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An AHP based visual tool assignment model for accident avoidance in manufacturing workplaces

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I am submitting herewith a thesis written by Riddhi Pradeep Shah entitled "An AHP based visual tool assignment model for accident avoidance in manufacturing workplaces." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Industrial Engineering.

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An AHP based visual tool assignment model for accident avoidance in manufacturing workplaces

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Dedication

To the loving memory of my father.

To my mother, who had the arduous task of raising me.

To Pooja and Rakesh, for their constant support through this journey.

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To my mother, Vibha and my father, Pradeep, for giving me access to a quality education and life. They are the reason I am here today.

Abstract

Collaborative risk management techniques place management and workers equally while developing a safety culture in workplaces. Traditional risk awareness methods which are commonly carried out in workplaces, such as training and safety manuals, are inherently passive in nature. On the other hand, visual tools are active risk communication mechanisms which deliver specific risk information in a work area. The presented study places emphasis on risk awareness for workers through the assignment of visual tools, which is critical to the success of a collaborative framework. Traditionally, the assignment of visual tools to work area locations has been arbitrary, potentially causing the risk information to be ineffective. The framework presented in this study provides a systematic visual tool assignment method for safety managers in manufacturing work areas. This placement is based on the attributes of the work area. The use of multi-criteria decision making (MCDM) techniques such as Analytic Hierarchy Process (AHP) incorporates the expertise of safety managers for a successful visual tool assignment by considering work area and entity variables. Analysis of Variance (ANOVA) and Data Envelopment Analysis (DEA) reduce the number of variables that act as the criteria for AHP. The scenario-based case study indicate that these variables had an impact on the choice of visual tools. These scenarios are designed to depict multiple locations in a heavy manufacturing plant layout. The presented study is applicable to mobile entity interfaces in manufacturing industries. It can be applied to other manufacturing safety incident categories and industries which could benefit from visual communication of risk information in work areas.

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Chapter 1

Introduction

Manufacturing industry safety has been a cause of concern due to its impact on human life and the associated costs that a company has to bear [73]. Based on the reports of occupational injury statistics by [18], manufacturing accidents accounted for over 7.5% fatal work injuries across all the industrial sectors. This was the sixth highest fatality rate among all the industry sectors as depicted in Figure 1.1. The number of non-fatal injuries amounted to $425,700$ for the year 2015.

The impact on human life causes us to investigate the cause of these work area injuries. A close examination of the reports by [18] shows us that transportation incidents caused the highest number of fatal occupational injuries in the year 2015 with $2,054$ recorded incidents. Due to the heavy movement of materials through different types of vehicles and the involvement of personnel who work in the proximity of these vehicles, pedestrian-vehicular incidents accounted for 26% of all transportation fatalities in the year 2015. This study classifies the incidents between pedestrians and vehicles as ***"mobile entity interfaces"***.

In addition to the loss of human life and injuries, mobile entity interfaces had a severe cost implication as well. [50] calculated the cost of mobile entity interfaces as the sum of wage and productivity losses, medical expenses, administrative expenses, motor vehicle damages, and employer's uninsured costs. In addition to these, by identifying the cost of lost quality of life through empirical studies, the average comprehensive cost for each worker could be obtained. While the average cost of death was $10,082,000 for the year 2015, it was surprising to observe that in cases with no observed injuries the average costs were still as

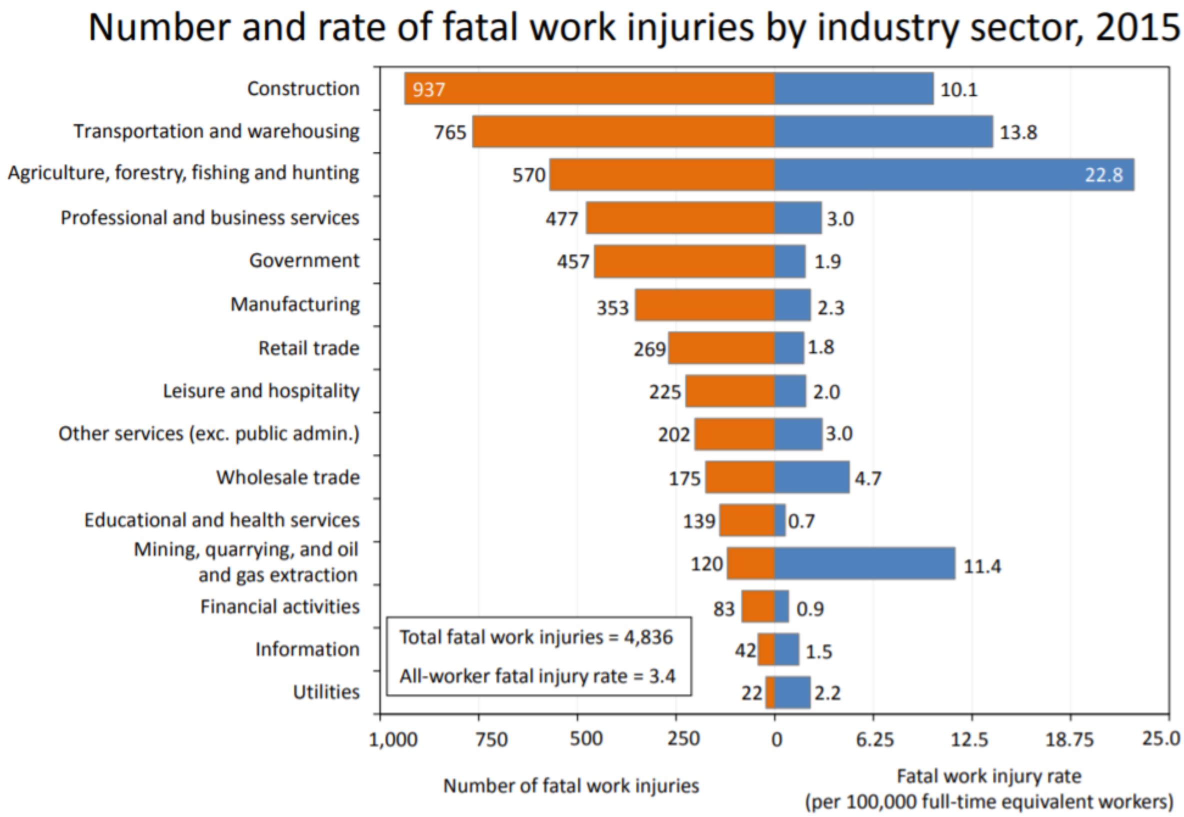

Figure 1.1: Number and rate of fatal occupational injuries, by industry sector, 2015 [18]

high as $46,600. Table 1.1 provides the costs for the different injury severities observed in transportation accidents.

Table 1.1: Average comprehensive cost by injury severity, 2015 [50]

Death	$ 10,082,000
Disabling	$ 1,103,000
Evident	$ 304,000
Possible injury	$ 141,000
No injury observed	$ 46,600

Mobile entity interfaces are hard to prevent due to their ad-hoc occurrences. The only form of control is by changing the path of motion of one of the entities. To do so, a quick communication of risk information is required to allow the workers to make the necessary decision of altering their course. Hence, the visual tool assignment framework presented in this study is tasked with improving worker safety for mobile entity interfaces.

1.1 Importance of analyzing individual risk incidents

The rate of incidents and financial implications led safety managers to an identification and management of accidents [73]. Several advancements have occurred in researching the causes of accidents [16], organizational factors leading to unsafe work environment [65] and identification of safety practices that can control the frequency of risk incidents [71]. Despite these, injuries still occur at alarming rates. This is because there is an evident lack of focus towards a singular incident.

The work of [16] discussed certain organizational policies which influenced a worker's safety behavior. However, these policies were generic and hence applying them to all risk incidents may not provide the same results. Specific managerial practices and their effect on safety must be studied for them to have any real meaning. For example, while it may be true that relieving production pressure from workers may ensure that they do not exhibit cavalier attitudes towards safety, the impact of production pressure may still result in falls and slips [13].

There is a need to study factors from the perspective of mapping safety practices to specific risks. While [65] attempted to study factors affecting risk, these factors do not play a regular role in all incident categories. For example, a cluttered work area due to excessive machines and materials lying around might increase the chances of a mobile entity interface or a worker tripping more than the chance of a worker slipping.

[71] observed the effects of safety practices in an unsafe environment. They concluded that proactive measures of safety resulted in financial benefits to organizations. However, their work did not concentrate on a single safety issue. This can be problematic as the performance of safety tools and practices that work for one incident category may not necessarily be as effective for another risk category. For example, while having training to ensure that workers are aware that they need to wear safety equipment such as gloves to pick a piece of hot metal might be a good practice, it may not be the single sufficient solution to avoid a slip. This is because regular maintenance and housekeeping must be coupled with the training sessions to avoid a slip.

A positive step to bridge the identified gaps is to concentrate research efforts towards a single incident category. This guides identification of "variables" that affect specific safety incidents in the work area and use them to select the right safe practices. The work presented in this research investigates the variables affecting mobile entity interfaces. This facilities the selection of the right risk communication tools to mitigate the risk of mobile entity interfaces by improving the worker's risk awareness.

1.2 Risk communication

A successful risk management framework involves a collaboration between the management and employees [30, 16]. Figure 1.2 highlights traditional models where risk assessment led to the risk management, which could be in the form of risk communication. This communication of risk increases a worker's risk awareness. These traditional models failed to achieve trust from the workers, as risk assessment and management were treated as separate functions [30]. This trust is believed to be achieved only by making this a collaborative practice with the integration of employees. Management still holds the responsibility of reducing work area accidents. They identify risks [48], or introduce policies that can affect accident rates [1, 32, 37, 63]. Management then communicates the identified risk-related information to their employees with the intention that employees will take the necessary steps to avoid the risk, hence making the employees in control of their safety [4, 54, 30].

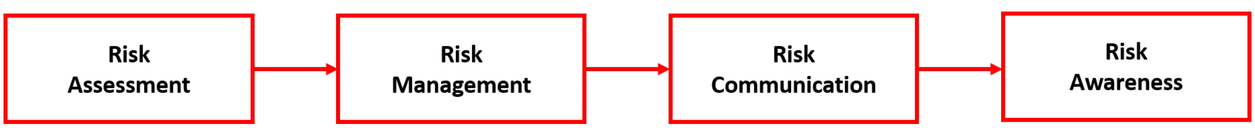

Figure 1.2: Based on traditional models of risk analysis, [30]

Risk communication is a crucial process in improving the safety of a work area. [28] defined effective risk communication to be "the process by which actions create and sustain meaning". It has been identified as an effective way of instigating a response to impending risks [72, 43], and hence has the ability to effectively mitigate mobile entity interfaces. Studies by [26, 39, 4] also focused on the employee's "right to know" the hazards that threaten the work area and require them to take action against such hazards. To sufficiently succeed in improving work area safety, a risk awareness mechanism must be put in place. According to [40], in order to build a reliable risk awareness mechanism, the understanding of the psychology of risk must be leveraged [36]. This guides the classification and choice of risk communication tools for the presented framework to avoid mobile entity interfaces.

Risk communication tools such as safety training [24], manuals for safe work operation [21] and visual tools [14] increase a worker's risk awareness. While risk communication in the form of manuals and training may help them be aware of the possibility of this occurrence, they require extensive memorization and are not suitable to get the attention of a worker under an immediate and unpredictable threat. It is important to simplify the processes and create an environment where there is a general awareness of impending risks because workers generally tend to not practice precaution while walking through a work-area [16]. They are more likely to react to risk information that is given to them in the form of an alarm/warning.

Visual tools are an obvious choice to mitigate mobile entity interface because they do not require memorization of risk information [55]. The information can be presented in the form of texts, graphs, videos, pictures, and sounds. This allows safety managers to account for various scenarios and share information in a simple and effective manner [28]. They can convey specific information and capture the attention of a worker through flashy messages, sirens or simply visually indicating their ability to move along a certain path. This would make the worker more aware of the possibility of an interface and help them take the necessary course of action to avoid such an interface. Unlike the previously mentioned passive risk communication tools, visual tools continuously signal the personnel on safety procedures and protocols and allow the workers to act on the situation, thus enabling them to mitigate risks.

1.3 Risk awareness using visual tools

Visual tools are the preferred alternative for risk awareness [14, 68, 46, 31, 55]. The current approach of choosing visual tools using the subjective discretion of plant and safety managers is insufficient. An important question to be asked is, how do we know that a visual tool could effectively communicate the risk information for a *specific* location? While the work of [14] attempted to map visual tools to work areas, the selection process is still ad-hoc in nature. This approach does not consider work area variables that can divert attention from risks. This has a direct impact on the safety of the work area. Hence, a systematic identification of visual tools for a given work area by identification of work area variables is required.

Visual tools have little to no effect when they are assigned arbitrarily to a work area. For example, placing an audio andon may provide unfavorable results in a noisy work area, and footprints placed on the shop floor may go unnoticed by large mobile entities in the area. However, audio andons may be rendered effective in a quiet environment and footprints may be easily noticeable by pedestrians. Thus, the work area and entity variables that influence the mobile entity interfaces and the choice of visual tools must be considered.

When the right visual tool is used in a work area, it can effectively communicate information about impending mobile entity interfaces. For example, in a quiet work area, if an employee notices a pedestrian who is unaware of a forklift backing up a car, they can pull the trigger to a siren and alert both the mobile entities of each others presence. The pedestrian and the forklift driver can then alter their paths to avoid this interface. However, a siren could go unnoticed in a noisy work environment. This calls for the study of variables that have an effect on mobile entity interfaces.

Past research efforts have focused on the identification and comparison of variables or factors that cause fatal and non-fatal accidents [42, 19]. However, there is a lack of specific research of variables leading to mobile entity interfaces in manufacturing industries. There is also no research pointing to the variables which improve risk awareness in manufacturing work environments.

Chapter 3 investigates literature to create an extensive list of variables which have a causal connection to risk and safety. These variables are then filtered to retain variables which may influence mobile entity interfaces and grouped as work area and entity variables to make them suitable for the presented research framework.

1.4 Problem Statement

Some of the current shortcomings of past research efforts that we must deal with are :

- There is a lack of a systematic mechanism to map a visual tool to a given work area
- There is a lack of understanding of the differences of work areas from the perspective of unsafe incidents and visual tool assignments. This makes it hard for us to represent work areas to deal with safety issues.
- There is a lack of a satisfactorily clear representation of work areas while studying risks.
- A study of variables that affect safety and performance of visual tools is required in order to better represent work areas and assign visual tools.
- The use of expert opinions is underrated and underutilized for visual tool allocation.
- There exists a need to create a framework to bring together past research to allocate the best visual tool for a mobile entity interface.

This framework will result in an effective risk management for mobile entity interfaces.

1.5 Approach

Figure 1.3 is a depiction of the visual tool assignment framework followed in this study. This study aims to assign visual tools to a node in the work area by studying the relationship between the variables of the work area and the mobile entities that affect the level of risk. The framework has been divided into 7 phases.

Phase 1: The *variable selection* phase relies on the understanding of the need to invest in the right risk management approaches for a given problem. In order to do so, specific risk incidents are studied as opposed to accidents in general. As a part of the presented study, an extensive literature review was conducted to identify the variables affecting specific manufacturing safety incidents. These variables are then classified as work area and entity variables, to make them apt for the research scope. This process is discussed in detail in chapter 3

Phase 2: The *work area representation* phase follows the principle that there is a marked difference in the work area and entity variable states across specific locations in the manufacturing work area. For example, a specific location within the work area may be more noisy than another due to the presence of large and noisy equipment. This influences the choice of visual tools. Hence, we represent work areas using nodes. Tools such as Failure Modes and Effects Analysis then help us identify critical nodes where mobile entity interfaces are most likely to occur. This guides management in selectively placing these visual tools within the facility.

Phase 3: The *visual tools selection* phase is important because several visual tools are available to be selected for this study. However, it is impossible to study all of them. To better test the presented approach, it was important to narrow down on the most apt visual tools using a classification system. An extensive literature search, coupled with the aptness to presented scope, facilitated the selection of active visual tools for this study.

Phase 4: The *ANOVA & DEA* phase was an essential step for reducing the variable set. A scenario-based survey was designed using the findings of phases 1 and 2. The scenarios were presented using the variable states for the selected nodes. Due to the large number of computations required in the next phase, experts were asked to select the variables that were most important for a visual tool assignment framework for each given node. The filtering of variables was conducted using Data Envelopment Analysis (DEA) and ANOVA. The results of DEA were found to be more favorable.

Phase 5: The *AHP* phase ties together the components from phase 4. The short list of variables and the visual tools selected, from the previous phases were used to create the final survey. A survey was built to feed into an AHP based visual tool assignment framework. The scenarios remained the same from the previous phase. The reduced set of variables from DEA provided the criteria for the AHP. The visual tools provided the alternatives for the AHP.

Phase 6: The *AHP Based Analysis* phase began with data collection using surveys administered to safety experts. Experts scored each variable against every other variable and for every variable, they scored each visual tool against every other visual tool. They perform this exercise for every node. Their scores are analyzed using AHP, and every individual's rankings provided a priority vector.

Phase 7: The *AIP* phase provided the results of the survey. group's responses were aggregated by finding the geometric mean of all the individual priority vectors. The aggregated inidividual priorities (AIP) were then analyzed to obtain the group's decisions to assign visual tools to each node.

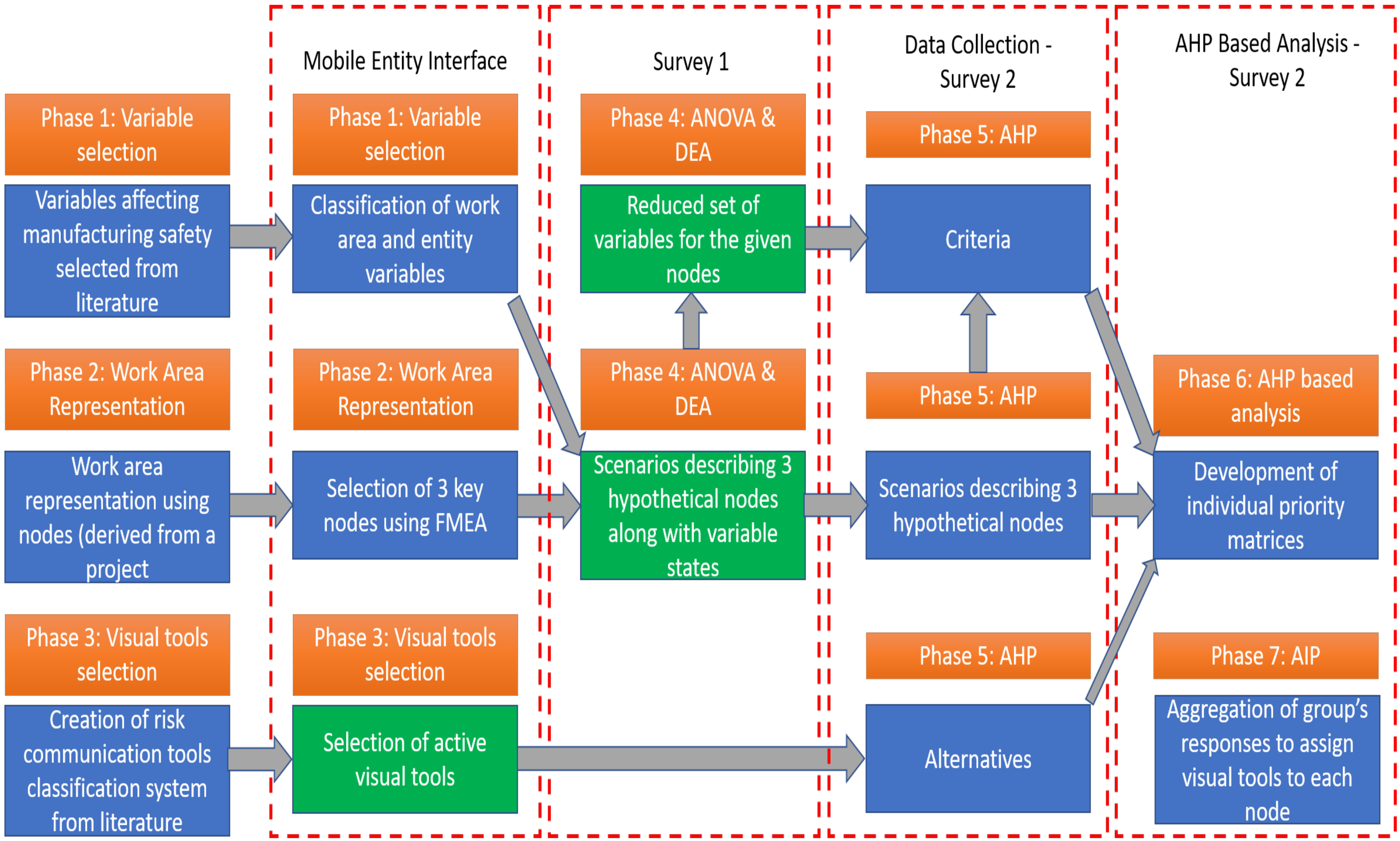

Figure 1.3: Proposed visual tool assignment framework: The blocks in orange represent the sequences of the phases followed. The blocks in blue represent the processes that were carried out during each phase. The blocks in green represent the outputs of literature search(for visual tools) and survey 1 (for scenarios and variables), that act as the inputs for survey 2. The arrows show the connection between processes.

1.6 Scope of study

The research methodology proposed in this study has the following scopes and limitations:

- This model was tested for mobile entity interfaces in manufacturing industries.
- This model could be applied to industries experiencing a high number of mobile entity interfaces.
- The work area of a heavy manufacturing company can be represented by building a scenario for the experts answering the survey.
- A set of variables related to work area safety are identified and tested.
- A set of visual tools is used to provide an understanding of the assignment system proposed.
- Safety expert opinions are collected and analyzed as a part of the data collection process. The methodology relies on their opinion to meet the goal of visual tool assignment.
- The model can be transferable to industries other than manufacturing industry. A detailed plan for this is discussed in chapter 6.

1.7 Impact of study

This study provides a more effective risk management approach, which is discussed by comparing different visual tools to improve a worker's risk awareness for mobile entity interfaces. The results help safety managers make safe organizational policies to deal with these risks, thus making the work area safer. These policies can prove to be a good investment by offsetting the costs associated with risks.

The results of this study also provide reasoning to analyze all manufacturing incidents as separate events, as opposed to the traditional approach of viewing risk as a blanket issue. As a follow up to this analysis we study the varying influence of the variables used to analyze mobile entity interfaces. The causal relationship between the variables and the visual tool selection is an important discovery as mobile entities are exposed to a high level of risk due to the influence of these variables.

1.8 Organization of the study

This document is organized into six chapters, as shown in figure 1.4. Following the introduction of this research, Chapter 2 provides a comprehensive review of theses and journal articles related to the study of variables affecting risk, visual communication research, past attempts to map visual tools to work areas, and a review of the tools used in this study and how past research led to their usage. Chapter 3 delves into the model formulation that provides the basis of the methodology. Chapter 4 discusses the methodology proposed to obtain a visual tool assignment for mobile entity interfaces in manufacturing work areas. Chapter 5 provides a case study, along with a validation of the obtained results. Chapter 6 is the final chapter, which discusses the managerial and research implications of the study, leading to possible future work, along with a discussion of the research limitations.

