way of planning space allocation. The vertical requirements consisted of two vertical aspects: an optimal position for the workers and the height of platform.

To evaluate the horizontal space requirement in the bolted support system, as illustrated as A.1.1 line in Table 3, according to the first interviewee, 3ft 6in space around the outside of the object is required, which is also highlighted as the optimal space in any situation. Therefore, if there is no special space requirements in horizontal direction mentioned for other types of connections, we adopted a 3ft 6in space outside the object as the requirement principle. Specifically, the first interviewee pointed out when a worker executes a bolted connection to the wall, the space requirement is 3ft 6in from the wall as well. To verify the accuracy of this principle, superintendent 3 and superintendent 5 respectively provided us with the horizontal requirements. Specifically, superintendent 3 addressed that the platform should be 7 by 4ft, which means a 3ft 6in space outside the element and supports the principle mentioned above. Superintendent 5 suggested that a minimum space of 3ft outside the element is needed to allow enough space, so there is a 6in difference between the results of superintendent 1 and 5. To meet all the horizontal requirements suggested by the interviewees, we adopted the maximum horizontal space requirement, 3ft 6in space outside the element, as the optimal horizontal requirement.

The vertical component of the work envelope for these described scenarios is more complex, which 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 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 a 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. Further research is needed to develop optimization algorithms to identify how individual scaffold system can accommodate multiple work envelopes.

As in the case of a bolted support system shown in A.1.2 line of Table 3, the optimal height for bolting illustrated in the first interviewing results is above waist and below chest. This is validated by the result from superintendent 5, who suggested the optimal bolting height to be at waist height. On the other hand, superintendent 2 highlighted that bolting above head the platform should be 5ft below the connection. At the same time, superintendent 4 identifies in this situation that bolting should be done in a way that the connection point is at face height. These two suggestions seem to be hard to compare. But considering that the mean height for males 20 years of age and older in the US (McDowell et al., 2008) is 5.825ft and the face height in scale in Figure 4 is 0.870H, it can be easily calculated that the absolute face height is 5.068ft, which means to achieve the goal of providing the workers with optimal height for bolting above head, the platform should be 5ft below the connection. Therefore, the results of superintendent 2 and 4 validated each other.

In the welded support system (A.2), the vertical space requirement (A.2.1) depends on the direction of the welding workface. For vertical welding, the result from the first superintendent illustrates that the comfortable welding position is below the chest and above the waist, which is accurately validated by the result of the superintendent 5 that the ideal position is between waist and chest. On the other hand for horizontal welding with sufficient head clearance, superintendent 1 indicated that the optimal position should be at face height, which is overwhelmingly agreed by superintendents 2, 3, 4 and 5. Specifically, superintendent 2 suggested that the height of platform to be 5ft below the connection. When interpreting 5ft into semantic information using anthropomorphic data (McDowell et al., 2008), we concluded welding should be at face height. Meanwhile, superintendent 3 stressed that the welding process required more space here since the welder needs to be at welding workface, and superintendent 4 suggested that welding requires increased complexity so the welding should be at face height. Superintendent 5 directly pointed out that for a horizontal welding the optimal height is better at face height. By comparing the vertical requirements from five interviewees, the optimal height for vertical welding can be determined to be at face height. In addition, superintendent 1 suggested that horizontal welding with insufficient head clearance a comfortable reaching arm extension above the head is required.