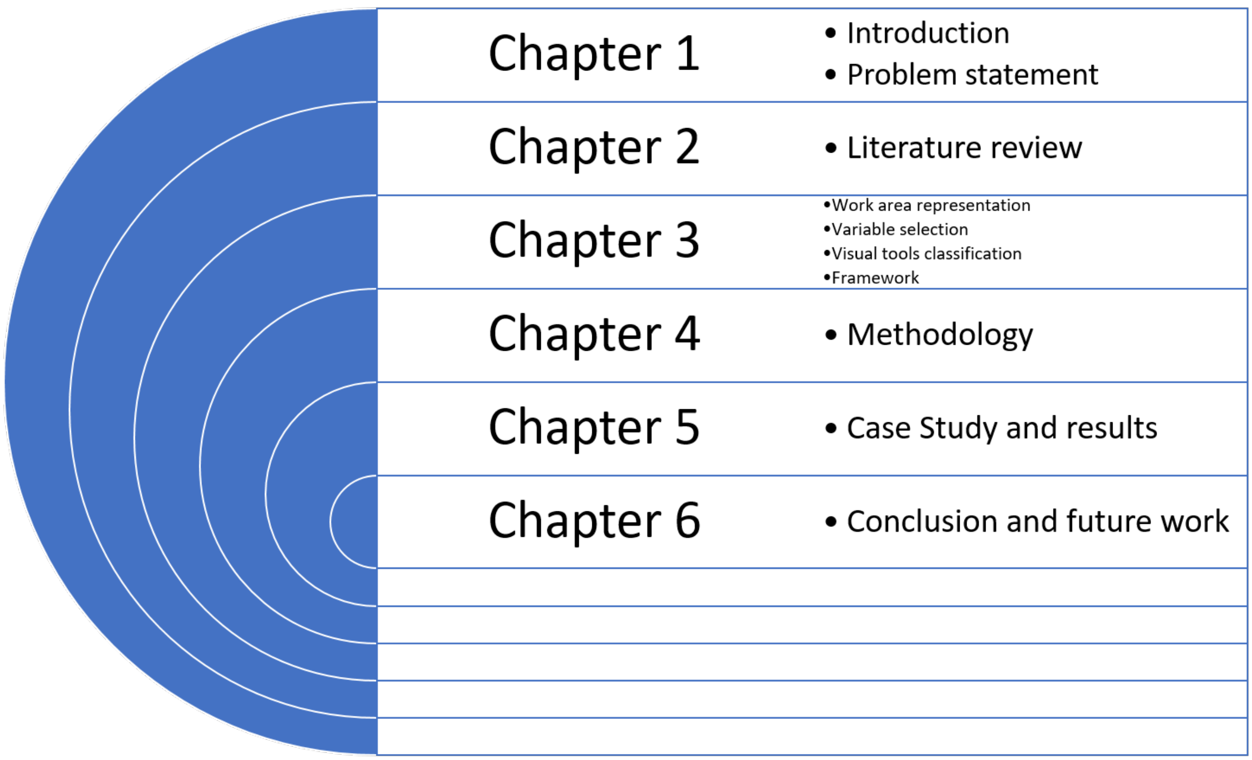

Figure 1.4: Organization of the thesis

Chapter 2

Literature Review

Injury and fatality rates have been a reason of concern in manufacturing facilities. Research on accident prevention strategies provides us with several options to create risk awareness to lower the rates of work area accidents. This chapter presents selected literature that develops the groundwork for assigning visual tools to work areas to improve their risk awareness. The following sources were used for the literature search:

- Journal papers downloaded using Google Scholar
- Journal papers and E-books downloaded using the University of Tennessee's Library's OneSearch engine
- Reports generated by Bureau of Labor Statistics
- Reports generated by National Safety Council

The following keywords were used to perform the literature search:

2.1 Efforts in increasing work area safety

To provide an overview of the past research efforts used to support the presented research, this chapter is divided into six areas, as shown in figure 2.2.

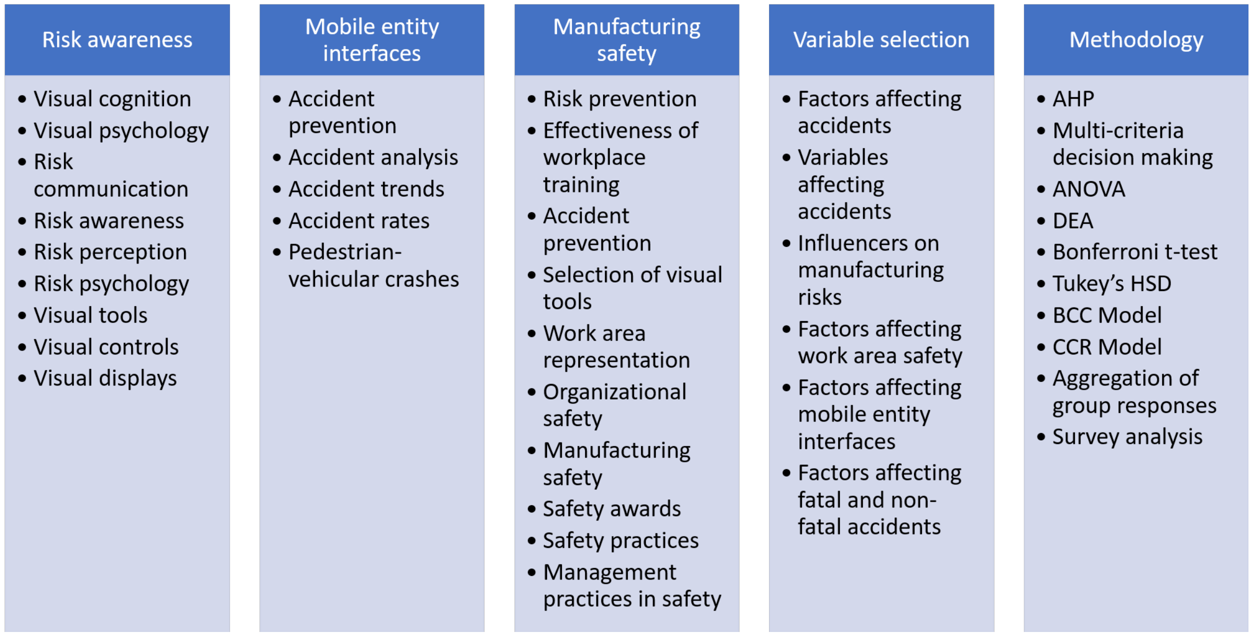

Figure 2.1: Keywords searched for literature review: The searches have been classified under 4 categories for simplicity

1) Identification of variables that influence unsafe incidents : This section highlights the inappropriateness of the focus on a collection of unsafe events, as opposed to studying specific incidents. The specific incidents are microscopically viewed with the help of variables that influence them.

2) Risk mitigation without risk categorization : This section dealt with understanding how the identification of specific incidents can contribute to a better selection of modes of risk communication.

3) Common management policies to reduce mobile entity interfaces: This section explores the reasons for the failure of management strategies to deal with mobile entity interfaces, other than risk communication.

4) Risk awareness tools: This section investigates the merits and demerits of risk communication strategies that are commonly implemented in manufacturing industries.

5) Visual tools research: This section discusses the visual cognition of risks, visual data representation studies, benefits of visual communication and past methodologies to identify the best visual tools.

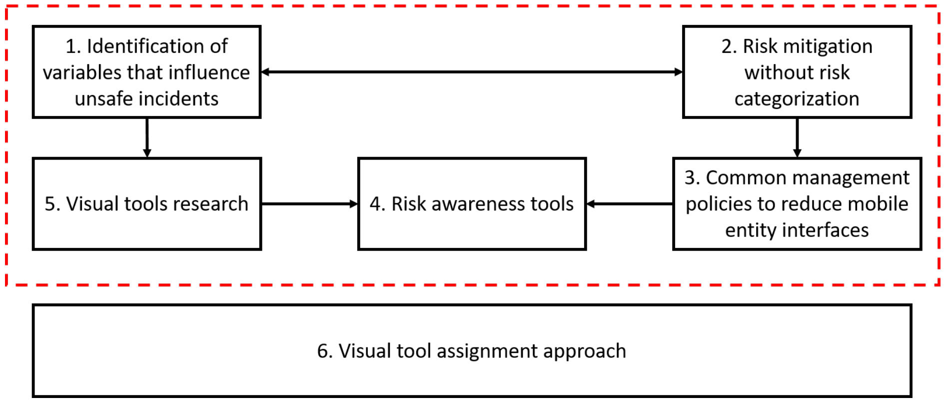

Figure 2.2: Focus areas of the literature review

6) Research gaps that contribute to the visual tool assignment approach designed for the presented work: This section provides an insight into the reasons behind the chosen approach for the visual tool assignment framework proposed in this study.

2.1.1 Identification of variables that influence unsafe incidents

Table 2.1: Summary of past research efforts towards the identification of variables and practices that lead to unsafe workplace accidents

Author, Year	Title	Advantages	Research gaps
[16]	Predicting safe employee behavior in the steel industry: Development and test of a socio-technical model	Identified that a synchronized effort of people and the system influenced safety	No specific strategies and their effect on safety were identified
[65]	Factors apparently affecting injury frequency in 11 matched pairs of companies	Identified management involvement, quality of record systems, accident costs, number of employees per supervisor to be related to low frequency injury rates	Factors were not mapped to specific risks
[42, 19]	Causation of severe and fatal accidents in the manufacturing sector	Identified differences in the impact of variables during fatal and non-fatal accidents	Results do not aid in the selection of risk mitigation strategies

The study of unsafe manufacturing incidents has been common in the past. The work of [16] concentrated on finding whether the people, the system or the people, as well as, the system influence these incidents. It was concluded that both influence safety. On the other hand, [65] claim that management involvement, quality of record systems, accident costs and number of employees per supervisor influence safety. While research efforts by [16] and [65] have studied influencers of work area risks in a more general setting, they fail to identify variables affecting specific risk incidents at the work areas. A common practice in past research has been to have a blanket approach of safety incidents within a work area. A lack of categorization of risks makes the identification of variables affecting safety redundant from the perspective of providing mitigating solutions.

Research efforts have focused on the identification of several variables that contribute to work area accidents [16, 45, 19, 42, 65, 71] . These studies compare the contribution of sets of variables towards fatal or non-fatal accidents in manufacturing industries [42, 19]. Most of these studies obtain the information using the annual statistics of industrial accidents and deaths. They then categorize the information collected by variables that either leads to fatalities or cause injuries among the workers. Statistical tests such as the Chi-square test help in understanding the impact of each variable towards a fatal or non-fatal accident. While these studies help us create an exhaustive list of variables to consider for work-area accidents, they do not focus on mapping these variables to specific accidents. The proposal of integrating risk-based variables while evaluating risks takes the research scope forward by identifying the need to connect the variables back to specific accidents [11]. Chapter 3 helps in understanding the connection between the variables picked in this study with mobile entity interfaces in manufacturing industries, hence bridging this research gap.

2.1.2 Risk mitigation without risk categorization

Table 2.2: Summary of past research efforts towards the mitigation of risks without categorizing them

Author, Year	Title	Advantages	Research gaps
[71]	Organizational safety: Which management practices are most effective in reducing employee injury rates?	Tested effectiveness of safety practices by using them as injury predictors	Limited the test to a hospital environment, Did not prove that these safety practices could work for all risk categories
[14]	Visual factory: Basic principles and the 'zoning' approach?	Identified importance of visual communication of risk	Failed to provide the applications of their findings

[71] focused on identifying safety practices that reduce the frequency of occurrences of manufacturing risks by conducting tests to see how these practices could act as predictors of

injury rates. On the other hand, [14] identified training, teamwork and facility design as the ways of transmitting risk information through the work area. They classified the information channels based on the functions performed by the worker. While these safety practices may be effective in mitigating certain risks, they may not be ideal for a different type of risk. Since these studies fail to map the benefits of these safe practices to specific incidents, their performance under different scenarios is unexplored.

2.1.3 Common management policies to reduce mobile entity interfaces

Table 2.3: Summary of past research efforts towards the common management policies to reduce mobile entity interfaces

Author, Year	Title	Advantages	Research gaps
[71]	Organizational safety: Which management practices are most effective in reducing employee injury rates?	Highlighted the importance of correctly designing incentive programs to avoid accidents	Fails to map the design benefits of incentive programs with accidents
[37]	Disability management, return to work and treatment	Introduces concepts of comprehensive workplace disability management programs and its ability to prevent specific injuries	These programs cannot prevent ad-hoc accidents such as mobile entity interfaces

[71] focused on identifying safety practices that reduce the frequency of occurrences of manufacturing risks by conducting tests to see how these practices could act as predictors of injury rates. On the other hand, [14] identified training, teamwork and facility design as the ways of transmitting risk information through the work area. They classified the information channels based on the functions performed by the worker. While these safety practices may be effective in mitigating certain risks, they may not be ideal for a different type of risk. Since these studies fail to map the benefits of these safe practices to specific incidents, their performance under different scenarios is unexplored.

In order to reduce the impact of mobile entity interfaces, safety experts in manufacturing industries introduce concepts to influence the worker behavior towards safety through short-term disability plans [37], providing safety awards [71], or by involving the workers directly by increasing the risk awareness. Short-term disability plans pay workers for short-term absences from the workplace for non work-related causes. While these may motivate workers to avoid certain risks, they cannot change the responses of an impending threat caused by another entity. Safety awards provided to workers for safe practices may help them have a positive outlook towards the company's involvement in safe practices. However, they still do not help them prevent risks. This can be achieved through providing them with the right risk information to act upon such situations.

2.1.4 Risk awareness tools

Table 2.4: Summary of past research efforts towards risk awareness tools

Author, Year	Title	Advantages	Research gaps
[38, 21]	'Diagnosis of safety culture in safety management audits' and 'Performance evaluation of process safety management systems of paint manufacturing facilities'	Evaluated benefits and shortcomings of safety audits	Audits were found to be complex and hence could not be used to improve workers' risk awareness
[21]	Performance evaluation of process safety management systems of paint manufacturing facilities	Evaluated benefits and shortcomings of safety manuals	Manuals were not adaptive to new risk information and hence presented outdated information
[14]	Visual factory: Basic principles and the 'zoning' approach?	Evaluated benefits and shortcomings of safety training	Training was cost intensive and was considered passive since it could not be frequently repeated
[68, 46]	'The Functions of Visual Management' and 'The visual communication of risk'	Highlighted key benefits of visual tools in risk communication	Failed to leverage these benefits to mitigate mobile entity interfaces

Risk awareness can be created through several ways. Some of the most common ones are mentioned by [14]. These include:

1) Conducting safety audits and providing their reports: Safety audits are a compilation of work observations during plant tours which provide details on the safety measures implemented in the work areas [38]. They use injury frequency rates or injury severity rates to present the current safety status of the work area. While audits may provide a current safety scenario to the management, they are never provided to the personnel who are under the risk of these interfaces [21]. Even if they were shared with the personnel, they are complex and difficult to understand. Besides, the injury rates

do not really provide the management with any information for improvement of the current scenario [14]. They possess the same problems of resource crunch as training.

2) Providing manuals of safety guidelines to the employees: Manuals of safe work operation are detailed documents which provide the workers with an insight into safety procedures and practices that are expected of them [21]. While these are less cost-intensive, they are not adaptable to the changing environment at the facility. They have the potential to partly/completely be outdated due to newer technology being introduced in the work-areas or due to changes in the work-area itself. Like audits, these prove to be passive sources of information communication. This means that they do not allow for feedback to be easily incorporated and hence the communication channel is 1-way.

3) Training of employees: Training is the most common tool used to acquaint new employees with the safety procedures followed in the work area. Training is a simple way of delivering this information and can be modified more easily. While this is a necessity for new employees to familiarize themselves with the work-area and know the safety standards and protocols of the plant, it cannot be a long-term option. Training is rarely repeated as it would lead to loss of production hours for the personnel [14]. Training requires resources such as personnel for training and, time off production hours to conduct training, planning towards training and its schedule and, training tools. If training can allow for feedback and change based on the feedback from the workers, it can be more active than manuals or audits. However, this is time-consuming and rarely practiced.

4) Placing visual tools at select areas of importance: [68] show how visual tools help in creating an environment where there is shared ownership of tasks through the transparency of information. This encourages employee participation in the work area. With the advancement in technology, several attractive visual tools are available in the market. One of the benefits of using these tools is that they can instigate responses better than the other alternatives as they are more noticeable and attractive [14]. The use of technologically advanced visual tools minimizes computation efforts [46].

This can be extremely helpful in allowing an employee in a risky situation, take the appropriate course of action to avoid the risk. They are free-form in nature. This requires a careful planning on their selection and placement in a work area.

2.1.5 Visual tools research

Table 2.5: Summary of past research efforts towards the identification of variables and practices that lead to unsafe workplace accidents

Author, Year	Title	Advantages	Research gaps
[12]	Implementing 5S: To promote safety & housekeeping	Found visual controls to enhance understanding of safety information	Failed to demonstrate this using a case study
[27]	Behavioral correlates of individual differences in road-traffic crash risk: An examination of methods and findings	Linked visual communication of risk to accident and environment factors	Did not talk about the design of visual tools to communicate the risk information under distractions
[74]	Guided search 2.0 a revised model of visual search	Found visual tools to grasp the attention of a worker among all other information channels	This potential benefits of visual cues being the most identifiable were not tapped into to convey risk information
[46, 31]	'The visual communication of risk' and 'Designing visual aids that promote risk literacy: A systematic review of health research and evidence-based design heuristics'	Focused on how data could be represented using charts, histograms, etc.	This research is not at par with the available technology and the communication of risk information using digital modes and audio indicators
[55, 68]	'Application of lean visual process management tools' and 'The Functions of Visual Management'	Found visual tools to create transparency and shared ownership	Failed to map these benefits to specific functions
[14]	Visual factory: basic principles and the'zoning'approach	Attempted to assign visual tools by classifying work areas as zones	Assumed risk information to be standard and not varying over time

Visual cognition of risk information

Visual controls have been found to enhance safety programs in manufacturing facilities by making information easily understandable to even those who may be unfamiliar with their surrounding environment [12]. It is important to understand what guides the successful understanding of the risks, to be able to leverage the benefits of these visual tools in a mobile entity interface setting. This relies heavily on the understanding of visual psychology and understanding of risk information using these tools.

[27] studied roadway crashes to find that slower detection of hazards were associated with higher crash rates. This detectability of risk information was also linked to several driver, as well as, environmental factors. It was also concluded that, of all the measures, visual attention to risk had the highest correlation with crash rates. While these results were useful, corresponding solutions to combat these rates were not presented.

[74] proposed a theory on visual search that helps us understand that risk information disseminated using visual tools can be effectively identified in manufacturing environments. They propose that when the visual cues have certain distinctive features from their surrounding environments, they can be easily noticeable. For example, if a visual andon delivering risk information about mobile entity interfaces was placed next to a board that displayed standard information found in manufacturing work areas, such as quality issues identified, it is easy to efficiently locate and understand the risk information. This can be achieved since visual tools display information in using flashy messages, colorful boards, coded sirens or alarms and painted markings, that is normally not seen in the other information present in a manufacturing work area. Hence, there is a lack of distraction from this sort of risk information, and the target messages can be identified.

Comparison of data representation techniques of risk information

Studies by [46] and [31] which focused on visual tools to be the best forms of risk communicators, mostly only focused on the effective representation of the data to be communicated through different forms. [46] mainly critiqued tools such as histograms, risk ladders and pie charts to represent risk information. Similarly, [31] studied influence of the numeracy on risk literacy in a hospital environment. Since this area of the research has barely made advancements with the growing technology, its contributions are insufficient [31]. For example, understanding the performance of risk ladders over graphs may have been beneficial when charts or control boards were primarily used to highlight risk information. However, with the introduction of automatic and digital visual tools such as andon boards, the past research has limited applications. Their relevance is further questionable due to the presence of standardized warning signs and codes.

Benefits of visual communication

On the other hand, [68] and [55] identified the benefits of visual communication. [68] highlighted benefits such as transparency and creation of shared ownership through visual tools. [55] spoke about the applications of these tools in increasing the productivity of work areas. However, they failed to map these benefits to specific functions, such as mitigating mobile entity interfaces.

Methodologies in visual tool assignment process

There exists very limited research that tries to assign visual tools to select work-areas in manufacturing industries. The closest work is by [14]. This paper divides the work-area into several zones. While a plant worker usually moves on a horizontal axis that defines a specific work area by function, its main communication sense, vision, and the workers manual operations are extended and executed vertically, that is on vertical surfaces [14]. While this hints at the investigation of variables, it does not take into account that each node in a work-area has a different value for each of the variables. It categorizes information as standard and variable, and maps zones to the information types identified based on function of the zones without providing any validation on its classification or mapping technique. It also does not link a specific tool to a work-area. However, the most alarming issue with this research is its assumption that safety information is standard, and not variable. This is not true as mobile-entity interface related information can change based on the course traveled by all entities at a particular instance.

2.1.6 Research gaps that contribute to the visual tool assignment approach designed for the presented work

All the previously mentioned research focuses on just identifying the variables but did not combine them into a framework that would lead to pick a visual tool. [3] talks about identifying the varying levels of variables that actually qualify them as threats. It talks about mapping these variables to specific events to reduce the likelihood of its occurrence. In order to assess the vulnerability of the system, it focuses on building scenarios and filling

Table 2.6: Summary of past research efforts that contribute to the visual tool assignment approach designed for the presented work

Author, Year	Title	Advantages	Research gaps
[3]	Assess the vulnerability of your production system	Identified that variables must cross a thresh-hold to qualify as threats	Their methodology did not compare each variable against the other variables
[60]	How to make a decision: the analytic hierarchy process	Proposed a multi-criteria decision-making tool that can assign visual tools to work areas by comparing variables	This tool has not been leveraged to make the visual tool assignment

out risk rating forms to critically rank the variables and assess their impacts. However, this does not account for the relative importance of one variable over another in a certain scenario.

Using a multi-criteria decision making tool such as Analytical Hierarchy Process (AHP), proposed by [60] we can observe the relative importance of variables in different scenarios and map the visual tools to work areas using the obtained weights of the variables. The use of AHP has been common in the past [61] [70] as a decision making tool due to its simplicity. A large number of comparisons due to a large number of constraints has been identified as one of AHP's shortcomings. Table 3.1 has identified 10 variables and since the methodology proposed below uses 3 alternatives and 3 scenarios, this leads to each respondent answering to 225 questions. However, [62] has clearly stated that by limiting the number of criteria used to 7 ± 2 would still allow us to get favorable responses to our AHP. The methodology proposes the use of ANOVA and DEA to limit the number of criteria used in the AHP by creating a subset of the variables.

Chapter 3

Model Formulation

The focus of this research is to systematically assign visual tools to manufacturing work areas to increase the workers' risk awareness about mobile entity interfaces. The foundation for the conceptual framework and survey are presented in this chapter. In this chapter, the representation of work areas using nodes is discussed in detail. This is followed by the selection of work area and entity variables that are peculiar to mobile entity interfaces. The next section methodically abridges the visual tools.

3.1 Work area representation

Manufacturing work areas often comprise large physical spaces, which are divided according to functions. Departments such as the production, warehouse and quality are placed adjacent to one another within this large space. While there are similarities among these functions, they are affected by different types of risks. For example, the break room may have a greater probability of "trips" due to food spillages, while a shipping area may have a greater probability of a "mobile entity interface". Hence a different visual tool would be required to mitigate risks in each work area.

[14] demarcated "zones" within a large work area to make the design of visual communication systematic. The logic used for the demarcation was that while a worker moved along the horizontal work area marked on a plant view, their main interactions with

various risk variables are extended along the vertical surface of the plant view. The research on zones was developed for process-related visual awareness.