TABLE 3: *Comparisons among the results of the in-depth interviews*

Connection Types			Primary Interview	Validation Interviews			
			Superintendent 1	***Superintendent 2***	***Superintendent 3***	***Superintendent 4***	***Superintendent 5***
A. Steel trade	***A.1. Bolted support system***	***A.1.1***	3ft 6in space around the outside of the object is optimal (**in any situation**) For a bolted connection to the wall,the 3ft 6in clearance from the wall is required.	-	The platform should be 7 by 4ft (ie. 3ft 6in outside the element)	-	There should be 3ft clerance outside the element to allow enough space.
		A.1.2	The optimal height for bolting is above waist and below chest (3-4ft above the platform). The height of the platform is set using the highest elevation connection.	When bolting above head, aplatform should be 5ft below connection.	The height of the platform should be 16 ft above grade to comfortably reach each components.	Above head bolting should be done in order that the connection point is at face height.	The optimal bolting height is at waist height.
	A.2. Welded support system	***A.2.1***	The comfortable welding position is just below the chest to above the waist. For vertical welding with sufficient clearence: just above the waist. (ie. 3ft from the platform for a 5'10" worker)	-	-	-	For a vertical welding the ideal position is between waist and chest.
		A.2.2	If the situation involves horizontal welding with sufficient head clearance and at face height (5'5"). If horizontal welding with insufficient head clearance, comfortable reaching arm extension above the head	When welding overhead from below the platform should be 5ft below connection.	The welding process requires more space here since the welder needs to be at the weld face.	Increased complexity required that the weld should be at face height.	For a horizontal welding is better at face height.
B. Piping trade	***B.1. Vertical pipe welding***	***B.1.1***	For the vertical connection the width of the workspace can be 4ft, which is the standard width of a scaffold and is about what is required to bolt/weld.	-	-	-	There should be at least a 3ft clearance from the outside of the pipe to allow enouth space for the welder.
		B.1.2	The "sweet spot" is between waist and chest. (Applicable to all pipe connections.)	Ideal height for welding is at chest, i.e., 4 ft from the platform level.	The platform should be 3-4ft below the weld position.	Ideal welding position is between waist and chest . A welder can work as high as his face height and down to his knee height.	-
		B.1.3	-	For pipe welding, the worker should be able to see the top of the weld.	If the pipe is bigger than 4ft in diameter, two levels of scaffold are needed.	-	-
	B.2.	***B.2.1***	The bigger the pipe, the bigger the scaffold.	-	There is no real impact of the phasing since using the crane vs the chain fall	There should be between 3 and 4ft of space out of the pipe.	-

Other pipe welding				will require the same amount of welding workspace.		
B.3. Other pipe weld (alternate phasing)	***B.3.1***	-	-		-	There will be some space needed for the handling of components, but there is no real impact on the worker's space.
B.4. Flange connection	***B.4.1***	-	-	The platform should be 3ft 6in (around the pipe).	The worker should be able to turn around the actuator (3-4ft).	-
	B.4.2	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.	-	To be able to reach each flange the platform should be 6-8in below the lower flange	There is less restrictions on flanged connections but the optimal work height is between waist and chest	Workers should be able to reach the top and bottom of the flange
B.5. Butterfly valves	***B.5.1***	Don't necessary need a bigger workspace Stick with the 3ft 6in around.clerance	-	Also a 3ft 6in platform to go around the valve.	-	The workers need to be able to go around the valve.
	B.5.2	The larger the component the more workers 8"-12" Bolted valve: 2 workers 14"-24" Bolted valve: 3 to 4 workers.	-	-	-	-
B.6. Small Butterfly valves	***B.6.1***	The actuator won't always fit in the 3ft 6in range; so you have to make sure that this space is still available even with the actuator.	-	7 by 4 ft platform to be able to reach the other side of the tank.	-	-
	B.6.2	The "workable range for a worker is from 4-5in from the ground up to the eye level. (applicable broadly). The worker should be able to work on the actuator.	-	-	-	Workers can work on elements as low as mid-shin
	B.6.3	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)**.	-	Floor of the platform is just above the tank (room limitations).	-	-
B.7. Pipe Rack	***B.7.1***	Avoid having people working below someone else for safety reasons. Try to stagger scaffolds	-	-	Try to avoid having people working on top of each other at the same time.	-
	B.7.2	-	-	Comfortable working height is 3-4 feet above the ground but workers can use a bucket.	The connection points on a pipe rack should be treated as the other connections.	Welding on pipe racks requires the same amont of space as usual welding.

For vertical pipe welding as shown in B.1.1, the first interviewee addressed that a horizontal space requirement of 4ft width is required, while superintendent 5 highlighted 3ft from outside the pipe should be required to allow enough space for the welder. But considering the 3ft 6in space around the outside of the object is applicable in any situation, which also exceeds the 4ft width requirement of workspace and the 3ft space requirement outside the pipe, we can still adopt a 3ft 6in space requirement in the final decision process. Results from superintendent 1, 2, 3 and 4 illustrated in B.1.2 that the ideal welding position is between waist and chest, which can be interpreted into 3-4ft above the platform level. Obviously, their results were validated by each other. Besides, superintendent 4 also indicated a welder can work as high as his face height and down to his knee height, which means the acceptable range for welding is from knees up to face height. So if there is insufficient clearance, this principle can be applied in such situation.

In other pipe welding activities illustrated in B.2.1, the first interviewee stressed that the bigger the pipe, the bigger the scaffold. At the same time, superintendent 4 emphasized that there should be a 3 to 4ft space outside of the pipe once more. This implies that regardless of the pipe size diameter, a 3ft 6in space outside the pipe is required. Considering other pipe welding related to alternate phasing shown in B.3.1, superintendent 3 addressed that there was no real impact of the phasing, since using the crane vs. the chain fall will require the same amount of welding workspace. This can be verified by superintendent 5, who explained that there will be a space needed for the handling of components but there is no real impact on the worker's space. Therefore, we can consider other pipe welding as the normal vertical welding condition.

In the case of flange connections as shown in B.4, the principle of 3ft 6in space around the flange provided by superintendent 1 should be applied. To verify this principle once more, superintendent 3 and 4 respectively addressed in B.4.1 that the platform should be 3ft 6in around the pipe, and the worker should be able to turn around the actuator (3-4ft), which is exactly same as the aforementioned principle. For the vertical component of the work envelope as illustrated in B.4.2, from the first interviewee's answer, the worker needs to be able to see the top of the flange connection. This is validated by the superintendent 5, who suggested that workers should be able to reach the top and bottom of the flange. This opinion is also supported by superintendent 2 that to be able to reach each flange the platform there should be 6-8 in space below the lower flange. Meanwhile, superintendent 3 stressed that there is less restrictions on the flanged connection but the optimal work height for flange connection is between waist and chest.

In B.5.1 of Table 3, for butterfly valves, superintendent 1 highlighted that the horizontal space should stick with the 3ft 6in clearance. At the same time, superintendents 3 and 5 indicated that a 3ft 6in platform is required to be able to go around the valve. Obviously, these results were verified by each other.

In the instance of small butterfly valves (B.6.1), superintendent 1 emphasized even if the actuator cannot always fit in the 3ft 6in range, space planners should make sure that the 3ft 6in space is still available even with the actuator, which implies the principle of 3ft 6in space around the element should be applied. The result of superintendent 3 verified this principle, who suggested a 7 by 4ft platform is required for the workers to be able to reach the other side of the tank. For the vertical requirements of the work envelope shown in B.6.2, the first interviewee stressed that the workable range for a worker is 4-5in from the ground up the eye level. He emphasized this was applicable broadly as well, but superintendent 5 suggested that workers can work on elements as low as mid-shin. Therefore, comparing the two results, we can draw a conclusion that the workable range should be from mid-shin up to the eye level. Here in B.6.3, superintendent 1 suggested that in scaffolding planning, another level of scaffold will be needed if the connections are in a range bigger than between the "sweet spot", which is between waist and chest, and the eyes. He highlighted this principle can be applicable to all pipe connections as well.

In pipe rack connections illustrated in B.7, the first interviewee suggested to avoid having people working below someone else for safety reasons and try to stagger the scaffolds. This is verified by superintendent 4, who also suggested to try to avoid having people working on top of each other at the same time. In this part, the first interviewee did not address other requirements, but this can be complimented by superintendents 3, 4, and 5. Respectively, superintendent 3 highlighted in B.7.2 that the comfortable working height is 3-4 feet above the platform but that the workers can use a bucket. Meanwhile, both superintendent 4 and 5 agreed that the connections points on a pipe rack should be treated as the other connections so the welding on pipe racks requires the same amount of space as usual welding.

After all the comparisons were evaluated based on the types of connections, the high level of agreement gives sufficient confidence in the results in both the horizontal and vertical dimensions of the space requirements. Therefore, it can certainly generate a decision supporting tool containing all the detailed information of the spatial requirements.

4.1.2 Decision trees of work envelope

The focus of this research was piping and steel on oil and gas projects and connection points were 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-Pipe;
- Pipe-to-Valve.