However, to better suit mobile entity interfaces, specific locations in the work area called **"nodes"** are identified in the presented study. A node is a specific location which sees a heavy material movement, such as traffic intersections, pedestrian crossings, an entry point into the work area, etc. The placement of visual tools at select nodes is beneficial to the reduction of accident frequencies. For example, warehouses may have the maximum mobile entity interfaces. In the traditional approach, this would mean that visual tools could be placed at any location within a warehouse, which may not efficiently increase the workers' risk awareness. For instance, a particular aisle where the visual tool is placed, may not even have the maximum entity movement. However, using the proposed study, several key nodes can be identified. This helps in narrowing down a more specific location where the visual tool may be best suited. By placing the visual tools at a node which may have a higher chance of experiencing a mobile entity interface as opposed to a random point within the warehouse, there is a more efficient risk awareness created. Tools such as FMEA [48], when coupled with the node creation, can be helpful in identifying and selecting nodes with the highest mobile entity interfaces.

There is a clear distinction in variable states across nodes in large manufacturing work areas. For example, a node near a gate will experience a lower temperature due to good ventilation than a node near a heavy production equipment such as a furnace. The presented study hypothesizes that work area and entity variables affect visual tool assignment decisions. For example, Figure 3.1 depicts the nodes that were presented in our survey. Node 1 was marked as an area of moderate visibility and of a low natural lighting. The node was also marked as a noisy node. While these attributes might make the variables of visibility, lighting and noise level, important in this case, they are not as important at other nodes. On the contrary, the information provided for Node 2 describes that there is ample lighting in the area and good visibility, however there is still a bad noise level. Further sections of the presented study observe how these different scenarios create a preference for one type of visual tool over another.

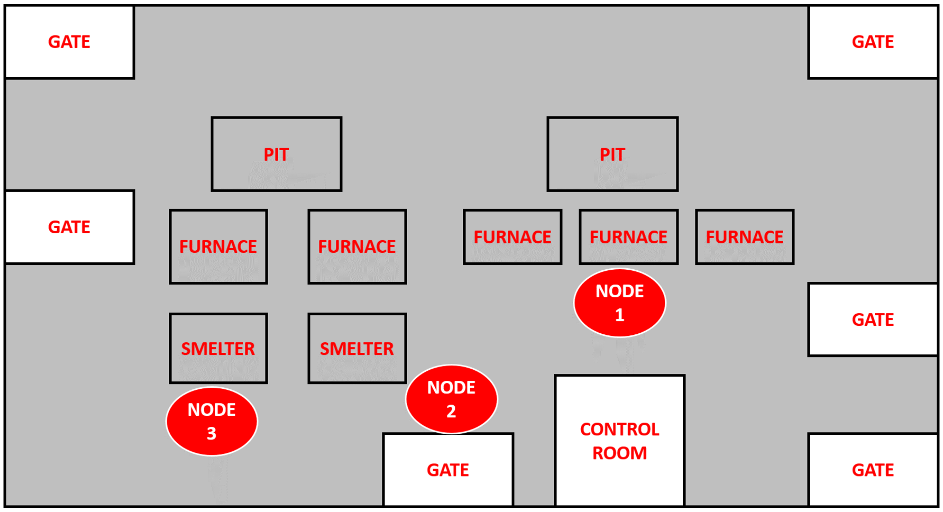

Figure 3.1: Work area representation highlighting the three nodes considered for scenario-building

The proposed study is based on three unique hypothetical case nodes. Each node is designed to account for variable attributes. Figure 3.2 presents how nodes are defined for the presented study. Chapter 4 describes the scenarios of each node in detail.

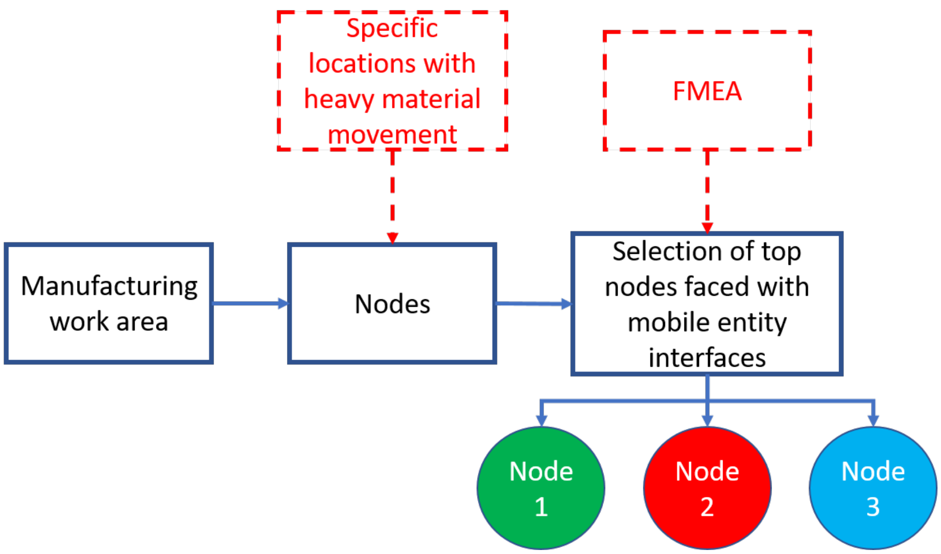

Figure 3.2: Process involved in defining nodes for the presented study

3.2 Selection of variables

As pointed out in chapter 2, to assign the right visual tool to a node it is important to study work area and entity variables. Figure 3.3 highlights how variables from the literature were selected to make them apt for the visual tool assignment framework. These variables were selected due to the following properties:

- Their repeated occurrence in literature
- Their connection with the visual tools selected in this study
- The causal relationship between the variables and a manufacturing work area
- Their influence in mobile entity interfaces

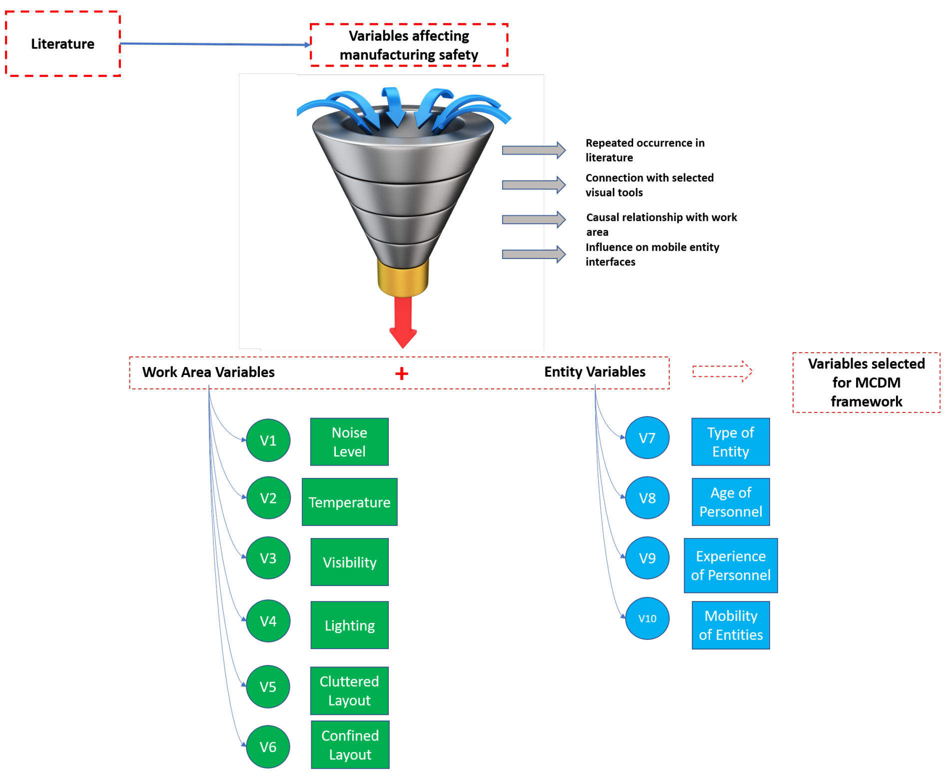

Figure 3.3: Process involved in selecting work area variables

3.2.1 Work-area variables affecting mobile-entity interfaces

1) Noise Level: Studies have shown that when the noise level exceeds an acceptable value, there is a greater chance of a risk [35, 11, 22]. It also distracts employees from paying attention to audio andons in the work-area.

2) Temperature: [42, 11, 22] discuss how an increased temperature leads to fatigue and distracts the worker from their task. It is also important to note that in several manufacturing industries, higher temperatures worsen the visibility of the area.

3) Visibility: [66, 42] state that obstructed vision is a common reason for errors and over-sights, hence adding to the risk of accidents.

4) Lighting: The use of natural versus artificial lighting, the amount of lighting in an area and the kind of lighting used can affect a person's ability to concentrate on a task and to view safety instructions ahead of them [16, 65]

5) Cluttered Layout: One of the highest causes for severe and fatal injuries is the workplace layout [19]. [65] break this down into the cluttered layout and confined layout. The cluttered layout refers to the area that has several objects such as machines, parts, people, and tools restricting a free movement of an entity.

6) Confined Layout: This refers to narrow and confined passageways in work-areas, making it harder for larger entities to move freely and makes it harder for multiple entities to cross.

3.2.2 Entity variables affecting mobile-entity interfaces

1) Type of entity: [11, 42] and [22] highlight the importance of knowing the entities involved in the node.

2) Age of personnel: The age of personnel impacts the probability of a worker being involved in a risky situation due to their ability to process risk information [65, 42].

3) Experience of personnel: This determines the familiarity that one has with the work area and the safety practices enforced in the area, and hence is a reflection upon the attitudes of workers towards safety [65, 42].

4) Mobility of entities: This mainly refers to the frequency with which the mobile entities travel and their freeness to travel during that time [11, 16].

Table 3.1 highlights past research that supports the selection of the above work area and entity variables.

Table 3.1: Past research supporting the selected work area and entity variables

No.	Variable	Literature sources
1	Noise Level	[65]; [35]; [11]; [22]; [57]; [34]
2	Temperature	[42]; [11]; [16]; [22]; [65]; [64]; [34]
3	Visibility	[66]; [42]; [22]; [65]; [11]
4	Lighting	[16]; [65]; [11]; [34]
5	Cluttered Layout	[16]; [19]; [65]; [34]
6	Confined Layout	[16]; [19]; [65]; [34]
7	Type of Entity	[42]; [11]; [16]; [22]; [65]
8	Age of personnel	[42]; [65]; [19]; [64]
9	Experience of personnel	[42]; [65]; [19]
10	Mobility of entities	[11]; [16]

3.3 Visual tools classification

Risk awareness takes place by placing visual tools in the work area. To select the best tools for a given work area, the safety incidents which influence the performance of these tools, must be specified. In the presented study, we select mobile entity interfaces as our safety incident, in order to increase risk awareness about them. Figure 3.4 highlights the choices available for visual tools.

There are two modes of communicating risk related information. The communication can be done using passive or active risk communication tools. While chapter 2 discussed the merits and demerits of the specific active and passive tools, the following section clearly maps the reason we pick active risk communication tools with the object of the study.

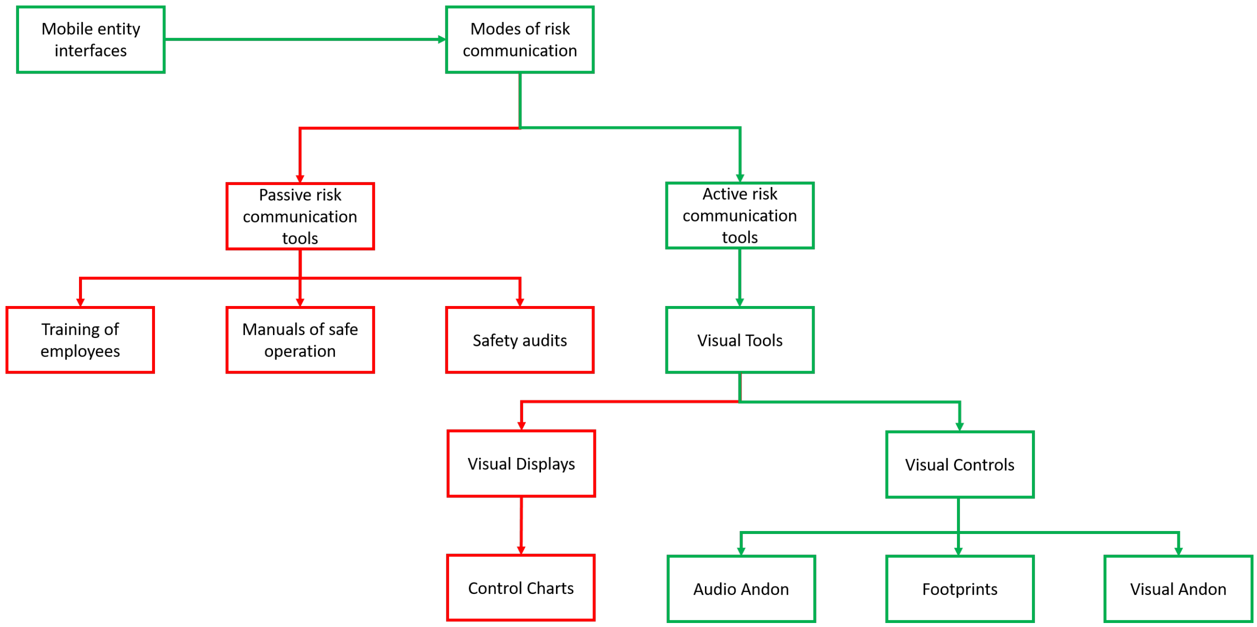

Figure 3.4: Classification of modes of risk communication

Passive risk communication tools preach caution. However, they do so using subtle approaches. Since workers in manufacturing work areas exhibit risk-taking behaviors [20], they ignore such information. This calls for a more aggressive awareness tool in the form of active risk communication as they constantly prompt workers to take safe measures. Some of the reasons supporting the choice of active risk communication over passive risk communication are highlighted in figure 3.5:

Criteria	Passive	Active
Repeatability	Rarely repeated	Quick change of information
Flexibility of information presented	Information change requires over 1 month	Information change can take place almost instantly
Influence over a worker's behavior	Information is often ignored due to workers' attitudes and lack of memorization of safety practices	Worker's notice information and take mitigating steps to avoid risk

Figure 3.5: Comparison between passive and active risk communication tools

Active risk communication can be done in the form of visual tools such as visual displays and visual controls. While visual displays improve the worker's understanding of risks in work areas by providing them with risk information, visual controls influence a worker's behavior directly [46], making them more active in comparison. Figure 3.6 shows a control board, which is an example of a visual display. These improve a worker's understanding of risks which occurred at the node at which they are placed. However, this may not necessarily prompt a safe response from a worker at that node. On the other hand, the audio andon depicted in figure 3.6 is a form of a visual control. These trigger the necessary safe responses when they are activated appropriately. For example: A crane operator can be alerted about the presence of a pedestrian near the crane at a node, by sounding an alarm. This may help the pedestrian change their direction or sensitize the crane operator to the presence of the pedestrian at the node. Since visual controls display a close linkage between risk awareness and risk mitigation, they become the subject of focus in this research.

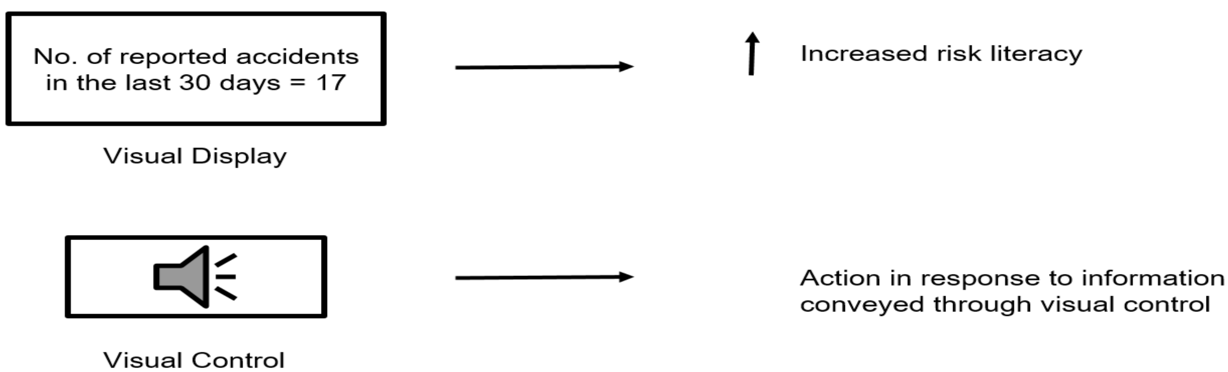

Figure 3.6: Examples of a visual display and a visual control

Three visual tools are selected in this study from different categories. They differ in their usability in a manufacturing work area. The following are the features that distinguish them from one another:

- Visual Andon: These are manual or automatic systems of signals that indicate a problem. The visibility of the incident makes them more traceable.

- Audio Andon: These are easy to install and trigger. They may use coded tones corresponding to different alerts.

- Footprints: These are markings on the floor which outline the boundaries that people, vehicles, and materials must adhere to. They are relatively cheap visual tools which have been in usage for long.

Chapter 4

Methodology

4.1 Introduction

This chapter illustrates the research design of the study which abridges the disconnect between the research goals and previous work. The visual tool assignment for mobile entity interfaces at the specified nodes requires the following considerations:

- The relative impact of the work area and entity variables on work area safety should be studied
- A framework to systematically map visual tools to work area nodes should be developed
- The expertise of safety managers should be leveraged

4.2 Visual tool assignment framework

Figure 4.1 represents the visual tool assignment framework that connects the work area representation, variable selection and visual tools classification from chapter 3. The visual tool assignment framework is predicated on the idea that variable states differ from node to node. Hence, the selection of nodes become the first step in the approach. The varying states of variables at each node can be designed to build three scenarios where visual tools must be assigned. Work area and entity variables act as the criteria that should be considered when assigning visual tools to each given node. The active visual tools are the available alternatives for this decision-making process. When these components are combined together, they can be used to assign a visual tool to a given node using a multi-criteria decision making framework. Further sections of this chapter discuss this in depth.

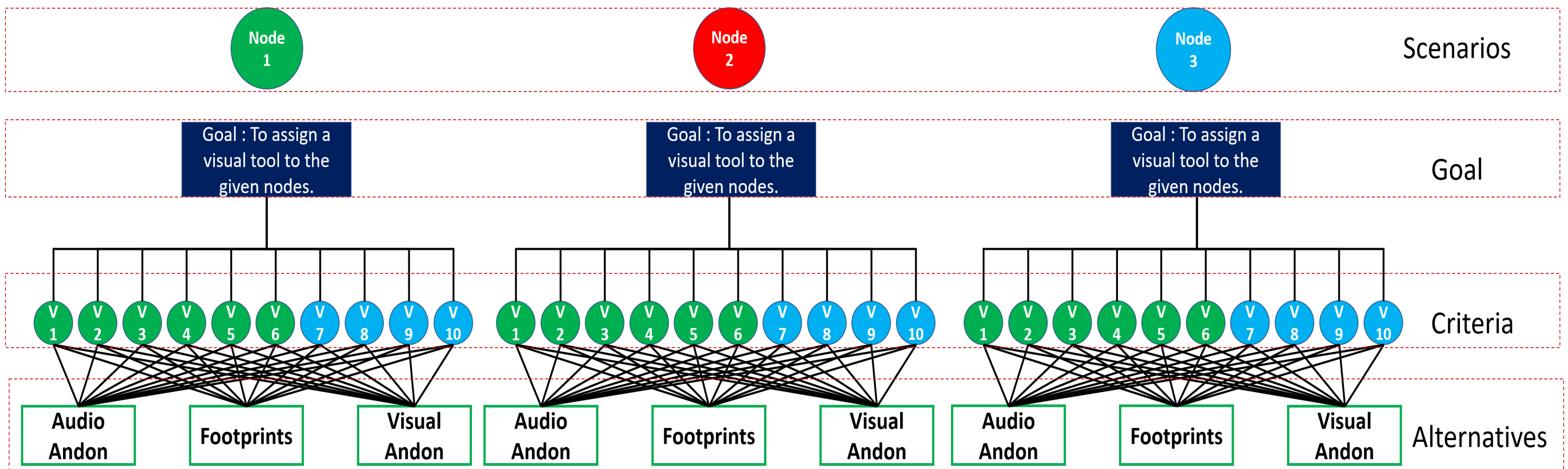

Figure 4.1: Visual tool assignment framework to increase risk awareness about mobile entity interfaces

4.3 Multi-criteria decision making

The assignment of visual tools is conducted by identifying the work area and entity variables and studying their relationship with each other. This decision is made by administering a survey to safety experts in manufacturing industries and asking them to compare each pair of variables and visual tools. This is a multiple criteria decision making (MCDM) problem, since [69] identified MCDM as a branch of decision-making that typically has predetermined goals and alternatives. It generally relies on the decisions made by experts in a certain field of study. The alternatives are screened, prioritized and ranked through the different techniques under MCDM by these experts.

Analytical Hierarchy Process (AHP), proposed by [59] is an MCDM technique that allows people to make logical decisions by organizing the judgments to be made in a hierarchical structure. Of the different types of MCDM approaches, AHP is most suitable due to its ability to work with quantitative and qualitative data and its simplicity to interpret the results [60, 70].

AHP uses a survey-based approach to allow experts to reach a goal by assigning an alternative through the comparison of the criteria affecting the decision. This approach applies to the visual tool assignment problem, where the variables act as the criteria and the visual tool options act as the alternatives. Priorities for the criteria and the alternatives are created by judging them in pairs for their relative importance. This creates pairwise comparison matrices. For the comparison of n elements,

$$\frac{n(n-1)}{2}$$

judgments are required [59].

In implementing AHP for the three scenarios presented in this study, the respondents make pairwise comparisons for a set of 10 variables and 3 visual tools.

For the criteria-criteria comparison -

$$\frac{10 \times 9}{2} = 45$$

judgments are made for each node.

For the alternative-alternative comparison -

$$\frac{3 \times 2}{2} = 3$$

judgments are made for each criteria at a given node.

For 10 such criteria, the judgments for alternative-alternative comparison at a node are -

$$3 \times 10 = 30$$

The total number of judgments made by the respondents for all 3 nodes are -

$$(45 + 30) \times 3 = 225$$

[62] identified that such large number of decisions pose a limitation on the cognitive spans of the survey respondents. Hence, it reduces the validity of the data obtained. To overcome this difficulty, the set of variables to be considered for this study are limited to to 7+/-2. This is because [49] identified this to be the upper limit on the number of questions that a respondent could handle, without losing the validity of the data. If the number of criteria were limited to 7, then responses would have a higher consistency, since the respondents would have a higher ability to process the given information. This increases the reliability of the obtained data set [62].

In order to reduce the set of variables to a smaller subset of 7 or less variables, a preliminary survey is built. This survey asks respondents to identify the variables that they believe would be most relevant to the selection of the visual tools for each node. This feeds into the second survey. The second survey requires safety experts to make pairwise comparisons for every pair of alternatives and visual tools. The outcome of the second survey is a visual tool assignment for each node. These surveys are detailed in the next sections.

Figure 4.2 demonstrates the research methodology that is developed to use the principles of MCDM to reach the goal of visual tool assignment in manufacturing work areas.

4.4 Scenario Design

The scenario setup is the core of the surveys. There was a common structure of the survey used in all the surveys administered, with the core remaining unchanged. The survey was then customized for three groups of respondents to be able to provide an appropriate input for the techniques used.

4.4.1 Case development

The visual tool assignment framework is designed and validated using a scenario-based survey design [11, 2]. In this approach, respondents are required to assess the safety scenarios of a hypothetical work area. Hypothetical work areas allow the designing of risky situations and incidents. This in turn allows the testing of the presented methodology without the risk of injuries. This may have occurred if the framework was tested at a single facility. This is because all of these risky situations may not have been observable inside a single facility in a reasonable period. During the testing phase, injuries could also occur due to the placement of a wrong visual tool at a node.