Starting from this initial classification, the interviewees revealed there were significant differences on how the work envelope was defined. For each of these two categories, seven decision trees (Figures 6, 7, 8, 9.) were developed to describe both the vertical and horizontal component of the work envelopes. These decision trees presented are using “break points” or nodes that drive the work envelope shape and dimensions, which are based on the connection type (bolted or welded), the connection orientation (horizontal or vertical) and the connection direction (upward or downward).

While each of the individual decision trees is unique, 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 as 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 takes 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 connection, 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 pipe welded connection versus a bolted connection 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, which requires greater physical use of arm strength.

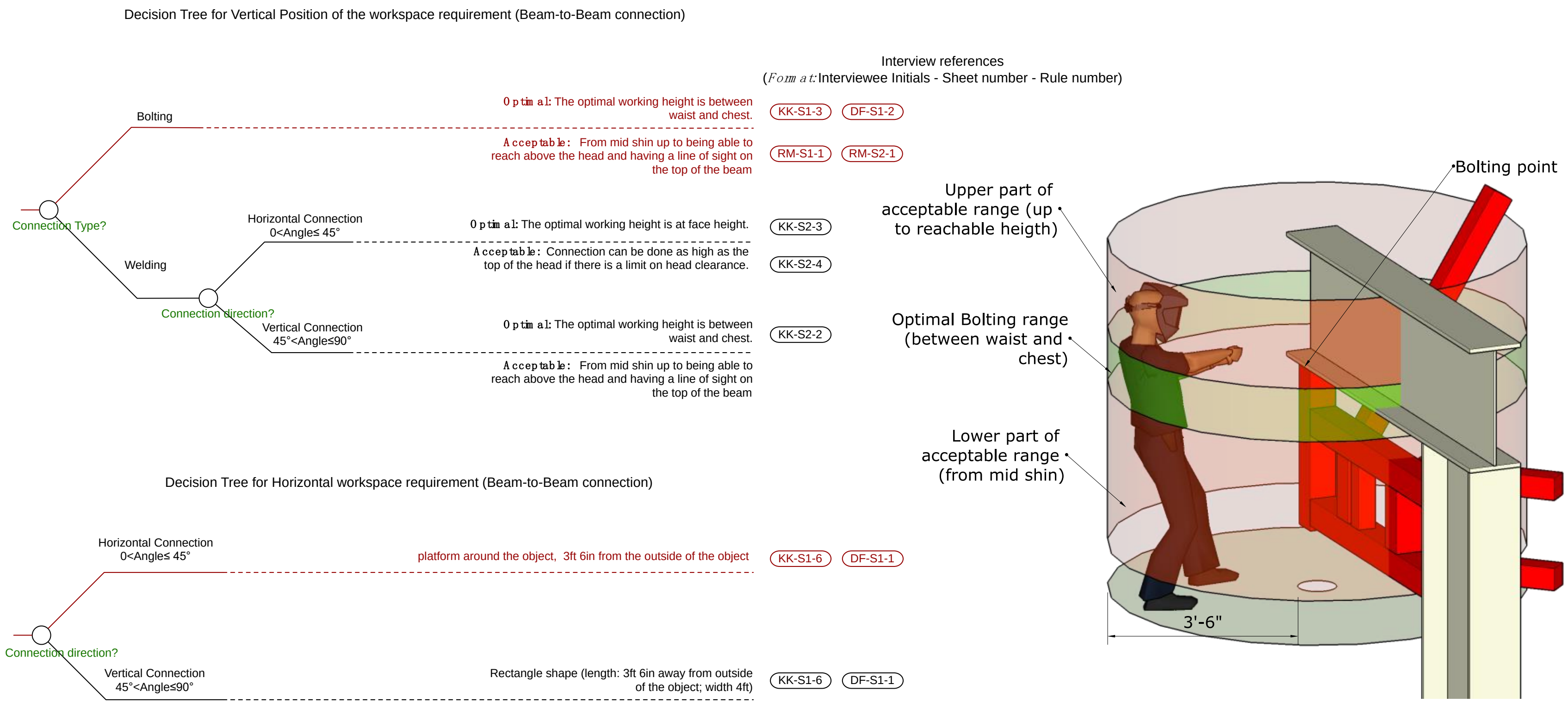

FIGURE 6: *Decision tree for a Beam-to-Beam connection*

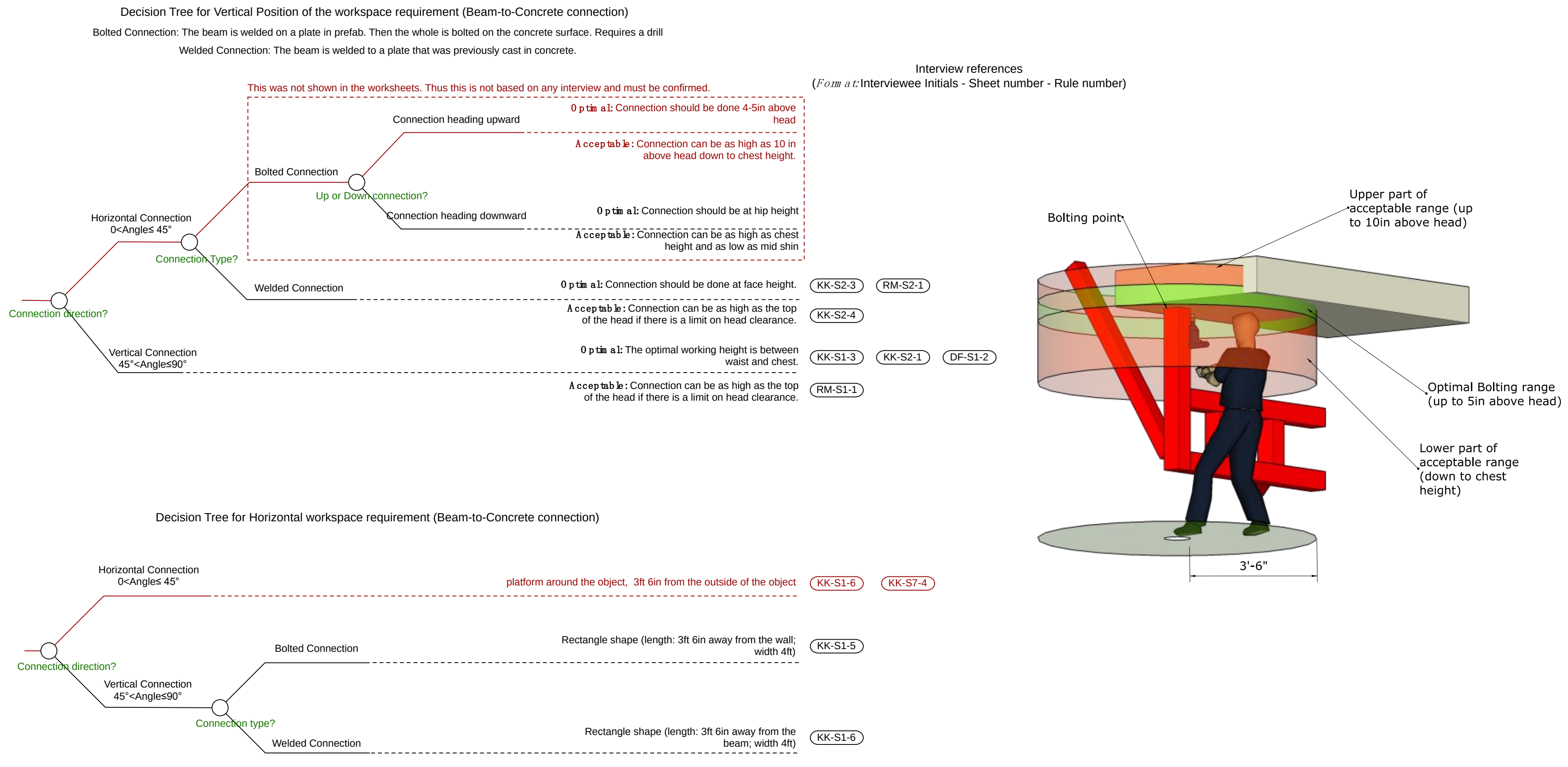

FIGURE 7: *Decision tree for a Beam-to-Concrete connection*

FIGURE 8: Decision tree for a pipe-to-pipe connection.