Figure 3.1 is the hypothetical work area, considered in this study. This work area was designed to replicate a heavy manufacturing company where a similar research project was undertaken to increase the work area safety by reducing the number of mobile entity interfaces. Minor modifications were made to the scenarios to maintain anonymity of the said company. The following characteristics are assumed in the scenario design, to make it apt for the study-

- The work area resembles a heavy manufacturing facility.
- The work area has frequent mobile entity interfaces due to movement of vehicles in the proximity of human operators performing functions in the work area.
- Internal lanes are designed for the easy movement of materials. This increases the probability of mobile entity interfaces, which result in severe accidents.
- Variables have different attributes at each node. For example, a node near a furnace may experience higher temperatures than a node near a break room.

In order to capture the differences between the nodes, three nodes with variable attributes were designed to emphasize on the inter-nodal differences. Figure 4.3 portrays the differences that were introduced in each scenario. Every variable was designed to have some characteristics that were not favorable at all node. The nodes were designed to have differing levels of favorableness for multiple variables. These differences were then translated in terms of a scenario description for the survey participants.

Table 4.1 is an overview of the scenarios provided to the respondents for the 2 surveys. The correlation between the scenarios and the visual tool preferences were noted after the survey data was analyzed, to support the hypothesis presented in chapter 3.

Table 4.1: Scenario overview for the three nodes

No.	Variable	Node 1	Node 2	Node 3
1	Age of personnel	Old Personnel	Young Personnel	All age groups
2	Experience of personnel	Highly experienced	Part time employees	Experienced Personnel
3	Noise Level	Noisy, ear-plugs required	Random loud noises	Noisy due to maximum entity movement
4	Temperature	High temperature causing heat stress	Low temperature due to gate	High temperature due to smelters
5	Type of Entity	Metal hauler, 18 wheeler, pedestrians	Metal hauler, 18 wheeler, skim truck, pedestrians	Metal hauler, pedestrians, overhead crane
6	Mobility of entities	High frequency	High frequency due to gate	Maximum entity movement
7	Visibility	Moderate	Good	Low visibility
8	Lighting	Lower since machines block light	Ample and natural lighting	Artificial lighting
9	Cluttered Layout	Machine and mobility add to clutter	Not cluttered	Cluttered due to machines and metal
10	Confined Layout	Spacious due to gateway and walkway	Narrow and confined pathways	Narrow and confined pathways

4.4.2 Setup of survey structure

Respondents were provided the aim of the study so that they could understand their role in the survey. They were presented with the objective that they were required to have in mind while answering the survey. It was believed to be important to do so since a hypothetical case study was used in the presented research.

The overview of the hypothetical manufacturing facility provided them with a detailed description of the plant layout. This included information on the size of the facility, the different mobile entities flowing through the facility, and a simple description of the work areas found in the facility. These work areas had distinct functionalities that could affect the attributes of some variables. For example, a node near the furnace will experience a higher temperature than one near the gate. For each node, a diagram of the layout was provided, which highlighted the node within the work area. This would enable the respondents to visualize the possible movements of the entities and the influence of the variables.

Respondents were also required to take a note of the past interfaces reported. Having background information on these interfaces would allow them to understand the impact of the type of entities flowing through the system. For example, an area with forklifts, overhead cranes and pedestrians may have had past interfaces only between overhead cranes and pedestrians. Hence the choice of the visual tool may be designed from the perspective of on-ground pedestrians as the over-head crane operator is also a pedestrian.

4.4.3 Pre-testing the survey

To ensure consistency in responses, the survey was pre-tested. [53] used a 3-step process to pre-test the survey. They administered the survey to two different groups of experts in the first two steps, which brought them clarity on the script of the survey. Next, they provided the survey to some more experts to make minor modifications to their survey, till the point that there was no further clarification required by the group. This approach was used in the presented study, to ensure that the respondents had the same understanding of the variables used and the functions of a work-area.

In the pre-testing phase of this study, respondents were asked about the phrasing, explanation and the length of the survey questions. Respondents were also asked about their ease of understanding the Likert Scale used in the survey. Minor changes were made based on the feedback received from them. The final survey was then administered to 24 industrial engineers [67].

4.4.4 Survey Considerations

The survey instrument and the data collection method was reviewed and approved by the Institutional Review Board of the University of Tennessee - Knoxville (see Appendix C.1). Participants were informed that their participation in the survey was voluntary. No personal information was collected from the participants about them or their company, to assure them that their responses would remain confidential. A consent statement was attached to the web-based survey (see Appendix C.2). Participants were asked to review the consent statement. Participants were then asked if they provided consent to answer the survey and were required to answer by selecting either "yes" or "no". If they chose the option yes, they could continue filling the survey. If they chose the option no, the survey would end without allowing them to respond any other question.

4.4.5 Survey population

Since the two surveys had a different goal, the survey populations had different criteria to meet. Figure 4.4 highlights the expectations from the survey respondents. While survey-1 could be answered by an industrial engineering postgraduate student, with a past industrial experience, survey-2 required a more proficient group in the area of manufacturing safety. Hence safety experts were contacted for the survey-2. This decision was supported by consulting a survey and statistics expert at the University of Tennessee's OIT department.

4.5 Survey - 1

4.5.1 Data Collection

The data was collected from a group of 24 industrial engineering postgraduate students, over a period of 3 days. The survey would take approximately 25 minutes to complete. To maintain clarity, participants were briefed about the intent of the study and the use of the 5-point Likert scale.

After reviewing the case description highlighting the attributes of each node, respondents were asked to answer if the variables can be included in a visual tool assignment algorithm so that risk awareness at the node is increased (Table 4.2). They were required to score their decision on a 5 point Likert scale. The 5 point Likert scale is used in support of the findings by [47], who conducted a Monte Carlo simulation to find this scale reliable.

4.5.2 Data Coding

The survey instrument was administered using printed data collection templates. The survey responses were manually entered into an MS-Excel Workbook. Rows A2 - A11 had the variable names. Column B2 - B11 stored respondent 1's scores for the corresponding variables, C2-11 stored respondent 2's scores for the corresponding variables, and so on, till column Y2 - Y11, which stored respondent 24's scores for the corresponding variables. Each node's data was stored on a separate worksheet. Since the responses were to be tested under different tools and by different softwares, the data required some formatting. The data coding steps were as follows:

1) Create new sheets. Sheet 4, 5 and 6 are generated to store the responses received for nodes 1, 2 and 3, for testing the responses with ANOVA, using SAS Enterprise Guide.

2) Create independent variable column. Cell A2 was selected from sheet 1 and pasted at the position A1 on sheet 4, 5 and 6. This cell was copied and pasted from cell A1 to cell A10. Cell B2 was selected from sheet 1 and pasted at the position A1 on sheet 4, 5 and 6. This cell was copied and pasted from cell A11 to cell A20. Similarly, all the variables from sheet 1 were copied and pasted in 10 cells at column A of sheets 4, 5 and 6.

3) Transposing the data. All the scores of each variable were selected and pasted from rows of sheets 1, 2 and 3 to corresponding columns of sheets 4, 5 and 6. For example, cells B2 - B24 were copied from sheet 1 and pasted as cells B1 - B10 on sheet 4.

4.5.3 Data Screening

Data screening is an important step to avoid the influence of invalid data on the results. This section deals with un-engaged responses and missing data.

1) Unengaged responses: It is necessary to flag off and omit the un-engaged responses from the study, as they affect the results. As the responses were collected manually, all survey sheets that were not returned during the study period, were not considered

for the study. 24 out of the 25 responses were returned. Hence only 1 un-engaged response was found.

2) Missing data: Missing data entails missing values in the columns of the responses. Since the data entry was manual, this was detected during the data entry phase. 3 missing values were identified in node 1, 1 in node 2 and none in node 3. Respondents were contacted and asked if they would prefer going through the scenario again and provide the missing score. 100% respondents agreed to do so. Hence, there were no missing responses.

4.6 Variable Reduction

To reduce the set of variables from 10 to 7 ± 2, the responses of the first survey were analyzed using ANOVA and Data Envelopment Analysis (DEA). ANOVA finds several applications in reduction of variable sets by testing the equality of population means [15]. On the other hand, DEA tests the efficiency of variables using the survey responses, by eliminating least efficient variables.

Due to ANOVA's simplicity, the variable set is tested through ANOVA first. If ANOVA does not satisfy the condition of providing 7 ± 2 variables (as shown in figure 4.5), then DEA can be used to reduce the variable set. The resulting subset of variables from these studies act as the criteria of the AHP.

4.6.1 ANOVA

Analysis of variance (ANOVA) is a popular tool used to analyze survey responses which aim to study the relationship between factors and to determine their level of differences [15]. In its simplest form, ANOVA tests the equality of population means, hence generalizing the t-test to more than two groups [52]. While more than two t-tests can achieve the results, they lead to a higher Type I error than the α value set for the t-test. Hence, ANOVA considers all the population means under a single null hypothesis. However it requires the following conditions to be satisfied -

1) Each of the populations has a normal distribution.

2) The variances of the populations are equal.

3) The sets of measurements are independent random samples from their respective populations.

The null hypothesis for a one-way ANOVA is that $\mu_1 = \mu_2 \cdots = \mu_t$, where μ is the sample mean of a population t.

The alternate hypothesis is that at least one of the t population means differs from the rest.

ANOVA determines the ratio of the means squares between the samples and the mean square within the sample to determine the test statistic, which can be represented using equation 4.1.

$$F = s_B^2 / s_W^2 \tag{4.1}$$

The F ratio assumes a value close to 1 when the null hypothesis is true, since both the numerator and denominator are estimates of the same quantity, i.e., the variance of sampling errors. However, under the alternate hypothesis, the F ratio is larger than 1, due to the differences between the population means.

4.6.2 DEA

DEA is a non-parametric methodology based on the applications of linear programming [67]. In past research, it has been employed for assessing the relative performance of a set of companies, usually called "decision making units" (DMUs), which use a variety of identical "inputs" to produce a variety of identical "outputs" [23]. DEA can give a single index of performance, usually called the "efficiency score", synthesizing the diverse characteristics of different DMUs. Due to this ability, DEA has found several industrial applications [44, 5, 10, 6, 7, 8, 9].

DEA has two major models include CCR and BCC models. The CCR model has a constant return to scale and the BCC model has a variable return to scale. This means that under the CCR model, for every change in input, there is a proportional change in output. On the other hand, in a BCC model, for every change in input, there is a variable change in output. In this study, the results are obtained by the CCR model as the study has a constant return to scale. A brief explanation of CCR is as follows:

Assume that there are n DMUs which convert i input to j outputs. In particular, the mth DMU produces outputs y_{jm} using x_{im} inputs. To measure the efficiency of this conversion process by a DMU, a fractional mathematical programming model, denoted by equation 4.2 is proposed. The objective function of the model is to maximize the ratio of weighted outputs to weighted inputs for the DMU under consideration. It is subject to the condition that similar ratios for all DMUs are less than or equal to one. Hence:

$$
\begin{aligned}
&\text{Max}\frac{\sum_{j=1}^{J} v_{jm}y_{jm}}{\sum_{i=1}^{I} u_{im}x_{im}} \\
&\text{Subject to: } 0 \leq \frac{\sum_{j=1}^{J} v_{jm}y_{jn}}{\sum_{i=1}^{I} u_{im}x_{in}} \leq 1 \\
&v_{jm}, u_{im} \geq \epsilon \geq 0
\end{aligned}
\tag{4.2}
$$

Where the subscripts i, j and n stand for inputs, outputs, and DMUs, respectively. The variables $v_{jm}$and u_{im} are the weights to be determined by equation 4.2. The term is an arbitrarily small positive number introduced to ensure that all of the known inputs and outputs have positive weight values the mth DMU is the base DMU in 4.2. The optimal value of the objective function of equation 4.2 is the DEA efficiency score assigned to the mth DMU. If the efficiency score is 1 the mth DMU satisfies the necessary condition as efficient DMU. Otherwise, it is considered as an inefficient DMU. Note that the inefficiency is relative to the performance of other DMUs under consideration.

However, it is difficult to solve equation 4.2 because of its fractional objective function. If either the denominator or numerator of the ratio is forced to be unity, then the objective function becomes linear, and a linear programming problem can be obtained. By setting the denominator of the ratio equal to unity, the following output maximization linear programming problem is obtained, denoted by equation 4.3.

$$\text{Max} \sum_{j=1}^{J} v_{jm} y_{jm}$$

$$\begin{aligned} &\text{Subject to: } \sum_{i=1}^{I} u_{im} x_{im} = 1 \\ &\sum_{j=1}^{J} v_{jm} y_{jn} - \sum_{i=1}^{I} u_{im} x_{in} \leq 0 \\ &v_{jm}, u_{im} \geq \epsilon \end{aligned} \tag{4.3}$$

4.7 Survey - 2

4.7.1 Data Collection

The target population of this study were safety experts from manufacturing industries. While the work of [53] tries to ensure consistency in responses by selecting the respondents from the same manufacturing sector, this is not required in the presented study. This is because unlike their work, this research does not require the respondents to think about the internal validity of the questions with their companies. This research focuses on a hypothetical case study to demonstrate the validity of the data. Hence, it requires the respondents to have an understanding of the terms introduced in the survey. Consistency is ensured by providing definitions, in the areas of possible discrepancies.

23 responses were collected, over a period of 1 month. The survey instrument (appendix B.1) was administered electronically, by distributing web-friendly and mobile-friendly links to safety experts. The survey would take approximately 25 minutes to complete. Participants were contacted via e-mails and were briefed with the intent of the survey to avoid any confusion (appendix D.1).

4.7.2 Data coding

The survey was administered to the participants using the University of Tennessee's Qualtrics survey software package. The responses were recorded in the Qualtrics server. The data was downloaded as a pdf and formatted for the use of AHP using the following steps.

1) Create an AHP template using MS-Excel with a 7 element square matrix, a 6 element square matrix and a 3 element square matrix for the variables in node 1, variables in node 2 and 3 and the visual tools in node 1,2 and 3, respectively.

2) Transfer scores from pdf to MS-Excel. Scores were carefully transferred from the pdf to Excel. The survey used the scale of -9 to $+9$ instead of $1/9$ to 9. Hence the data transformation required caution while converting the scores to suit AHP.

4.7.3 Data screening

Data screening was a necessary component of the study, to ensure that the data was clean and ready for analysis. The following areas of concern were resolved during the screening phase:

1) Screening for requirements: The survey required respondents to be visual tool experts or safety experts who belonged to the manufacturing industry. The first question of the survey asked the respondents if they considered themselves to be visual tool experts/safety experts. If they chose the option "yes", they were allowed to continue the survey and provide a brief description of their manufacturing sector type (optional question). However, respondents who chose the option "no" were not allowed to proceed further in the survey and their surveys were terminated. Using this filtering mechanism, 3 responses were found unfit for our survey.

2) Lack of consent: The survey required respondents to provide their consent before collecting any data from them (appendix C.2). If the respondents did not provide their consent, the survey would be terminated, thus not allowing the recording of the responses. 1 respondent did not provide their consent to participate in the survey.

3) Blank responses: 8 respondents had blank responses for all three nodes. This was automatically highlighted by the Qualtrics software. These responses were highlighted in "grey" colored font in the pdf reports. These responses were omitted from the study.

4) Missing responses: The survey required participants to answer questions about all three nodes for the responses to be considered as valid. 1 responded answered questions about node 1 and node 2, however did not respond to questions on node 3, either purposely or inadvertently. Hence this response was not used in the survey analysis.

4.8 AHP

Saaty's AHP is a widely used MCDM technique [61, 60, 59, 70, 67]. The standard AHP approach is used to reach the visual tool assignment goal.

AHP is typically performed using a standard 7-step approach [61].

1) Determine the goal of the problem.

2) Determine the criteria that must be considered to reach the goal.

3) Determine the available alternatives to reach the goal.

4) Structure the problem, representing the hierarchy of each level.

5) Conduct pairwise comparisons between criteria-criteria and, alternative-alternatives for every criterion.

6) Weight the priorities obtained using the pairwise comparison matrices for each element.

7) Obtain the overall priorities, hence ranking the alternatives available to satisfy the goal.

The following sections detail the computational steps that form the basis of AHP. The applicability of these steps to the presented study is discussed in chapter 5.

4.8.1 Single response calculations

Saaty's scale of relative importance [60] is used to guide the pairwise comparisons (shown in Table 4.3). This scale guides all the respondents through the ranking system used in the survey. This allows them to compare the importance of a variable relative to another variable or an alternative relative to another alternative, during pairwise comparisons. This scale allows a respondent to rank the relative importance between 1/9 to 9. The pairwise comparison matrices are represented as A_{n*n},

$$A_{n*n} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & \dots & a_{1n} \\ a_{21} & a_{22} & a_{23} & \dots & a_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & a_{n3} & \dots & a_{nn} \end{bmatrix}$$

where $a_{ij}, (\forall i, j \in n)$ represent the degree of importance of the i^{th} element in comparison with j^{th} element. The value of n is dependent upon the node and the type of matrix being constructed. For example, the scenario at Node 2 consists of 6 variables (criteria) and 3 visual tools (alternatives). In this case, the pairwise *criteria* comparison matrix will have $n = 6$ and the pairwise *alternative* comparison matrix will have $n = 3$.

After the pairwise matrix have been formulated, several computational steps are executed, according to the formulation of [59].

The "priority vector" $\mathbf{w}$ is determined by using the geometric mean method [17],

$$\mathbf{w} = (w_1, w_2, w_3 ... w_n)^T \tag{4.4}$$

where w_i is a value that estimates the geometric mean for the ith elements of an alternative or criteria. The "consistency index" (CI) and "consistency ratio" (CR) of each pair-wise comparison matrix are calculated next. CI is defined as

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{4.5}$$

where λ_{max} is the maximum eigenvalue of the pairwise comparison matrix and n is the number of variables or alternatives considered in the case study scenario. CR is defined as

$$CR = \frac{CI}{RI} \tag{4.6}$$

where $RI \in [1, n]$ is selected as a random index value of the scenario from Table 5.5. The CR value is calculated as part of the process since it is occasionally used to filter out responses [59].

4.8.2 Aggregation of group responses

Individual responses can be combined to reach a group decision by the following methods [29]:

1) Aggregation of individual judgments (AIJ)

2) Aggregation of individual priorities (AIP)

When the group acts together as a singular unit to reach a consensus on a decision, it requires the aggregation of the individual judgments. Since individuals may/may not make the judgments for every cluster of the hierarchy, their priorities are unimportant. When an individual's judgments are inconsistent, they may be asked to revise their judgments or the group could decide to omit their response. Individual judgment matrices, $A_1, A_2, \ldots, A_m$ can be aggregated into a single pairwise comparison matrix, $A^G = (a_{ij}^G)$, and then the priority vector can be calculated from A^G by finding its geometric mean.

When individuals act as separate units and maintain their decisions, an aggregation of individual priorities is provides the group's decision. Individual priorities can be combined by determining the weighted geometric mean by :

$$w_i^G = \prod_{h=1}^{m} w_i^{(h)_i^\lambda} \tag{4.7}$$

where $m \geq 2$ is the number of decision-makers, and λ_h is the importance of the h^{th} decision maker.

For the presented study, the following considerations must be made to determine which of the two approaches is more apt:

- Do the survey respondents belong to the same organization?
- Do the survey respondents belong at the same level within their safety teams?
- Do they have an equal stake in the visual tool assignment problem?
- Is the designed scenario-based survey equally close to every respondent's current work area environment?

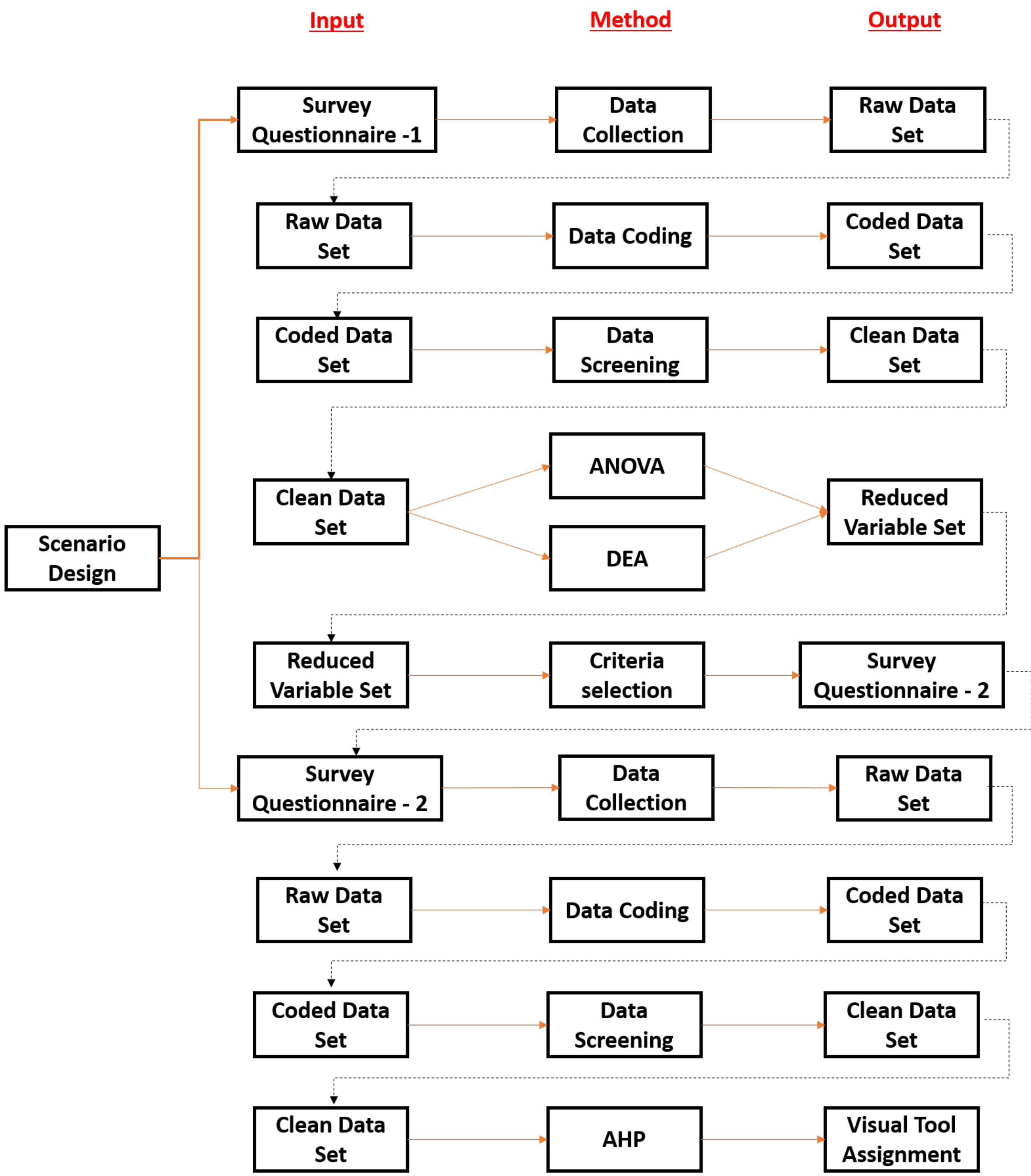

Figure 4.2: An overview of the research methodology adopted, where an input(shows on the left) is converted into an output(shown on the right) using the method(shown in the center)

	Age of personnel	Experience of personnel	Noise level	Temperature	Type of entity	Mobility of entities	Visibility	Lighting	Cluttered Layout	Confined Layout
Node 1	✓		✓	✓	✓			✓	✓	
Node 2	✓	✓	✓		✓					✓
Node 3			✓		✓	✓	✓	✓	✓	✓

Figure 4.3: Design of scenarios to maintain differences between the nodes

Requirement	Survey 1	Survey 2
Respondents must understand the purpose of the study	✓	✓
Respondents must be familiar with the idea of mobile entity interfaces occurring in manufacturing work areas	✓	✓
Respondents must understand the variables selected for the study and their possible influence in a visual tool assignment framework	✓	✓
Respondents must understand the basic functions performed in a manufacturing work area	✓	✓
Respondents must understand the differences between the scenarios from a safety perspective	✓	✓
Respondents must be familiar with the visual tools and their functions		✓
Respondents must be able to place the right visual tools in a work area		✓

Figure 4.4: Criteria that each survey's respondent was expected to fulfill

Table 4.2: Survey questionnaire used to collect responses for survey-1 to create a shortlist of variables, using the 5-point Likert scale

Question	Strongly Agree (5)	Somewhat Agree (4)	Neither Agree nor Disagree (3)	Somewhat Disagree (2)	Strongly Disagree (1)
Given that older personnel are operating machines, young drivers are operating metal haulers and 18 wheelers, would age of personnel be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					
Given that there are metal haulers, 18 wheelers and pedestrians present/passing through the node, would the type of entities at the node be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					
Given that there are highly experienced personnel working at the node, would the experience of personnel be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					
Give that there is a high frequency of mobile entities present due to multiple gates, would mobility of entities be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					
Given that the temperature of the node is high enough to cause heat stress, would temperature be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					
Given that there is a moderate visibility, would visibility be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					
Given that there is a lower lighting due to the machines which block the light, would lighting be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					
Given that the node is very noisy and workers require earplugs around the node, would noise level be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					
Given that the presence of machinery and excessive mobility clutter the node, would cluttered layout be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					
Given that the presence of gates and walkways reduce the confinement of a path, would confined layout be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					

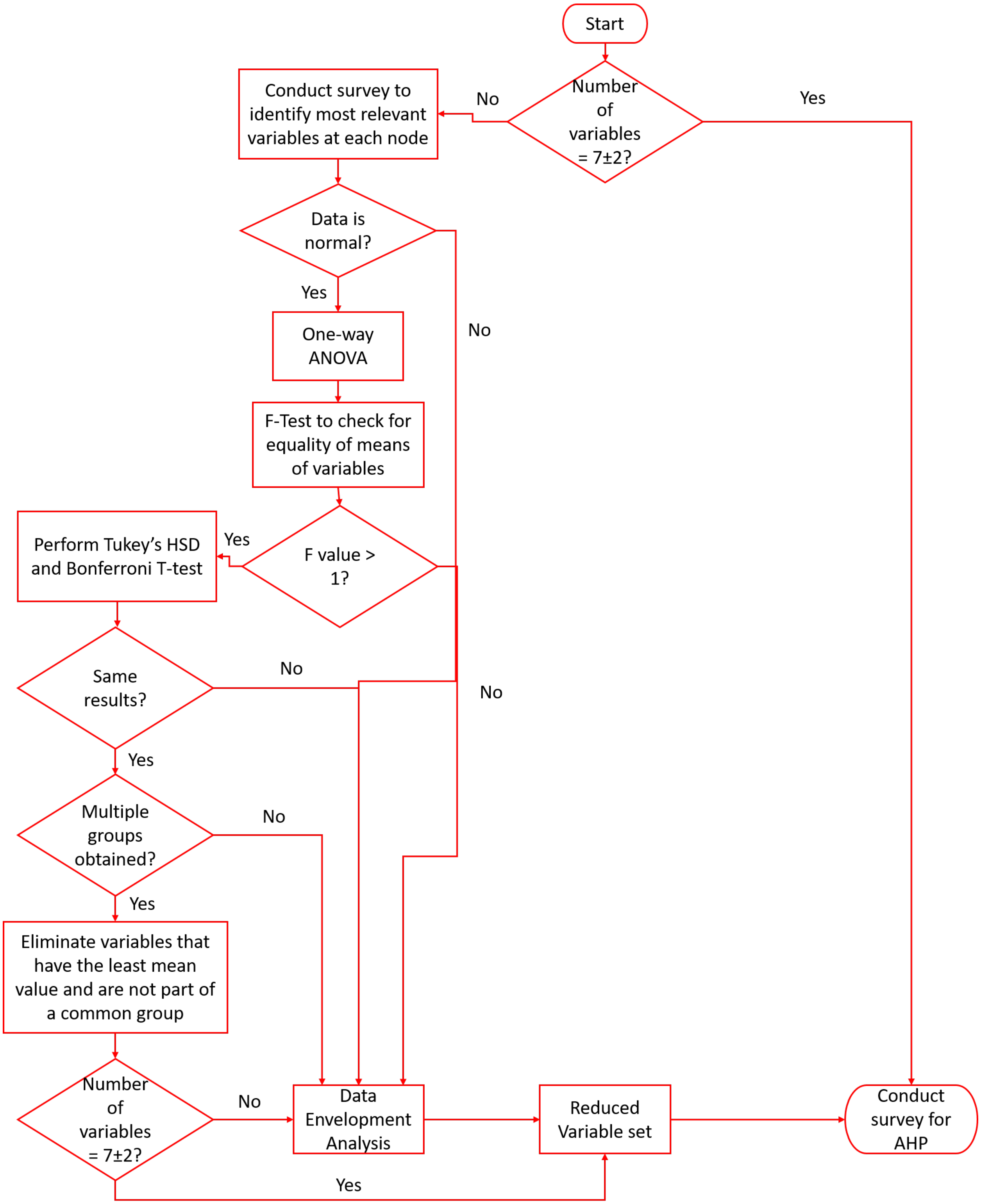

Figure 4.5: Flowchart required to decide between performing ANOVA and DEA to reduce the variables to 7 ± 2

Table 4.3: Saaty's scale for pairwise comparison [60]

Importance Intensity	Definition
1	Equal importance
3	Moderate importance of one over another
5	Strong importance of one over another
7	Very strong importance of one over another
9	Extreme importance of one over another
2,4,6,8	Intermediate values
Reciprocals	Reciprocals for inverse comparison

Chapter 5

Case Study

5.1 Survey - 1

The objective of the first survey is to create a shortlist of the work area and entity variables while ensuring that the subset of variables consist of 7 ± 2 variables [62]. The survey asks respondents to identify the most relevant variables for visual tool selection at three nodes. The scores provided by each respondent for every variable at a node were entered along the columns of figure 5.1. ANOVA and DEA are used for the variable reduction.

5.1.1 Application of ANOVA to Survey - 1

The survey results were analyzed using the University of Tennessee's SAS Enterprise Guide software package. For the set of 10 variables,

Null Hypothesis - $\mu_1 = \mu_2 \cdots = \mu_{10}$

Alternate Hypothesis - At least one of the population means differs from the rest.

where, $t = 10$

Per the assumptions made in chapter 4, the data was first tested for normality using the goodness of fit tests. Since the survey population size was small, the results of the Shapiro-Wilk test were considered to be most reliable [33]. When the p-value is more than .05, it fails to reject the null hypothesis and thus the assumption holds.

	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19	R20	R21	R22	R23	R24
Age of personnel	4	4	3	2	4	4	4	5	3	5	3	3	5	4	2	4	3	3	4	2	3	3	4	3
Type of entity	5	2	5	4	3	3	4	4	5	4	3	5	4	5	5	4	5	4	5	4	4	5	5	5
Experience of personnel	2	4	3	2	4	5	5	4	5	1	4	1	5	4	4	3	1	5	2	4	5	5	4	3
Mobility of entities	5	4	5	5	2	5	4	3	5	4	3	5	5	4	3	5	5	4	5	4	4	4	3	4
Temperature	5	4	5	4	5	4	3	2	5	1	5	5	1	3	4	5	5	5	5	3	5	3	3	5
Visibility	4	5	5	4	3	5	4	5	5	5	2	5	5	3	3	5	5	4	5	4	5	5	3	4
Lighting	5	3	5	5	2	4	4	4	2	4	2	5	4	5	5	5	5	5	4	3	5	5	5	4
Noise Level	4	4	5	4	4	4	2	1	5	4	4	5	2	4	4	5	1	4	5	4	3	5	3	4
Cluttered Layout	3	3	4	4	3	5	3	2	3	4	3	4	5	4	2	4	5	4	4	3	3	3	3	2
Confined Layout	3	3	3	4	5	3	2	3	3	3	2	5	3	5	2	4	5	3	2	3	3	4	3	2

Figure 5.1: Data obtained from Survey - 1 at Node - 1

Figure 5.2 presents the results of the goodness of fit test for age of personnel. The test shows a small p-value of 0.0102 suggesting that the data does not follow normal distribution. Although this automatically disqualifies the testing of the data-set using ANOVA, further steps are performed for the sake of demonstrating the methodology.

A "one-way" ANOVA was performed and the descriptive statistics were obtained. It can be observed from figure 5.3 that all the sample means are different.

Hence, we perform the F test to determine the difference between the mean squares between the groups and mean square within the group. A significant F value is indicated by a value of F greater than 1, as shown in figure 5.4. Additionally, the significance level of the F test is 0.0012. Hence, we conclude that there is an unequal priority given by the respondents to each variable.

To confirm the results and to select 7 ± 2 variables for the next phase of our study, we perform Tukey's HSD test and Bonferroni t-test. These tests offer multiple comparisons for the means [56]. The differences between the variables obtained from first survey can be identified using Tukey grouping and Bon grouping. The letters A and B indicate the grouping of the variables obtained using these tests.

The following key observations are made about the obtained results from these tests -

- Group A contains variables 1,2,3,4,5,6,7,8 and 9.
- Group B contains variables 2,3,4,5,6,7,8,9 and 10.
- Differences between means that share a letter are not statistically significant.

Distribution analysis of: F2

The UNIVARIATE Procedure
Variable: F2
F1 = Age of personnel

Basic Statistical Measures			
Location		Variability	
Mean	3.500000	Std Deviation	0.88465
Median	3.500000	Variance	0.78261
Mode	3.000000	Range	3.00000
		Interquartile Range	1.00000

Note: The mode displayed is the smallest of 2 modes with a count of 9.

Basic Confidence Limits Assuming Normality			
Parameter	Estimate	95% Confidence Limits	
Mean	3.50000	3.12644	3.87356
Std Deviation	0.88465	0.68756	1.24095
Variance	0.78261	0.47274	1.53997

Tests for Normality				
Test	Statistic		p Value	
Shapiro-Wilk	W	0.884451	Pr < W	0.0102
Kolmogorov-Smirnov	D	0.214029	Pr > D	<0.0100
Cramer-von Mises	W-Sq	0.23326	Pr > W-Sq	<0.0050
Anderson-Darling	A-Sq	1.263965	Pr > A-Sq	<0.0050

Figure 5.2: Normality test performed for survey responses collected for age of personnel at Node-1

- Variables 1 and 10 do not share a letter, which indicates that at node 1, visibility has a significantly higher mean than confined layout.

While the grouping obtained from both the tests is the same, the results are not satisfactory. This is because the study does not allow us to eliminate more than 1 variables, hence making the subset of variables unsuitable for AHP. Hence, Data Envelopment Analysis is used as an alternative to ANOVA.

One-Way Analysis of Variance

Results

Means and Descriptive Statistics

F1	Mean of F2	Variance of F2
	3.8333333333	1.18550
Age of personnel	3.5	0.78261
Cluttered Layout	3.4583333333	0.78080
Confined Layout	3.25	0.97826
Experience of personnel	3.5416666667	1.91123
Lighting	4.1666666667	1.10145
Mobility of entities	4.1666666667	0.75362
Noise Level	3.75	1.41304
Temperature	3.9583333333	1.69384
Type of entity	4.25	0.71739
Visibility	4.2916666667	0.82428

Figure 5.3: Test statistics obtained for ANOVA at Node - 1

5.1.2 Application of DEA for Survey - 1

In this study, the variables are considered as the DMUs, and the experts' opinion regarding each criterion are considered as the output. This means that, as the experts score a higher value in the survey for each criterion, the output is more desirable. It is noteworthy that no external input is considered for this DEA. Instead, a dummy input of 1 is defined to linearize the objective function. The outcome of the DEA methodology will be the ranking of variables based on their corresponding efficiency scores. GAMS software package is used to perform DEA on the data collected from Survey 1 (Appendix E.1).

The study is determined by the responses for the survey sought from the group of 24 industrial engineers. These decision makers create an efficiency-based ranking on work area variables. DEA uses the highest preference of the Likert scale used in the study, '5', to be the benchmark against which all other responses are compared. A threshold value of 0.8 allows us to reduce the number of variables to 7 ± 2 [62]. In fact, any variable that has efficiency score greater than threshold value will be selected as the final variable for the AHP.

Table 5.1 displays the outcome of the DEA for node 1, obtained using the GAMS software. The variables which cross the threshold value of 0.8 are highlighted and selected for the

One-Way Analysis of Variance

Results

The ANOVA Procedure

Class Level Information		
Class	Levels	Values
F1	10	Age of personnel Cluttered Layout Confined Layout Experience of personnel Lighting Mobility of entities Noise Level Temperature Type of entity Visibility

Number of Observations Read	240
Number of Observations Used	240

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One-Way Analysis of Variance

Results

The ANOVA Procedure

Dependent Variable: F2

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	9	31.3333333	3.4814815	3.18	0.0012
Error	230	252.0000000	1.0956522		
Corrected Total	239	283.3333333			

R-Square	Coeff Var	Root MSE	F2 Mean
0.110588	27.30611	1.046734	3.833333

Source	DF	Anova SS	Mean Square	F Value	Pr > F
F1	9	31.33333333	3.48148148	3.18	0.0012

Figure 5.4: Results obtained for ANOVA at Node - 1

AHP study. Depots 1 to 10 correspond to the variables selected for the study and have been explained in the table.

7 variables were selected from node 1, 6 from node 2 and 6 from node 3. These act as the criteria for the AHP.

5.2 Survey - 2

In addition to the information which was provided to the participants of the first survey, the features of the visual tools selected for our study were also provided to ensure consistency in the understanding of the tool. A survey is administered to safety experts in the manufacturing industries. 10 responses were analyzed using the standard AHP setting described in chapter 4. Small respondent pools are typically acceptable in AHP [67].

5.3 AHP

To obtain the weights of the variables selected through the data envelopment analysis, and assign visual tools to each node, AHP uses a hierarchical structure to set up the pair-wise

Bonferroni (Dunn) t Tests for F2

Note: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	230
Error Mean Square	1.095652
Critical Value of t	3.30248
Minimum Significant Difference	0.9979

Means with the same letter are not significantly different.				
Bon Grouping		Mean	N	F1
	A	4.2917	24	Visibility
	A			
	A	4.2500	24	Type of entity
	A			
B	A	4.1667	24	Lighting
B	A			
B	A	4.1667	24	Mobility of entities
B	A			
B	A	3.9583	24	Temperature
B	A			
B	A	3.7500	24	Noise Level
B	A			
B	A	3.5417	24	Experience of personnel
B	A			
B	A	3.5000	24	Age of personnel
B	A			
B	A	3.4583	24	Cluttered Layout
B				
B		3.2500	24	Confined Layout

Figure 5.5: Results obtained for Bonferroni t-test at Node 1

comparisons in a simple manner [60]. Figure 5.7 displays the relationship between the 10 variables and 3 visual tools to r reach the goal of assigning the best visual tool at a node.

Table 5.3 provides the pairwise comparison matrix for seven criteria (variables) considered in Node 1. This matrix can be represented as A_{7*7}. Here, a_{ij} represents the degree of importance of the i^{th} element with the j^{th} element, $(\forall i, j \in 7)$. To extract the relative importance of the criteria from the rankings of the safety experts, we perform the following steps:

Step 1: Multiply values in each row. For example, for age of personnel, the products across the row would be calculated as $1 \times 1/6 \times 1/7 \times 1/9 \times 1 \times 1/8 \times 1.9 = 0.0000367431$. Similarly, table 5.2 shows the products across all the rows in a criteria-criteria comparison at Node 1.

Step 2: Take the n^{th} root of the product of each row.

Tukey's Studentized Range (HSD) Test for F2

Note: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	230
Error Mean Square	1.095652
Critical Value of Studentized Range	4.51851
Minimum Significant Difference	0.9654

Means with the same letter are not significantly different.				
Tukey Grouping		Mean	N	F1
	A	4.2917	24	Visibility
	A			
	A	4.2500	24	Type of entity
	A			
B	A	4.1667	24	Lighting
B	A			
B	A	4.1667	24	Mobility of entities
B	A			
B	A	3.9583	24	Temperature
B	A			
B	A	3.7500	24	Noise Level
B	A			
B	A	3.5417	24	Experience of personnel
B	A			
B	A	3.5000	24	Age of personnel
B	A			
B	A	3.4583	24	Cluttered Layout
B				
B		3.2500	24	Confined Layout

Figure 5.6: Results obtained for Tukey's HSD test at Node 1

Row 1: $\sqrt[7]{0.0000367431} = 0.232$

Row 2: $\sqrt[7]{54.000} = 1.768$

Row 3: $\sqrt[7]{28.000} = 1.609$

Row 4: $\sqrt[7]{0.0857} = 0.704$

Row 5: $\sqrt[7]{0.00148} = 0.394$

Row 6: $\sqrt[7]{448.000} = 2.391$

Row 7: $\sqrt[7]{315.000} = 2.274$

Step 3: Determine the sum of the nth roots.

$$0.232 + 1.768 + 1.609 + 0.704 + 0.394 + 2.391 + 2.274 = 9.375$$

Table 5.1: DEA outcome for Node-1, depicting the corresponding variable name and efficiency score for each depot. The highlighted rows indicate the variables that were selected for AHP.

Depot	Variable Name	Efficiency Score
Depot 1	**Age of Personnel**	**0.8**
Depot 2	**Type of Entity**	**1.0**
Depot 3	Experience of Personnel	0.4
Depot 4	**Mobility of Entities**	**1.0**
Depot 5	**Temperature**	**1.0**
Depot 6	**Visibility**	**0.8**
Depot 7	**Lighting**	**1.0**
Depot 8	**Noise Level**	**0.8**
Depot 9	Cluttered Layout	0.6
Depot 10	Confined Layout	0.6

Table 5.2: Product for row multiplications at Node 1 - Response 1

Criteria	Age of Personnel	Lighting	Mobility of Entities	Noise Level	Temperature	Type of Entity	Visibility	Product
Age of Personnel	1	1/6	1/7	1/9	1	1/8	1/9	0.0000367431
Lighting	6	1	1	3	3	1	1	54.000
Mobility of Entities	7	1	1	1	4	1	1	28.000
Noise Level	9	1/3	1	1	1	1/7	1/5	0.08571
Temperature	1	1/3	1/4	1	1	1/8	1/7	0.00148
Type of Entity	8	1	1	7	8	1	1	448.000
Visibility	9	1	1	5	7	1	1	315.000

Step 4: Normalize the n^{th} roots by dividing them by the sum of the n^{th} roots. The resulting column provides us with the priority vectors.

For example, for the age personnel, the priority given by respondent 1 can be calculated as:

$$\frac{0.232}{9.375} = 0.024$$

Table 5.3 provides the priority vector obtained for the pairwise comparison between criteria, on following the above steps.

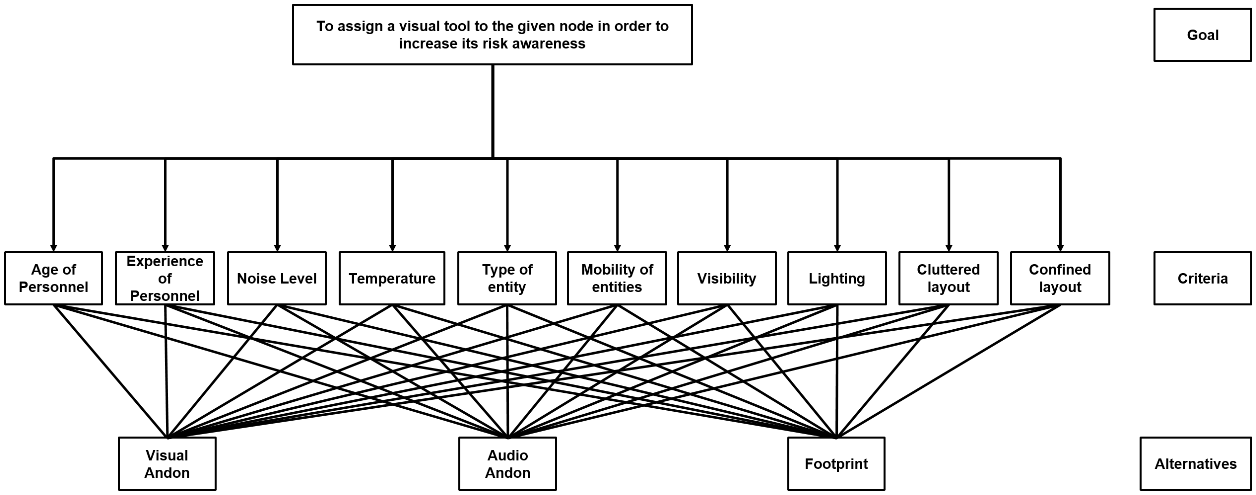

Figure 5.7: Hierarchical structure of visual tool assignment

Table 5.3: Pairwise comparison matrix for seven criteria using AHP for Node 1- Response 1

Criteria	Age of Personnel	Lighting	Mobility of Entities	Noise Level	Temperature	Type of Entity	Visibility	Priority Vector
Age of Personnel	1	1/6	1/7	1/9	1	1/8	1/9	0.0248
Lighting	6	1	1	3	3	1	1	0.1885
Mobility of Entities	7	1	1	1	4	1	1	0.1716
Noise Level	9	1/3	1	1	1	1/7	1/5	0.0750
Temperature	1	1/3	1/4	1	1	1/8	1/7	0.0420
Type of Entity	8	1	1	7	8	1	1	0.2551
Visibility	9	1	1	5	7	1	1	0.2426

5.3.1 Evaluation of data consistency

To evaluate the consistency of the paired comparisons, the consistency index, the λ_{max} value, and the consistency ratio are calculated using the following steps:

Step 1: Add the columns in the judgment matrix 5.3. For example, for age of personnel, the sum of the values is :

$$1 + 6 + 7 + 9 + 1 + 8 + 9 = 41$$

Table 5.4 shows the vector of sums obtained for each column.

Step 2: Multiply the vector of sums with the priority vector to obtain the λ_{max} value.

Table 5.4: Sum of columns in the judgment matrix for Node 1- Response 1

Criteria	Age of Personnel	Lighting	Mobility of Entities	Noise Level	Temperature	Type of Entity	Visibility
Age of Personnel	1	1/6	1/7	1/9	1	1/8	1/9
Lighting	6	1	1	3	3	1	1
Mobility of Entities	7	1	1	1	4	1	1
Noise Level	9	1/3	1	1	1	1/7	1/5
Temperature	1	1/3	1/4	1	1	1/8	1/7
Type of Entity	8	1	1	7	8	1	1
Visibility	9	1	1	5	7	1	1
Sum	41.000	4.833	5.392	18.111	25.000	4.392	4.453

$$\begin{pmatrix} 41.000 \\ 4.833 \\ 5.392 \\ 18.111 \\ 25.000 \\ 4.392 \\ 4.453 \end{pmatrix}^{-1} \times \begin{pmatrix} 0.0248 \\ 0.1885 \\ 0.1716 \\ 0.0750 \\ 0.0420 \\ 0.2551 \\ 0.2426 \end{pmatrix}$$

$= 7.4676$

Step 3: The CI value is obtained by:

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

Hence, for the criteria-criteria matrix of respondent 1 at Node 1, where $n = 7$, CI is:

$$CI = \frac{7.4676 - 7}{7 - 1} = 0.0779$$

Step 4: CR is calculated as

$$CR = \frac{CI}{RI} \tag{5.1}$$

where $RI \in [1, n]$ is selected as a random index value from Table 5.5. The CR value is occasionally used to filter out responses [59].