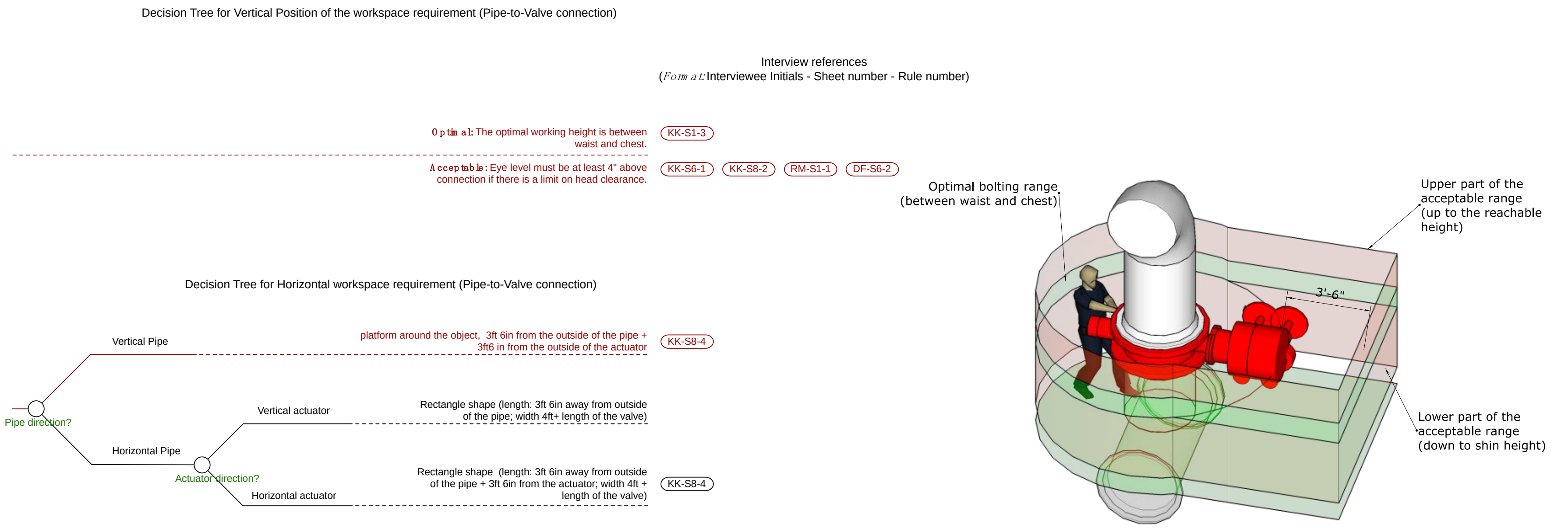

FIGURE 9: *Decision tree for a valve-to-pipe connection*

4.2 Phase 2: The Influence of Global Anthropomorphic Data on Work Envelopes

As mentioned previously, the work envelope is mainly defined relative to body parts, which is specifically the case involving 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 the research assumes that anthropomorphic differences among global populations would result in negligible variances in the required horizontal workspace requirements. Instead, this section focuses on the vertical components on the work envelopes and how global differences in anthropomorphic differences could be expected to impact the resulting scaffolding requirements.

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 was used with a required overlap of 25%, 50% and 75%. The required overlap measures the tolerance on vertical component of the work envelope is allowed. This can be translated in the level on comfort is required. The corresponding joint probabilities are displayed in Tables 4 and 5.

TABLE 4: Joint probability of meeting the required overlap of work envelope for the "face height"

Face height - ratio=0.87

Required overlap 50%

	International	North American	Latin American	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				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	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				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 3 shows the corresponding joint probabilities meeting 50%, 75% overlap for the "at face height". Taking the 50% required overlap for instance, the joint probability between International and North American is 0.776, which means if an individual is randomly picked from the International population and another from the North American population, they have a 77.6% chance of the "face height" overlap. So in this case, it is quite likely that they have a 50% overlap.

Regarding the "face height" area, the populations can be distinguished into two groups. A first group includes International, North American, Latin American, North Europe and Eastern Europe. A second population includes North India and South China. There is a high level of agreement within each of these two groups, which means that the work envelope can be considered as identical for the population within each of them. Applying this to scaffold planning, adaptations would be acquired from a project located in North America to another one located in North India to account for the population specificities on some tasks involving the "face height" dimensions. This is the case in regards to most of the welded connections.