Table 5.5: Random index table

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

For the given scenario, since $n = 7$, $RI = 1.32$. Hence,

$$CR = \frac{0.0779}{1.32} = 0.05905$$

Pairwise matrices are similarly generated for each survey respondent for comparison of alternatives. Table 5.6 shows an example output for Node 1, which resulted in the following λ_{max}, CI, and CR values:

$$\begin{aligned} \lambda_{max} &= 3.3762 \\ CI &= 0.1881 \\ CR &= 0.0590 \end{aligned} \tag{5.2}$$

Table 5.6: Pairwise comparison matrix for three alternatives for age of personnel for Node 1- Response 1

Alternative	Visual Andon	Audio Andon	Footprints	Weight
Visual Andon	1	7	1/7	0.1965
Audio Andon	1/7	1	1/8	0.0513
Footprints	7	8	1	0.7520

Note :

The consistency ratio is often used to threshold responses in AHP [58]. The presented study does not use a CR threshold to eliminate responses. This is due to the following reasons:

1) Enforcing a CR threshold may require multiple survey iterations, making the data collection process time-consuming and impractical [41].

2) Inconsistency in expert opinions is common and inevitable and hence cannot be the grounds for elimination [51].

5.3.2 Aggregation of responses

The 10 individual responses were combined to reach a group decision. AIP was the preferred aggregation method, as opposed to AIJ due to the following properties of the given study [29]:

1) Safety experts who filled the survey questionnaire belonged to different organizations.

2) Since the safety experts may have belonged to different levels within their safety teams, they might have a different stake from each other.

3) The hypothetical work area may have been more close to some respondents work areas than others, hence leading to different stakes.

Since the roles of all $m = 10$ respondents are assumed to be equally important, $\lambda = \frac{1}{m} = 0.1$ in equation 4.7. The aggregate of individual priorities for visual andons, when age of personnel is considered can be calculated by finding the geometric mean of all individual priorities for visual andons, when age of personnel is considered. This can be shown as:

$$w_i^G = (0.196 \times 0.256 \times 0.761 \times 0.332 \times 0.559 \times 0.787 \times 0.333 \times 0.236 \times 0.643 \times 0.17)^{0.1}$$

Table 5.7 is the final matrix obtained when the individual priorities for Node 1 are combined. The last column shows the final score obtained for each tool. It can be seen that visual andon is the preferred tool at node 1 since they have the highest score.

Table 5.7: Group aggregation of AHP using AIP approach for Node 1

Criteria	Age of Personnel	Lighting	Mobility of Entities	Noise Level	Temperature	Type of Entity	Visibility	Preferences
Weights	0.0363	0.1802	0.1018	0.1017	0.0618	0.0973	0.2764	
Visual Andon	0.3723	0.2714	0.3435	0.6010	0.3284	0.3946	0.3048	0.3016
Audio Andon	0.1665	0.3285	0.1979	0.0885	0.2247	0.1599	0.2777	0.2007
Footprints	0.1964	0.1423	0.2099	0.1759	0.2050	0.2083	0.1803	0.1549

Table 5.8: Global priorities for each node

	Node 1	Node 2	Node 3
Visual Andon	0.3016	0.3147	0.2661
Audio Andon	0.2007	0.1589	0.2234
Footprints	0.1549	0.1806	0.1447

Table 5.9: Number of respondents who ranked each visual tool as their 1st, 2nd and 3rd choice respectively

	Node 1			Node 2			Node 3		
	Visual Andon	Audio Andon	Footprints	Visual Andon	Audio Andon	Footprints	Visual Andon	Audio Andon	Footprints
Rank 1	3	4	3	6	2	2	4	6	0
Rank 2	7	2	1	4	3	3	3	1	6
Rank 3	0	4	6	0	5	5	3	3	4

5.4 Results

Chapter 3 presented the research hypothesis that work area and entity variables affect visual tool assignment decisions. The design of scenarios in table 4.1 was a deliberate effort to introduce variations at the 3 nodes by differing the variable attributes. The results presented in tables 5.8 and 5.9 indicate that the presented hypothesis is subjectively validated. The following section interprets the results from the perspective of visual tools:

1) Visual Andon : Table 5.8 indicates that visual andons are the preferred choice of visual tools, when the group's decision is taken into consideration. However, table 5.9 indicates that this selection is not unanimous. This can be attributed to the conditions presented at each node (see table 4.1).

   1.1) 3 respondents preferred visual andons over the other tools at node 1. 7 respondents picked visual andons as their second choice. No respondent ranked visual andons as their last choice. While moderate visibility, lower lighting and heat stress may make visual andons a less preferrable choice, they may have been favored since a noisy and cluttered environments make audio andons and footprints as the less favorable alternative.

   1.2) Visual andon was placed first by 6 respondents at node 2. This made it the obvious choice at the node, since it received only 2 second and 2 third places. This can be linked to the fact that the node has a good visibility and ample lighting. The temperature at the node is low due to the presence of the gate, hence reducing the chances of lower visibility due to heat stress.

1.3) However, the results at node 3 are inconclusive. The node experiences bad visibility conditions, coupled with high temperatures and artificial lighting, which could potentially make the visual andons less readable. The aggregate score of the group's priorities are only marginally higher than the other tools. Since visual andons were ranked 1^{st} by only 4 respondents, as opposed to audio andons which were ranked 1^{st} by 6 respondents, a cost-benefit analysis may be helpful to select the better alternative in future research attempts.

2) Audio Andon : Table 5.9 indicates that audio andons are the preferred choice of visual tools at nodes 1 and 3, for several respondents. However, table 5.8 indicates that they are not picked as the 1^{st} choice when the individual results are aggregated. This can be attributed to the following reasons:

2.1) Busy manufacturing work areas can use audio cues to focus the attention of the workers on important safety information. However, such environments can turn out to be extremely noisy. Nodes 1 and 3 have an extremely high frequency of mobile entity movement and are closely situated to heavy production equipment. This makes their environment noisy. Hence, while audio andons were ranked higher at these nodes, the priority scores of audio andons over visual andons were not considerably higher.

2.2) Node 2 finds the audio andon ranked third, along with the lowest group aggregate. This is because, unlike nodes 1 and 3 which have experienced personnel working at the node, this node has part time employees. Since this node has aperiodic random noises, these part time employees may find it hard to differentiate between the audio notifications and the noise at the node. Hence, this awareness mechanism is deemed unreliable at node 2.

3) Footprints : Table 5.9 indicates that footprints are the least preferred at nodes 1 and 2 and are the 2^{nd} most preferred visual tool at node 3. However, table 5.8 indicates that while they receive the least aggregate scores at nodes 1 and 3, they perform better than audio andons at node 2 . This can be attributed to the fact that node 2 is the only node without clutter, making them more noticeable. They also have narrow and confined pathways, making it important to demarcate the pathways for mobile entities.

Chapter 6

Discussion and Future Work

6.1 Conclusion

AHP's widespread and diverse applications [70] shows that a multi-criteria framework may be easily transferred to other risk awareness problems in various industrial sectors. This requires a few steps to be performed. First, the set of work area and entity variables needs to be modified based on application, and reduced using ANOVA or DEA, to simplify AHP's implementation [62]. Second, nodes and available visual tools should be selected and the scenarios at each node must be designed clearly. Third, a survey must be constructed using the standardized AHP template, and safety experts should respond to it. Finally, responses are aggregated [29], possibly using a standard software interface to assign visual tools to the nodes under consideration.

6.2 Limitations

This research provides a visual tool assignment framework for mobile entity interfaces in manufacturing industries, thus making valuable contributions to the existing literature on risk awareness. However, it is important to be aware of the limitations when concluding the reported results. The research study has the following limitations:

- The results presented in this study subjectively conclude the hypothesis that work area variables have an influence on the choice on visual tools. However, this conclusion needs a quantitative backing based on experimental design or testing the presented solutions in a manufacturing facility with the same variable influences.

- The selection of the work area variables is an improvement on the work of [19, 42]. The selection was specific to mobile entity interfaces in manufacturing industries under this study. However, to make this study transferable to incident categories, research efforts must focus on understanding the variables influencing the specific risks.

- It is important to recognize that visual tools cannot solely ensure a work area safety. It is equally important to ensure that workers are trained to recognize the visual cues and know how to react to them. Hence a detailed implementation plan which places these two awareness tools concurrent to each other must be looked into.

- This research places equal importance on all the respondents of the survey. It is necessary to identify the applicability of the AIP or the AIJ method of aggregation of responses based on the importance of respondents, when using the methodology. Necessary modifications must be made if different groups of respondents are asked to fill the survey, before following the presented methodology [29].

- This research is based only on the effectiveness of the communication of risk information. However, an implementation-ready version may require conducting a cost benefit analysis in combination with AHP, for it to be beneficial to plant and safety managers [75].

- This research provides a subjective classification system to select the best visual tools for mobile entity interface. A more systematic procedure may be beneficial to further the benefits of risk communication.

6.3 Research implications

This study opens discussions in the following key areas:

1) Focus on specific categories of incidents as opposed to broad safety issues

2) A systematic risk awareness framework to improve work area safety

Focusing on specific incident categories maps work area variables identified with risk awareness methods. This furthers prior work [19, 42] by making the selection of variables incident specific. This study aims to improve risk awareness in the case of mobile entity interfaces. The visual tool assignment results subjectively confirm the hypothesis that work area variables influence the choice of risk awareness tools. Quantitative experimental designs or case studies conducted at manufacturing plants can support this hypothesis. In order to study the effect of these variables on visual tool selection in other incident categories, research efforts may be conducted in the same work area but on incidents other than mobile entity interfaces.

The visual tool assignment framework places the information delivery mechanism at the core of its risk awareness strategy. Visual tools are proven to improve risk awareness. This makes the risk awareness approach a method of safety research practice, instead of being limited to safety training research [54] or to comparative studies of communication mechanisms [21]. The systematic visual tool assignment principles presented in this study can be easily generalized to risk awareness objectives for all work areas. This can be validated by the design of a comparable system for a different work area, which may or may not be connected to manufacturing or mobile entity risks. Hence, the generality of the framework can be validated.

6.4 Managerial implications

The assignment of visual tools in companies is not unusual [25]. Visual tools are perceived as good investments for safe manufacturing practices. They have the potential to lower the costs of injury and disability. The results of this study negate the arbitrary assignment of visual tools, making them truly effective at the location at which they are deployed. This provides managers with a strategic visual tools selection process for their specific work areas.

The presented methodology acknowledges that the expertise of plant and safety managers about work areas is valuable to visual tool assignment. Using AHP, expert opinions are aggregated to collectively choose visual tools. The use of ANOVA, DEA and AHP, which are standard MCDM tools, makes it simple to automate several components of the implementation framework, making it easy, cost-effective, and flexible. Further, by conducting a cost-benefit analysis in combination with AHP [75], a more practical and industry ready application of the presented research can be conducted.

Finally, it is key for safety managers to realize that the sophistication in visual tool assignment for risk awareness is only one part of creating a safe work area. The other, equally critical component, is training all employees to ensure that they respond to the signal provided by the visual tool satisfactorily. An implementation-ready version of this study will require visual tool assignment and training for risk response to be concurrent events. Doing so will lead to safer work areas by creating a stronger safety culture within organizations.

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Appendices

A Survey Conducted for DEA

A.1 Survey questionnaire used to collect responses for survey-1 at node 2 to create a shortlist of variables, using the 5-point Likert scale

Question	Strongly Agree (5)	Somewhat Agree (4)	Neither Agree nor Disagree (3)	Somewhat Disagree (2)	Strongly Disagree (1)
Given that young drivers are operating metal haulers and 18 wheelers, would age of personnel be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					
Given that there are metal haulers, 18 wheelers, skim trucks and pedestrians present/passing through the node, would the type of entities at the node be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					
Given that the drivers may/may not be full time employees and the maximum experience they have is between 1-2 years, would the experience of personnel be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					
Give that there is a high frequency of mobile entities present due to an entry gates, would mobility of entities be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					
Given that the temperature of the node is low due to the presence of a gate, would temperature be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					
Given that there is a good visibility to assist the drivers, would visibility be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					
Given that there is ample natural and artificial lighting, would lighting be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					
Given that there are random loud noises due to the movement of entities and their sirens, would noise level be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					
Given that the node is not cluttered, would cluttered layout be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					
Given that due to the narrow and confined pathways, the larger mobile entities may have difficulty in smooth movements leading to chances of travelling in reverse direction to avoid crashes, would confined layout be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					

A.2 Survey questionnaire used to collect responses for survey-1 at node 3 to create a shortlist of variables, using the 5-point Likert scale

Question	Strongly Agree (5)	Somewhat Agree (4)	Neither Agree nor Disagree (3)	Somewhat Disagree (2)	Strongly Disagree (1)
Given that there is an equally balanced age group of personnel, would age of personnel be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					
Given that there are metal haulers, pedestrians, overhead cranes present/passing through the node, would the type of entities at the node be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					
Given that there are highly experienced workers at the node, would the experience of personnel be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					
Give that there is maximum entity movement due to an entry point and vicinity to some exit points, would mobility of entities be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					
Given that the node experiences extremely high temperatures due to the presence of smelters and walls/machinery, would temperature be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					
Given that there is a low visibility due to lack of open spaces, would visibility be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					
Given that mostly artificial lighting is used, would lighting be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					
Given that the node is noisy due to maximum entity movement around the area, would noise level be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					
Given that the node is machinery and stored metal blocks make the node cluttered, would cluttered layout be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					
Given that the node has narrow and confined pathways, would confined layout be included in a visual tool assignment algorithm so that risk awareness at the node is increased?					

B Survey Conducted for AHP

B.1 Survey conducted for AHP

Thesis Survey

Start of Block: Default Question Block

Q1 The University of Tennessee's Industrial & Systems Engineering Department is conducting a study to assign visual tools to work areas in manufacturing industries to increase the risk awareness in their environment. For this we would like you to consider participating in this study by filling out a survey.

Manufacturing companies report accidents between entities *(vehicles and pedestrians)* in the work-area. Visual tools are commonly placed in such work-areas to increase risk awareness among these entities. Currently, there does not exist a logical method to make this placement. This study proposes a methodology that companies can use to assign visual tools to a work area by studying all the risk factors.

We need participants in the following roles:

- Safety Experts in manufacturing environment
- Between 21-70 years of age

Q2 Please describe the sectors in which you have worked as a safety/visual tool expert. (Eg: Manufacturing Industry, Food Industry, etc.)

____

Q3 Are you a Safety expert/ Visual Tool Expert? *(Note: Survey will continue only if your answer is yes.)*

○ Yes

○ No

Q4 **Please download the consent statement provided below before proceeding to the survey.**

Q5 Consent cover statement

Q6 Do you provide your consent to conduct this survey? *(Note: Survey will continue only if your answer is yes.)*

○ Yes

○ No

Q7 **Objectives for Respondent:**

To observe and understand the given layout diagram and description.
To read and understand the details of each highlighted node.
To understand the risks at the highlighted node.
To assign scores based on the respondent's understanding of:
The work-area
The work environment
The entities moving in the work-area
Visual tool assignment to maximize risk awareness of the work-area.

Q8 **Overview of the Plant :**

A heavy manufacturing industry for metal recycling The work-area is about 25 acres
The work-area has the following entities flowing through it –
Pedestrians   **18 wheelers** (carrying metallic slabs)
Over-head cranes (carrying metallic slabs)
Metal haulers (carrying scrap metal)
Forklift (carrying scrap metal)
Personnel operating the machinery
Skim Truck (carrying molten metal)
There have been multiple events in the past that have led to fatalities, injuries or near-miss events

The following pages depict nodes that have been identified as the three highest risk areas using Failure Modes and Effects Analysis (FMEA).

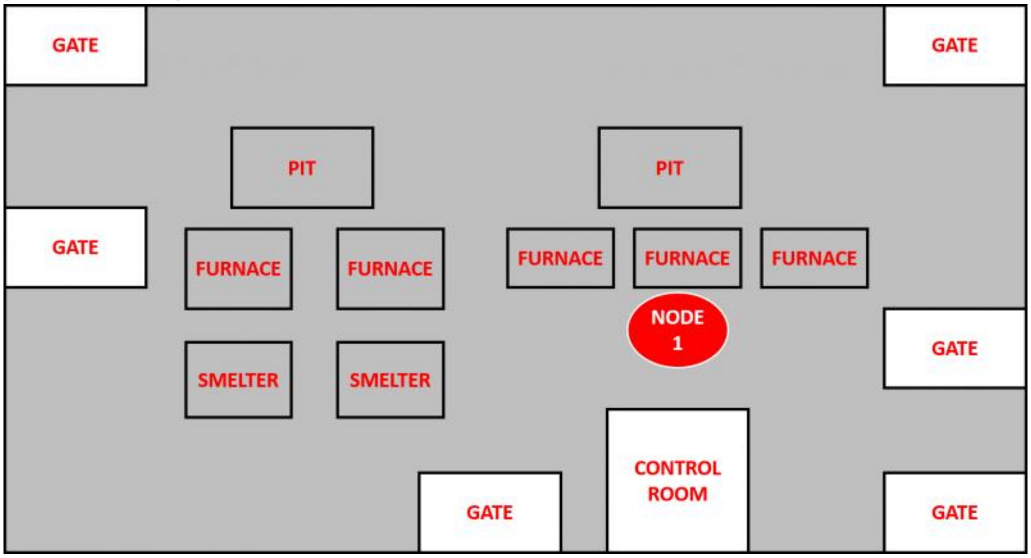
Visual Tools to be assigned:

Visual Andons: Digital displays of texts/graphics, coded signal lights, etc. Audio Andons: Coded tones/tunes, buzzers/alarms, pre-recorded messages, etc. Footprints: Floor markings/borders around work-areas or paths,etc

Q9 **Important terms in the layout:**

Furnace – A device used for high-temperature heating.
Smelter – A device used for extraction of metal from its oxides using electric discharge and gaseous matter.
Pit – Storage of processed metal sheets/slabs
Gate – Entry/Exit point
Node – Region of study

Q10 The image below is a representation of the hypothetical work-area that is under consideration in this study. **We assign the visual tool for the highlighted Node 1. All data provided below pertains to this node.**



Q11 **<u>Past interfaces reported:</u>**

a. Metal Hauler- Pedestrian b. 18 Wheelers – Pedestrian

<u>Node description:</u>

Age of Personnel: Older personnel are operating machines, young drivers are operating metal haulers and 18 wheelers

Type of Entity at the Node: Metal haulers, 18 wheelers and pedestrians present/passing through the node

Mobility of Entities: High frequency of mobile entities present due to multiple gates

Temperature: Temperature of the node is high enough to cause heat stress

Lighting: Lower lighting due to the machines which block the light

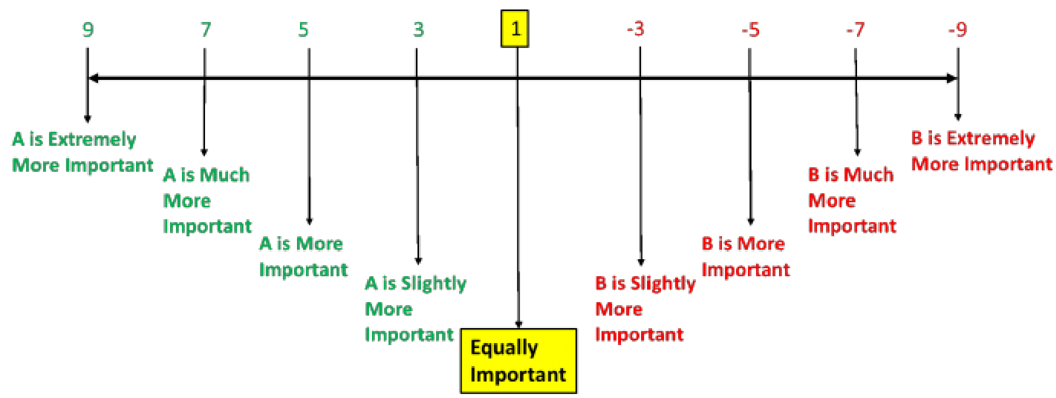
Visibility: Moderate visibility

Noise Level: The node is very noisy and workers require earplugs around the node

Q12

Pairwise Comparison between the criteria

The scale for the questionnaire ranges from +9 to -9, as shown below. The intensities 2,4,6,8 can be used to express intermediate values.



Q13 **Using the information provided before, give the importance of Criteria A when compared to Criteria B when assigning a visual tool to a given work area to increase risk awareness.**

(For example: When A = Age of Personnel and B = Lighting, if your choice is +9 then, you believe that Age of personnel is extremely important compared to Lighting when assigning a visual tool to a given work area to increase risk awareness.)

Or

(When A = Age of Personnel and B = Lighting, if your choice is -9 then, you believe that Lighting is extremely important compared to Age of Personnel when assigning a visual tool to a given work area to increase risk awareness.)

	9	8	7	6	5	4	3	2	1	-2	-3	-4	-5	-6	-7	-8	-9	

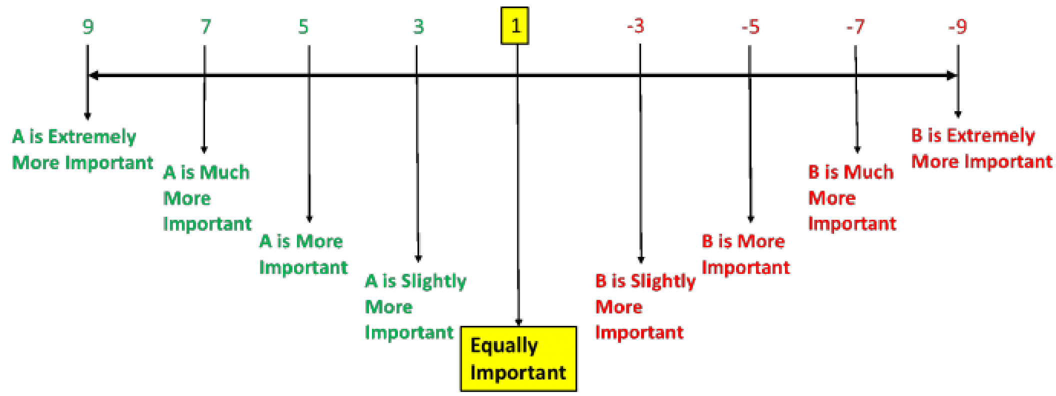
A = Age of personnel	B = Lighting
A = Age of personnel	B = Mobility of Entity
A = Age of personnel	B = Noise Level
A = Age of personnel	B = Temperature
A = Age of personnel	B = Type of Entity
A = Age of personnel	B = Visibility
A = Lighting	B = Mobility of Entity
A = Lighting	B = Noise Level
A = Lighting	B = Temperature
A = Lighting	B = Type of Entity
A = Lighting	B = Visibility
A = Mobility of Entities	B = Noise Level
A = Mobility of Entities	B = Temperature
A = Mobility of Entities	B = Type of Entity
A = Mobility of Entities	B = Visibility
A= Noise Level	B = Temperature

A= Noise Level	B = Type of Entity
A= Noise Level	B = Visibility
A = Temperature	B = Type of Entity
A = Temperature	B = Visibility
A = Type of Entity	B = Visibility

Q14

Pairwise Comparison between the alternatives for each criteria

The scale for the questionnaire ranges from +9 to -9, as shown below. The intensities 2,4,6,8 can be used to express intermediate values.



Q15 Give the importance of Visual tool A over Visual Tool B, keeping in mind that "***Older Personnel are Operating Machines, Young Drivers are Operating Metal Haulers and 18-wheelers."***

	9	8	7	6	5	4	3	2	1	-2	-3	-4	-5	-6	-7	-8	-9	
A = Visual Andons																		B = Audio Andons
A = Visual Andons																		B = Footprints
A = Audio Andons																		B = Footprints

Q16

Give the importance of Visual tool A over Visual Tool B, keeping in mind that ***"Metal Haulers, 18 wheelers and pedestrians are present/ passing through the node."***

	9	8	7	6	5	4	3	2	1	-2	-3	-4	-5	-6	-7	-8	-9	

A = Visual Andons		B = Audio Andons
A = Visual Andons		B = Footprints
A = Audio Andons		B = Footprints

Q17
Give the importance of Visual tool A over Visual Tool B, keeping in mind that ***<u>"High frequency of mobile entities are present at the node due to multiple gates."</u>***

	9	8	7	6	5	4	3	2	1	-2	-3	-4	-5	-6	-7	-8	-9	
A = Visual Andons																		B = Audio Andons
A = Visual Andons																		B = Footprints
A = Audio Andons																		B = Footprints

Q18
Give the importance of Visual tool A over Visual Tool B, keeping in mind that ***<u>"Temperature of the node is high enough to cause heat stress."</u>***

	9	8	7	6	5	4	3	2	1	-2	-3	-4	-5	-6	-7	-8	-9	

A = Visual Andons	B = Audio Andons
A = Visual Andons	B = Footprints
A = Audio Andons	B = Footprints

Q19

Give the importance of Visual tool A over Visual Tool B, keeping in mind that ***"The node experiences lower lighting due to machines which block the light."***

	9	8	7	6	5	4	3	2	1	-2	-3	-4	-5	-6	-7	-8	-9	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16		
A = Visual Andons																		B = Audio Andons
A = Visual Andons																		B = Footprints
A = Audio Andons																		B = Footprints

Q20

Give the importance of Visual tool A over Visual Tool B, keeping in mind that ***"There is Moderate Visibility at the node."***

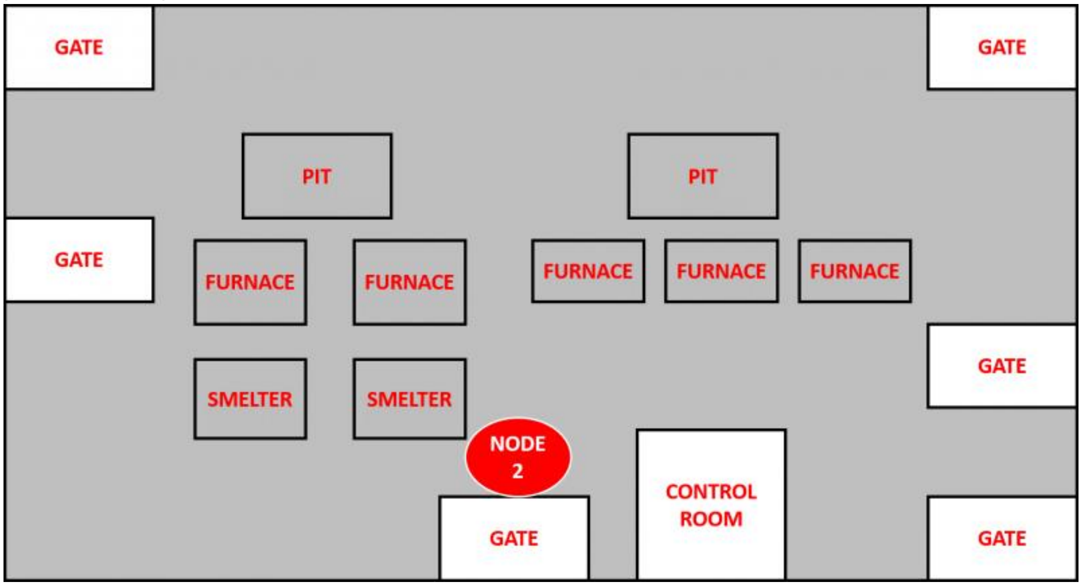
	9	8	7	6	5	4	3	2	1	-2	-3	-4	-5	-6	-7	-8	-9	

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16		
A = Visual Andons																		B = Audio Andons
A = Visual Andons																		B = Footprints
A = Audio Andons																		B = Footprints

Q21
Give the importance of Visual tool A over Visual Tool B, keeping in mind that ***"The node is very noisy and workers require earplugs around the node."***

	9	8	7	6	5	4	3	2	1	-2	-3	-4	-5	-6	-7	-8	-9	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16		
A = Visual Andons																		B = Audio Andons
A = Visual Andons																		B = Footprints
A = Audio Andons																		B = Footprints

Q22 The image below is a representation of the hypothetical work-area that is under consideration in this study. We assign the visual tool for the highlighted Node 2. All data provided below pertains to this node.

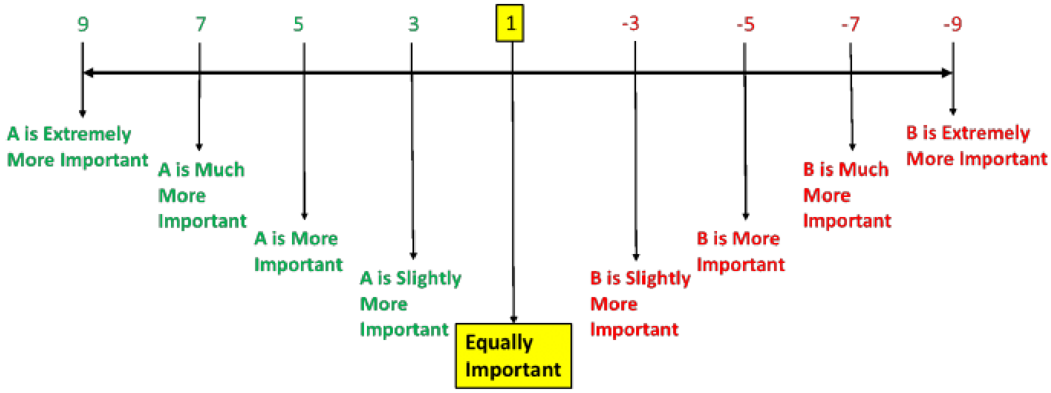


Q23 Past interfaces reported:

a. Metal Hauler- Pedestrian
b. Metal Hauler – Skim Truck
c. Skim Truck - Pedestrian
Node description:
Experience of Personnel: Drivers may/may not be full time employees and the maximum experience they have is between 1-2 years
Type of Entity at the Node: Metal haulers, 18 wheelers, Skim Trucks and pedestrians present/passing through the node
Mobility of Entities: High frequency of mobile entities present due to multiple gates
Confined Layout: Due to the narrow and confined pathways, the larger mobile entities may have difficulty in smooth movements leading to chances of traveling in reverse direction to avoid crashes
Cluttered Layout: The node is not cluttered Noise Level: Random loud noises due to the movement of entities and their sirens

Q24
<u>Pairwise Comparison between the criteria</u>

The scale for the questionnaire ranges from +9 to -9, as shown below. The intensities 2,4,6,8 can be used to express intermediate values.



Q25 **Using the information provided before, give the importance of Criteria A when compared to Criteria B when assigning a visual tool to a given work area to increase risk awareness.**

(For example: When A = Cluttered Layout and B = Confined Layout, if your choice is +9 then, you believe that Cluttered Layout is extremely important compared to Confined Layout when assigning a visual tool to a given work area to increase risk awareness.)

Or

(When A = Cluttered Layout and B = Confined Layout, if your choice is -9 then, you believe that Confined Layout is extremely important compared to Cluttered Layout when assigning a visual tool to a given work area to increase risk awareness.)

	9	8	7	6	5	4	3	2	1	-2	-3	-4	-5	-6	-7	-8	-9

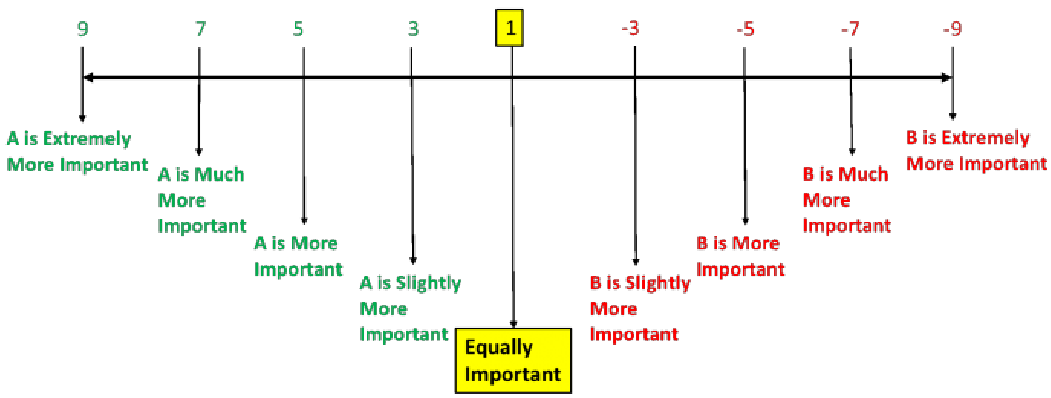
A = Cluttered Layout		B = Confined Layout
A = Cluttered Layout		B = Experience of Personnel
A = Cluttered Layout		B = Mobility of Entities
A = Cluttered Layout		B = Noise Level
A = Cluttered Layout		B = Type of Entity
A = Confined Layout		B = Experience of Personnel
A = Confined Layout		B = Mobility of Entities
A = Confined Layout		B = Noise Level
A = Confined Layout		B = Type of Entity
A = Experience of Personnel		B = Mobility of Entities
A = Experience of Personnel		B = Noise Level
A = Experience of Personnel		B = Type of Entity

A = Mobility of Entities		B = Noise Level
A = Mobility of Entities		B = Type of Entity
A = Noise Level		B = Type of Entity

Q26

Pairwise Comparison between the alternatives for each criteria

The scale for the questionnaire ranges from +9 to -9, as shown below. The intensities 2,4,6,8 can be used to express intermediate values.



Q27

Give the importance of Visual tool A over Visual Tool B, keeping in mind that ***"The drivers may/may not be full time employees and the maximum experience they have is between 1-2 years."***

	9	8	7	6	5	4	3	2	1	-2	-3	-4	-5	-6	-7	-8	-9	

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A = Visual Andons		B = Audio Andons
A = Visual Andons		B = Footprints
A = Audio Andons		B = Footprints

Q28
Give the importance of Visual tool A over Visual Tool B, keeping in mind that ***"Metal Haulers, 18 Wheelers, Skim Trucks and Pedestrians are present/passing through the node."***

	9	8	7	6	5	4	3	2	1	-2	-3	-4	-5	-6	-7	-8	-9	
A = Visual Andons																		B = Audio Andons
A = Visual Andons																		B = Footprints
A = Audio Andons																		B = Footprints

Q29
Give the importance of Visual tool A over Visual Tool B, keeping in mind that ***"High frequency of mobile entities are present due to multiple gates."***

	9	8	7	6	5	4	3	2	1	-2	-3	-4	-5	-6	-7	-8	-9	

Page 16 of 26

A = Visual Andons		B = Audio Andons
A = Visual Andons		B = Footprints
A = Audio Andons		B = Footprints

Q30
Give the importance of Visual tool A over Visual Tool B, keeping in mind that ***"Due to the narrow and confined pathways, the larger mobile entities may have difficulty in smooth movements leading to chances of travelling in reverse direction to avoid crashes."***

	9	8	7	6	5	4	3	2	1	-2	-3	-4	-5	-6	-7	-8	-9	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16		
A = Visual Andons																		B = Audio Andons
A = Visual Andons																		B = Footprints
A = Audio Andons																		B = Footprints

Q31
Give the importance of Visual tool A over Visual Tool B, keeping in mind that ***"The node is not cluttered."***

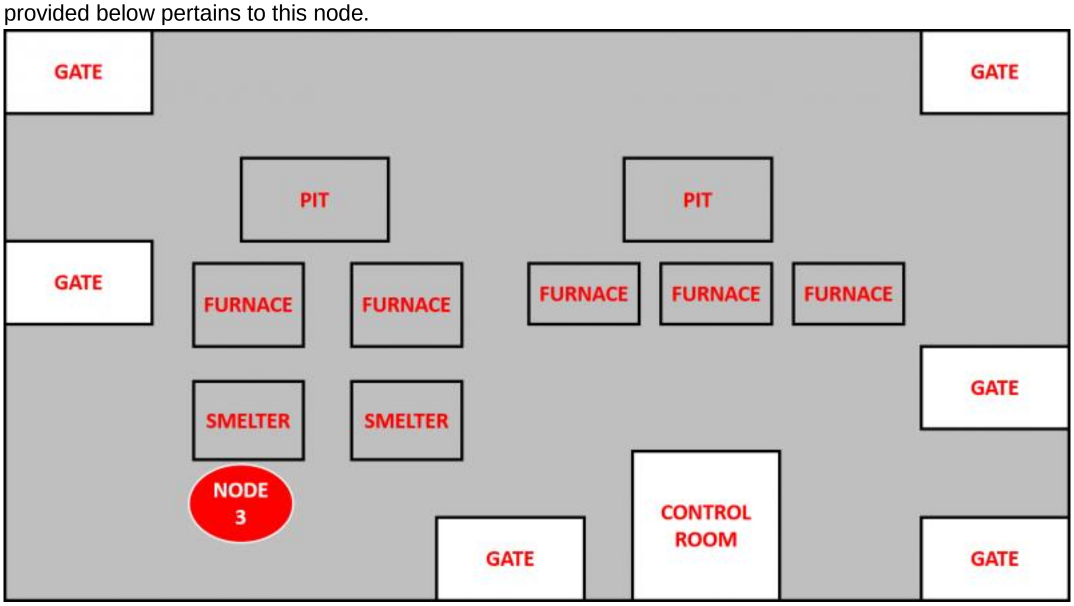
	9	8	7	6	5	4	3	2	1	-2	-3	-4	-5	-6	-7	-8	-9	

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16		
A = Visual Andons																		B = Audio Andons
A = Visual Andons																		B = Footprints
A = Audio Andons																		B = Footprints

Q32
Give the importance of Visual tool A over Visual Tool B, keeping in mind that ***<u>"Random loud noises are heard due to the movement of entities and their sirens."</u>***

	9	8	7	6	5	4	3	2	1	-2	-3	-4	-5	-6	-7	-8	-9	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16		
A = Visual Andons																		B = Audio Andons
A = Visual Andons																		B = Footprints
A = Audio Andons																		B = Footprints

Q33 The image below is a representation of the hypothetical work-area that is under consideration in this study. We assign the visual tool for the highlighted Node 3. All data provided below pertains to this node.

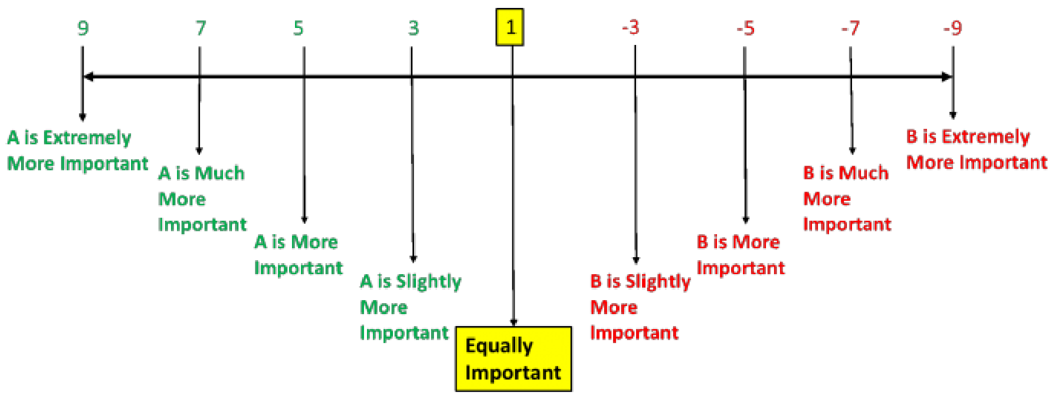


Q34 Past interfaces reported:
a. Metal Hauler-Pedestrian
b. Overhead Crane-Pedestrian
Node description:

Type of Entity at the Node: metal haulers, pedestrians, overhead cranes present/passing through the node Mobility of Entities: maximum entity movement due to an entry point and vicinity to some exit points Noise Level: Random loud noises due to the movement of entities and their sirens Temperature: node experiences extremely high temperatures due to the presence of smelters and walls/machinery Lighting: mostly artificial lighting is used Visibility: low visibility due to lack of open spaces

Q35
Pairwise Comparison between the criteria

The scale for the questionnaire ranges from +9 to -9, as shown below. The intensities 2,4,6,8 can be used to express intermediate values.



Q36 **Using the information provided before, give the importance of Criteria A when compared to Criteria B when assigning a visual tool to a given work area to increase risk awareness.**

(For example: When A = Lighting and B = Visibility, if your choice is +9 then, you believe that Lighting is extremely important over Visibility when assigning a visual tool to a given work area to increase risk awareness.)

Or

(When A = Lighting and B = Visibility*, if your choice is -9 then, you believe that Visibility is*

extremely important over Lighting *when assigning a visual tool to a given work area to increase risk awareness.)*

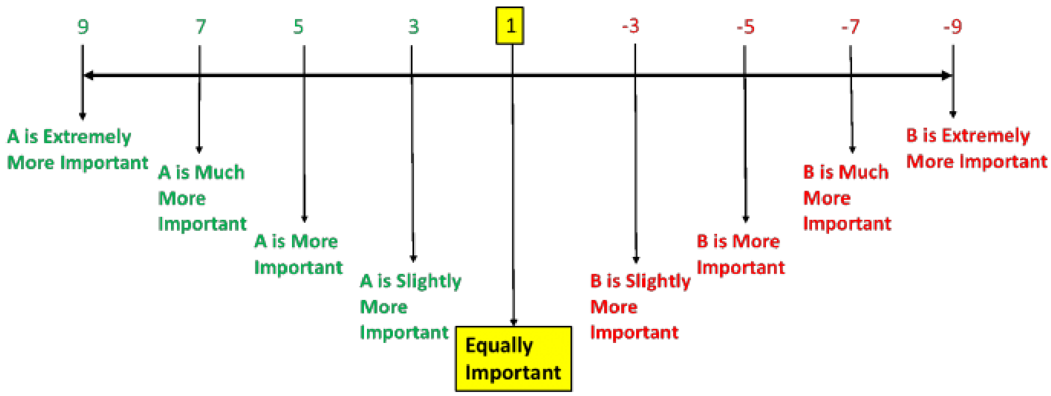
	9 8 7 6 5 4 3 2 1 -2 -3 -4 -5 -6 -7 -8 -9	

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
A = Lighting																	B = Mobility of Entities
A = Lighting																	B = Noise Level
A = Lighting																	B = Temperature
A = Lighting																	B = Type of Entity
A = Lighting																	B = Visibility
A = Mobility of Entities																	B = Noise Level
A = Mobility of Entities																	B = Temperature
A = Mobility of Entities																	B = Type of Entity
A = Mobility of Entities																	B = Visibility
A = Noise Level																	B = Temperature
A = Noise Level																	B = Type of Entity
A = Noise Level																	B = Visibility
A = Temperature																	B = Type of Entity
A = Temperature																	B = Visibility
A = Type of Entity																	B = Visibility

Q37

Pairwise Comparison between the alternatives for each criteria

The scale for the questionnaire ranges from +9 to -9, as shown below. The intensities 2,4,6,8 can be used to express intermediate values.



Q38

Give the importance of Visual tool A over Visual Tool B, keeping in mind that ***"Metal haulers, pedestrians, overhead cranes are present/passing through the node."***

	9	8	7	6	5	4	3	2	1	-2	-3	-4	-5	-6	-7	-8	- 9	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16		
A = Visual Andons																		B = Audio Andons
A = Visual Andons																		B = Footprints
A = Audio Andons																		B = Footprints

Q39

Give the importance of Visual tool A over Visual Tool B, keeping in mind that ***"There is maximum entity movement due to an entry point and vicinity to some exit points."***

	9	8	7	6	5	4	3	2	1	-2	-3	-4	-5	-6	-7	-8	-	

																	9	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16		
A = Visual Andons																		B = Audio Andons
A = Visual Andons																		B = Footprints
A = Audio Andons																		B = Footprints

Q40
Give the importance of Visual tool A over Visual Tool B, keeping in mind that ***<u>"There are random loud noises due to the movement of entities and their sirens."</u>***

	9	8	7	6	5	4	3	2	1	-2	-3	-4	-5	-6	-7	-8	-9	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16		
A = Visual Andons																		B = Audio Andons
A = Visual Andons																		B = Footprints
A = Audio Andons																		B = Footprints

Q41
Give the importance of Visual tool A over Visual Tool B, keeping in mind that ***<u>"The node experiences extremely high temperatures due to the presence of smelters and walls/machinery."</u>***

	9	8	7	6	5	4	3	2	1	-2	-3	-4	-5	-6	-7	-8	-9	

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16		
A = Visual Andons																		B = Audio Andons
A = Visual Andons																		B = Footprints
A = Audio Andons																		B = Footprints

Q42

Give the importance of Visual tool A over Visual Tool B, keeping in mind that ***"Mostly artificial lighting is used."***

	9	8	7	6	5	4	3	2	1	-2	-3	-4	-5	-6	-7	-8	-9	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16		
A = Visual Andons																		B = Audio Andons
A = Visual Andons																		B = Footprints
A = Audio Andons																		B = Footprints

Q43

Give the importance of Visual tool A over Visual Tool B, keeping in mind that ***"There is a low visibility due to lack of open spaces."***

	9	8	7	6	5	4	3	2	1	-2	-3	-4	-5	-6	-7	-8	-9	

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
A = Visual Andons																	B = Audio Andons
A = Visual Andons																	B = Footprints
A = Audio Andons																	B = Footprints

C IRB Approval and Consent Form

C.1 IRB Approval

THE UNIVERSITY of TENNESSEE
KNOXVILLE
Office of Research & Engagement
INSTITUTIONAL REVIEW BOARD (IRB)

1534 White Ave.
Knoxville, TN 37996-1529
865-974-7697
fax 865-974-7400

April 28, 2017

Riddhi Pradeep Shah,
UTK - College of Engineering - Industrial & Information Engineering

Re: UTK IRB-17-03694-XM
Study Title: Methodology to assign visual tools to a work area using Analytical Hierarchy Process in order to increase risk awareness.

Dear Riddhi Pradeep Shah:

The Administrative Section of the UTK Institutional Review Board (IRB) reviewed your application for the above referenced project. The IRB determined that your application is eligible for **exempt** review under 45 CFR 46 Category 2. In accord with 45 CFR 46.116(d), informed consent may be altered, with the cover statement used in lieu of an informed consent interview. The requirement to secure a signed consent form is waived under 45 CFR 46.117(c)(2). Willingness of the subject to participate will constitute adequate documentation of consent. Your application has been determined to comply with proper consideration for the rights and welfare of human subjects and the regulatory requirements for the protection of human subjects.

This letter constitutes full approval of your application (version 1.1), E-mail Script to Participants (version 1.0), Consent Cover Statement_Riddhi (version 1.3), and Survey Questionnaire (version 1.0), stamped approved by the IRB on 04/28/2017 for the above referenced study.

In the event that volunteers are to be recruited using solicitation materials, such as brochures, posters, web-based advertisements, etc., these materials must receive prior approval of the IRB.