Table 5: Joint probability of meeting the required overlap of work envelope for the "between chest and waist"
Waist and Chest - ratio=0.720 & 0.350

Required overlap 50%

	International	North American	Latin American	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				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	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				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							

Regarding the "between chest and waist" dimension, no such disagreement can be found across the selected populations. In Table 4, the table illustrating the 50% required overlap demonstrates all the joint corresponding probabilities in pairs are higher than 0.8, which indicates that there is a high level of agreement within the populations. As a result, no adaptation would be required for the tasks involving the "between waist and chest" dimension, which primarily relates to the case of bolted connections. Most of the bolted connections are in this case.

5. DISCUSSION AND CONCLUSIONS

Traditionally, workspace planning has mainly focused on workspace representation, execution management and congestion minimization. However, there is still a lack of research that addresses the factors and input parameters of workspace requirements against the actual information needs in industrial engineering, which is the initial step in space planning. The objective of this research is to develop a methodology to specifically describe workspace requirements in piping and steel trades, which could be extended to other trades. The methodology was implemented by in-depth investigations with experienced superintendents, which was not attempted before in prior related research efforts. In particular, we focused on accurate workspace parameters and properties for multiple activities, which were integrated into the workspace decision supporting tool with 3D visual representations. While we contribute the knowledge to this specific area of workspace requirements, the anthropomorphic influence of global populations to the workspace requirements was also analysed in order to improve the adaptation for space planning, especially temporary facilities. All of these new knowledges of workspace requirements have a direct impact on the determination of execution workspace and on-site planning of temporary facilities.

This research introduces a workspace decision supporting tool for space planning of piping and steel structures. In compliment to input variables and parameters of workspace requirements, multiple decision trees with 3D visual representation were used to determine the geometric parameters of work envelope. To assist scaffolding design worldwide, this research also presented a mathematical assessment describing the anthropomorphic impact on the accurate work envelope dimensions and scaffolding design. Based on the work envelope reasoning process, an interpretation process of geometric work envelope and semantic information from the body relative dimensions to absolute dimensions was presented. In addition, the work envelope is visualized in 3D environment, which enhances the applicability of workspace requirements in planning stage. Using the anthropomorphic data, the joint probabilities of work envelope overlap among different populations were compared to each other. Both the connection types and the connection directions have an impact on the optimal work height. The connection orientations determine the footprint of the work envelope. As a result, they were taken into account in the decision trees to provide the identification and decision making on the work envelope for space planners.

The primary contribution of this research to overall body of knowledge is the recognition that the work envelope is a three-dimensional object with two components, which in this case does significantly vary by the type of pipe connection and between global populations. Specifically, it stresses the independence between horizontal and vertical components of the work envelope; identifies the specific factors impacting those two components; and describe how the anthropomorphic data could impact the task execution and efficiency of construction.

Although most construction projects occur in a 3D environment, it is often a compilation of 2D planes, such as floors and other horizontal surfaces. However, confined projects, such as tunnels and bridges, are notable exceptions, since their work space is used at its fullest and requires work envelope in all directions. Therefore in most cases, the vertical and horizontal components are the most critical in an overcrowding management perspective. The proposed method herein introduced one application of vertical component, the scaffolding planning and optimization, which shows the vital usage of the vertical component to ensure good ergonomics and safety to the craft workers.

As a part of our future work, based on the specific workspace parameters identified in this research, spatial optimization for multiple work envelopes adjacent to each other are being conducted. Considering that workspace requirements have a significant impact on temporary facilities planning, further studies will also focus on how to utilize this workspace knowledge to evaluate the spatial relationship between work envelopes and temporary facilities and model the optimization problem on multiple work envelopes through mathematical algorithms to improve the efficiency of scaffolding planning and productivity of work crews. Moreover, the developed workspace decision making tool in this paper will be expanded to be utilized in the optimization module and implemented in the space planning of industrial piping project using BIM software. Therefore, future work on embedding the activity-based workspace requirements in BIM should potentially increase the productivity of space planning in industrial projects.

ACKNOWLEDGMENT

The authors wish to acknowledge the financial support of Bentley Systems, China Scholarship Council and the time and committee of the participating superintendents. Without these contributions, this work would now have been possible. All opinions are those of the authors and not necessarily reflected by any employee of Bentley Systems.

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