Any alterations (revisions) in the protocol, consent cover statement, or survey must be promptly submitted to and approved by the UTK Institutional Review Board prior to implementation of these revisions. You have individual responsibility for reporting to the Board in the event of unanticipated or serious adverse events and subject deaths.

Sincerely,

Colleen P. Gilrane

Colleen P. Girlane, Ph.D.
Chair

C.2 Consent Form

Consent Cover Statement

Methodology to assign visual tools to a work area using Analytical Hierarchy Process to increase risk awareness.

INTRODUCTION:

The University of Tennessee's Industrial & Systems Engineering Department is conducting a study to assign visual tools to work areas in manufacturing industries to increase the risk awareness in their environment. Graduate students from the department assigned on this project will be collecting responses for the survey. The responses will be used to develop a methodology for this visual tool assignment.

INFORMATION ABOUT PARTICIPANTS' INVOLVEMENT IN THE STUDY:

This survey would take anonymous responses from safety experts in manufacturing industries. All participants must be between 21 – 70 years of age. Once you provide consent to take the survey, you will be sent a Google Form with the survey. Once responses from all participants is received, the survey data will be analyzed to study the expert's perspective on which variable is more important than another, which variables impact which visual tool, and which visual tool can be assigned to a given work area. These studies will be performed using statistical tools.

RISKS:

There are no foreseeable risks to this survey other than those encountered in everyday life.

BENEFITS:

The survey allows the safety experts, visual tool experts or manufacturing experts to score variables that can be included in a visual tool assignment algorithm. The cumulative responses will be presented in scientific documents to help manufacturing industries make a systematic allocation of visual tools.

CONFIDENTIALITY:

The reported information will not be personally identifiable. No reference will be made in oral or written reports which could link participants to the study. The survey responses will be stored on CASRE (Center for Advanced System, Research and Education) server and will be available to the student advisor (Dr. Rapinder Sawhney), CASRE graduate students and The University of Tennessee. Only aggregated results of the survey will be reported.

DURATION:

They survey will take no longer than 20-25 minutes to complete.

CONTACT INFORMATION:
If you have questions at any time about the study, you may contact the researcher, (Riddhi Pradeep Shah), at (Address: 865 Neyland Dr, Knoxville, TN 37996), and (Office Phone Number at (858)-228-0693). If you have questions about your rights as a participant, contact the Office of Research Compliance Officer at (865) 974-3466.

PARTICIPATION:

Your participation in this study is voluntary; you may decline to participate without penalty. If you decide to participate, you may withdraw from the study at any time without penalty. If you withdraw from the study before data collection is completed your data will be discarded from all records immediately. However, we sincerely hope that you will agree to support this important study by completing a brief survey attached.

CONSENT:
I have read the above information. I have received (or had the opportunity to print) a copy of this form.
Return of the completed survey (questionnaire) constitutes my consent to participate. _OR_ clicking on the button to continue and completing the survey (questionnaire) constitutes my consent to participate.

D Participants' e-mail script

D.1 Participants' e-mail script

E-mail to Contacts

The University of Tennessee's Industrial & Systems Engineering Department is conducting a study to assign visual tools to work areas in manufacturing industries to increase the risk awareness in their environment. For this we would like you to consider allowing members of your esteemed organization to participate in this study by filling out a survey.

Manufacturing companies report accidents between entities passing through their system. Visual tools are commonly placed in such work-areas to increase risk awareness among these entities. Currently, there does not exist a logical method to make this placement. This study aims to propose a methodology that companies can use to make a visual tool assignment to a work area by studying all the variables that make the work area risky.

The survey below is to compare the different variables affecting a hypothetical work-area and visual tools that could be placed in such an area. The results of the survey are analyzed to make a visual tool assignment based on different pair-wise comparisons.

We need participants in the following roles:

- Safety Experts in manufacturing environment
- Between 21-70 years of age

Please forward this email to personnel within your organization that fit this criterion.

Please contact me if you have any questions.

Thank you,

Riddhi Pradeep Shah

MS Student

Department of Industrial and Systems Engineering

University of Tennessee

E DEA code for GAMS

E.1 DEA code for GAMS

```
*$title Data Envelopment Analysis - DEA (DEA,SEQ=192)
*$ontext
*Data Envelopment Analysis (DEA) is a technique for measuring the relative
*performance of organizational units where presence of multiple inputs and
*outputs makes comparison difficult.

*            efficiency = weighted sum of output / weighted sum of input

*Find weights that maximize the efficiency for one unit while ensuring
*that no other units has an efficiency < 1 using these weights. A primal
*and dual formulation is presented.


*Dyson, Thanassoulis, and Boussofiane, A DEA Tutorial.
*Warwick Business School. http://www.deazone.com/tutorial/

*$offtext

sets  i     units
      is(i) selected unit
      j     inputs and outputs
      ji(j) inputs
      jo(j)           outputs

Parameter data(i,j) unit input  output
          vlo       v lower bound
          ulo       u lower bound
          norm      normalizing constant

Variables v(ji) input weights
          u(jo) output weights
          eff   efficiency
          var   dual convexity

          lam(i) dual weights
          vs(ji) input duals
          us(jo) output duals
          Z

positive variables u,v,vs,us,lam;

Equations defe(i)  efficiency definition - weighted output
          denom(i) weighted input
          lime(i)  'output / input < 1'
          dii(i,ji) input duals
          dio(i,jo) output dual
          defvar    variable return to scale
          dobj      dual objective;

*  primal model

defe(is)..   eff =e= sum(jo, u(jo)*data(is,jo)) - 1*var;

denom(is)..  sum(ji, v(ji)*data(is,ji)) =e= norm;

lime(i)..    sum(jo, u(jo)*data(i,jo)) =l= sum(ji, v(ji)*data(i,ji)) + var;

```

```
*  dual model

dii(is,ji).. sum(i, lam(i)*data(i,ji)) + vs(ji) =e= z*data(is,ji);

dio(is,jo).. sum(i, lam(i)*data(i,jo)) - us(jo) =e=     data(is,jo);

defvar..     sum(i, lam(i)) =e= 1;

dobj.. eff =e= norm*z - vlo*sum(ji, vs(ji)) - ulo*sum(jo, us(jo));





model deap  primal / defe, denom,lime /
      deadc dual with CRS / dobj, dii, dio /
      deadv dual with VRS / dobj, dii, dio, defvar  /

sets  i  units / Depot1*Depot11 /
      j     inputs and outputs / R1*R25 /
      ji(j) inputs             /  R25                                    /
      jo(j)            outputs /               R1*R24/


Table data(i,j)
                          R1       R2       R3       R4       R5       R6      »
 R7       R8       R9      R10      R11      R12      R13      R14      R15      »
 R16      R17      R18      R19      R20      R21      R22      R23      R24      »
   R25
Depot1                    2        4        2        2        5        4       »
 4        4        3        1        3        3        5        4        3       »
  3        1        3        2        3        3        2        2        2      »
    1
Depot2                    5        3        4        4        3        5       »
 5        4        5        4        2        5        5        5        5       »
  4        1        4        5        2        4        5        5        5      »
    1
Depot3                    1        3        2        2        4        3       »
 4        5        5        4        2        3        4        4        2       »
  3        1        5        2        2        5        5        2        3      »
    1
Depot4                    4        3        5        4        2        5       »
 5        4        5        5        2        5        5        4        4       »
  5        2        4        5        4        5        4        3        2      »
    1
Depot5                    4        5        5        4        4        4       »
 3        3        5        4        4        5        1        4        4       »
  5        5        4        5        4        5        3        4        5      »
    1
Depot6                    5        4        5        4        3        3       »
 3        4        5        5        3        5        5        5        5       »
  5        2        5        5        4        5        5        4        4      »
    1
Depot7                    4        4        4        4        4        3       »
 4        5        5        5        3        5        2        4        5       »
  5        2        4        2        4        3        4        3        3      »
    1
```

```
Depot8                    5        4        4        3        3        4        »
  2        3        5        4        4        5        2        4        4        »
   4        3        4        2        4        3        4        3        2        »
     1
Depot9                    3        4        4        3        2        3        »
  1        3        3        4        4        3        5        5        3        »
   4        4        5        5        3        3        3        4        2        »
     1
Depot10                   3        4        4        4        5        4        »
  2        3        3        4        2        3        5        5        4        »
   4        4        4        2        3        3        3        4        3        »
     1
Depot11                   5        5        5        5        5        5        »
  5        5        5        5        5        5        5        5        5        »
   5        5        5        5        5        5        5        5        5        »
     1


$eolcom //
option limcol=0           // no column listing
       limrow=0           // no row listing
       solveopt=replace;  // don't keep old var and equ values



var.fx = 0;        // to run CRS with the primal model
*var.lo = -inf;    // to run VRS with the primal model
*var.up = +inf;    // to run VRS with the primal model
vlo=1e-4;
ulo=1e-4;
norm=100;

v.lo(ji) = vlo;
u.lo(jo) = ulo;

*deadc.solprint=%solprint.Quiet%;
*deadv.solprint=%solprint.Quiet%;
*deap.solprint=%solprint.Quiet%;

set ii(i) set of units to analyze / depot11 /;

*ii(i) = yes;       // use to run all depots
is(i) = no;

parameter rep summary report;

loop(ii,
   is(ii) = yes;
   solve deap us lp max eff;
   rep(i,ii) =  sum(jo, u.l(jo)*data(i,jo))/sum(ji, v.l(ji)*data(i,ji));
   rep('MStat-p',ii) = deap.modelstat;
   solve deadc us lp min eff ;
   rep('MStat-d',ii) = deadc.modelstat;
   rep('obj-check',ii) = deadc.objval - deap.objval;
   is(ii) = no);

rep(i,'Min') = smin(ii, rep(i,ii));
```

```
rep(i,'Max') = smax(ii, rep(i,ii));
rep(i,'Avg') =  sum(ii, rep(i,ii))/card(ii);

display rep;

```

F Individual priorities vectors and aggregation of individual priorities

F.1 Node - 1

1	Criteria	Age of personnel	Lighting	Mobility of Entities	Noise Level	Temperature	Type of Entity	Visibility	
	Weight	0.024800991	0.188581978	0.171692856	0.075092125	0.042082881	0.255134603	0.242614566	
	Visual Andon	0.19657019	0.104800202	0.179421641	0.510925964	0.10945229	0.499702962	0.177276126	0.26891785
	Audio Andon	0.051379316	0.499079855	0.142407051	0.069056776	0.308995644	0.073057016	0.085225472	0.177347358
	Footprints	0.752050494	0.396119943	0.678171308	0.42001726	0.581552067	0.427240022	0.737498402	0.553734792
2	Criteria	Age of personnel	Lighting	Mobility of Entities	Noise Level	Temperature	Type of Entity	Visibility	
	Weight	0.015540558	0.243990006	0.141963233	0.055684369	0.06827702	0.040920942	0.433623872	
	Visual Andon	0.256146188	0.239905956	0.313204663	0.753110927	0.275302927	0.736842105	0.247848147	0.305337374
	Audio Andon	0.679480224	0.701489271	0.618861492	0.183971653	0.658974425	0.210526316	0.688414616	0.631936553
	Footprints	0.064373588	0.058604773	0.067933845	0.06291742	0.065722647	0.052631579	0.063737237	0.062726073
3	Criteria	Age of personnel	Lighting	Mobility of Entities	Noise Level	Temperature	Type of Entity	Visibility	
	Weight	0.086430696	0.164853787	0.04724284	0.038374874	0.06102397	0.382630304	0.219443529	
	Visual Andon	0.761904762	0.073828188	0.578311105	0.77849057	0.741864203	0.19047619	0.470588235	0.356639356
	Audio Andon	0.19047619	0.214426064	0.364313167	0.041584359	0.202733595	0.761904762	0.470588235	0.477785924
	Footprints	0.047619048	0.711745748	0.057375728	0.179925071	0.055402202	0.047619048	0.058823529	0.16557472
4	Criteria	Age of personnel	Lighting	Mobility of Entities	Noise Level	Temperature	Type of Entity	Visibility	
	Weight	0.054858961	0.05463863	0.115999578	0.181920509	0.197630879	0.161180891	0.233770553	
	Visual Andon	0.332515928	0.711263763	0.584156411	0.771646483	0.310813683	0.263074223	0.222222222	0.421022104
	Audio Andon	0.527836133	0.226766438	0.280833111	0.053081678	0.493385967	0.547216435	0.666666667	0.425136087
	Footprints	0.139647939	0.061969799	0.135010478	0.175271839	0.195800351	0.189709342	0.111111111	0.153841808
5	Criteria	Age of personnel	Lighting	Mobility of Entities	Noise Level	Temperature	Type of Entity	Visibility	
	Weight	0.032738581	0.144685938	0.147141042	0.350541992	0.042978916	0.036842466	0.245071065	
	Visual Andon	0.559065046	0.559065046	0.559065046	0.591727402	0.249310525	0.559065046	0.546930565	0.554227849
	Audio Andon	0.35218891	0.35218891	0.35218891	0.333215866	0.157055789	0.35218891	0.344544666	0.335278068
	Footprints	0.088746044	0.088746044	0.088746044	0.075056733	0.593633685	0.088746044	0.108524769	0.110494082

6	Criteria	Age of personnel	Lighting	Mobility of Entities	Noise Level	Temperature	Type of Entity	Visibility	
	Weight	0.052073147	0.393414282	0.0386902	0.286782537	0.0386902	0.037959144	0.15239049	
	Visual Andon	0.78700985	0.77849057	0.78700985	0.78700985	0.78700985	0.78700985	0.77849057	0.782359986
	Audio Andon	0.045712851	0.179925071	0.045712851	0.045712851	0.045712851	0.045712851	0.179925071	0.118966521
	Footprints	0.167277298	0.041584359	0.167277298	0.167277298	0.167277298	0.167277298	0.041584359	0.098673492
7	Criteria	Age of personnel	Lighting	Mobility of Entities	Noise Level	Temperature	Type of Entity	Visibility	
	Weight	0.018734458	0.328965696	0.165041074	0.076973421	0.044685598	0.104204464	0.261395289	
	Visual Andon	0.333333333	0.333333333	0.333333333	0.678661622	0.333333333	0.333333333	0.333333333	0.359914433
	Audio Andon	0.333333333	0.333333333	0.333333333	0.074696377	0.333333333	0.333333333	0.333333333	0.313425162
	Footprints	0.333333333	0.333333333	0.333333333	0.246642002	0.333333333	0.333333333	0.333333333	0.326660405
8	Criteria	Age of personnel	Lighting	Mobility of Entities	Noise Level	Temperature	Type of Entity	Visibility	
	Weight	0.020795064	0.190952722	0.136164723	0.098568954	0.066557106	0.107444628	0.379516804	
	Visual Andon	0.236340702	0.287202762	0.348363014	0.190526272	0.614410656	0.582149192	0.177493987	0.296775747
	Audio Andon	0.081934745	0.077958824	0.069487794	0.068594684	0.268368573	0.069487794	0.518995565	0.255108844
	Footprints	0.681724553	0.634838414	0.582149192	0.740879044	0.117220771	0.348363014	0.303510448	0.448115409
9	Criteria	Age of personnel	Lighting	Mobility of Entities	Noise Level	Temperature	Type of Entity	Visibility	
	Weight	0.099630546	0.337350905	0.079719891	0.026884169	0.037421784	0.085310611	0.333682094	
	Visual Andon	0.643359719	0.260598386	0.131111685	0.567458326	0.290643076	0.322955082	0.333333333	0.327374479
	Audio Andon	0.255317474	0.656666784	0.660761488	0.075065329	0.604561961	0.110449084	0.333333333	0.444932086
	Footprints	0.101322807	0.08273483	0.208126827	0.357476345	0.104794963	0.566595833	0.333333333	0.227693435
10	Criteria	Age of personnel	Lighting	Mobility of Entities	Noise Level	Temperature	Type of Entity	Visibility	
	Weight	0.033358008	0.072443079	0.088309103	0.197865554	0.12808012	0.089183792	0.390760344	
	Visual Andon	0.179925071	0.151395248	0.179925071	0.77849057	0.179925071	0.179925071	0.179925071	0.296293777
	Audio Andon	0.041584359	0.796828305	0.041584359	0.179925071	0.041584359	0.041584359	0.041584359	0.123669418

	Footprints	0.77849057	0.051776447	0.77849057	0.041584359	0.77849057	0.77849057	0.77849057	0.580036805
AIP	Criteria	Age of personnel	Lighting	Mobility of Entities	Noise Level	Temperature	Type of Entity	Visibility	Preferences
	Weights	0.036355648	0.180256222	0.101865803	0.101706728	0.061866563	0.097383034	0.27644992	
	Visual Andon	0.372316602	0.271426538	0.343516822	0.601005712	0.32842561	0.394602172	0.304893584	0.301615003
	Audio Andon	0.166512804	0.328576774	0.197953148	0.088526173	0.224750513	0.15998238	0.277789462	0.200729039
	Footprints	0.196462841	0.142387093	0.209971416	0.17594058	0.205025404	0.208392041	0.180347707	0.154927117

F.2 Node - 2

1	Criteria	Cluttered Layout	Confined Layout	Experience of Personnel	Mobility of Entities	Noise Level	Type of Entity	
	Weight	0.031373263	0.218681821	0.188992314	0.281951174	0.038941858	0.24005957	
	Visual Andon	0.484410185	0.333333333	0.333333333	0.333333333	0.479121082	0.454545455	0.372848483
	Audio Andon	0.09241854	0.333333333	0.333333333	0.333333333	0.06261609	0.090909091	0.257036558
	Footprints	0.423171275	0.333333333	0.333333333	0.333333333	0.458262829	0.454545455	0.370114959
2	Criteria	Cluttered Layout	Confined Layout	Experience of Personnel	Mobility of Entities	Noise Level	Type of Entity	
	Weight	0.113398089	0.363225526	0.140095326	0.255636161	0.054004531	0.073640367	
	Visual Andon	0.200878741	0.219225367	0.626444711	0.200878741	0.717065041	0.217165609	0.296238277
	Audio Andon	0.735076724	0.723866214	0.301163205	0.735076724	0.217165609	0.717065041	0.640919591
	Footprints	0.064044535	0.056908419	0.072392084	0.064044535	0.06576935	0.06576935	0.062842132
3	Criteria	Cluttered Layout	Confined Layout	Experience of Personnel	Mobility of Entities	Noise Level	Type of Entity	
	Weight	0.134452893	0.239567821	0.125235985	0.16940003	0.165671635	0.165671635	
	Visual Andon	0.493385967	0.179925071	0.493385967	0.179925071	0.77849057	0.179925071	0.360492705
	Audio Andon	0.310813683	0.77849057	0.310813683	0.77849057	0.041584359	0.77849057	0.534955627
	Footprints	0.195800351	0.041584359	0.195800351	0.041584359	0.179925071	0.041584359	0.104551669
4	Criteria	Cluttered Layout	Confined Layout	Experience of Personnel	Mobility of Entities	Noise Level	Type of Entity	
	Weight	0.176982077	0.353964155	0.277935805	0.065645871	0.059116295	0.066355797	
	Visual Andon	0.365758814	0.701555385	0.251477928	0.279687511	0.737498402	0.202119987	0.45832327
	Audio Andon	0.332313937	0.225781426	0.673390446	0.626696471	0.085225472	0.700710858	0.418565936
	Footprints	0.301927249	0.07266319	0.075131625	0.093616018	0.177276126	0.097169155	0.123110795
5	Criteria	Cluttered Layout	Confined Layout	Experience of Personnel	Mobility of Entities	Noise Level	Type of Entity	
	Weight	0.152400712	0.219799861	0.05542934	0.163055532	0.345177615	0.064136941	
	Visual Andon	0.310813683	0.249310525	0.238487123	0.296961331	0.6	0.546930565	0.405992039
	Audio Andon	0.195800351	0.157055789	0.136499803	0.163424119	0.3	0.344544666	0.224225579
	Footprints	0.493385967	0.593633685	0.625013074	0.53961455	0.1	0.108524769	0.369782382

6	Criteria	Cluttered Layout	Confined Layout	Experience of Personnel	Mobility of Entities	Noise Level	Type of Entity	
	Weight	0.17773868	0.114488169	0.418947211	0.114488169	0.059849602	0.114488169	
	Visual Andon	0.78700985	0.77849057	0.78700985	0.77849057	0.78700985	0.78700985	0.785059137
	Audio Andon	0.167277298	0.179925071	0.167277298	0.179925071	0.045712851	0.045712851	0.148980064
	Footprints	0.045712851	0.041584359	0.045712851	0.041584359	0.167277298	0.167277298	0.065960799
7	Criteria	Cluttered Layout	Confined Layout	Experience of Personnel	Mobility of Entities	Noise Level	Type of Entity	
	Weight	0.129880598	0.214428144	0.299382326	0.231900552	0.038570153	0.085838227	
	Visual Andon	0.584156411	0.818181818	0.461538462	0.759436412	0.473684211	0.461538462	0.62348969
	Audio Andon	0.135010478	0.090909091	0.076923077	0.068344994	0.052631579	0.076923077	0.084540309
	Footprints	0.280833111	0.090909091	0.461538462	0.172218594	0.473684211	0.461538462	0.291970001
8	Criteria	Cluttered Layout	Confined Layout	Experience of Personnel	Mobility of Entities	Noise Level	Type of Entity	
	Weight	0.20964345	0.08015974	0.066609615	0.224300294	0.20964345	0.20964345	
	Visual Andon	0.202733595	0.273792093	0.260598386	0.217165609	0.226766438	0.234410916	0.227200353
	Audio Andon	0.055402202	0.076975065	0.08273483	0.06576935	0.061969799	0.080167406	0.067846164
	Footprints	0.741864203	0.649232842	0.656666784	0.717065041	0.711263763	0.685421678	0.704953483
9	Criteria	Cluttered Layout	Confined Layout	Experience of Personnel	Mobility of Entities	Noise Level	Type of Entity	
	Weight	0.160261396	0.264585734	0.171465782	0.171465782	0.08243215	0.149789157	
	Visual Andon	0.6	0.332515928	0.625013074	0.593633685	0.717065041	0.493385967	0.526105108
	Audio Andon	0.2	0.527836133	0.136499803	0.249310525	0.06576935	0.195800351	0.272613738
	Footprints	0.2	0.139647939	0.238487123	0.157055789	0.217165609	0.310813683	0.201281154
10	Criteria	Cluttered Layout	Confined Layout	Experience of Personnel	Mobility of Entities	Noise Level	Type of Entity	
	Weight	0.165881273	0.199212951	0.38730211	0.089094135	0.029141259	0.129368273	
	Visual Andon	0.179925071	0.179925071	0.179925071	0.179925071	0.179925071	0.041584359	0.162028172
	Audio Andon	0.041584359	0.041584359	0.041584359	0.041584359	0.041584359	0.179925071	0.059481258

	Footprints	0.77849057	0.77849057	0.77849057	0.77849057	0.77849057	0.77849057	0.77849057
AIP	Criteria	Cluttered Layout	Confined Layout	Experience of Personnel	Mobility of Entities	Noise Level	Type of Entity	Preferences
	Weight	0.132436766	0.208270947	0.175890783	0.161256469	0.077933534	0.117405949	
	Visual Andon	0.3749477	0.345151053	0.381773137	0.326394132	0.514146355	0.284137412	0.314754004
	Audio Andon	0.164257249	0.212080665	0.167448932	0.209620173	0.075344508	0.203479262	0.158940812
	Footprints	0.255211078	0.156965568	0.237487345	0.175776193	0.248993558	0.210133087	0.180683403

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1	Criteria	Lighting	Mobility of Entities	Noise Level	Temperature	Type of Entity	Visibility	
	Weight	0.090101676	0.285305159	0.073374869	0.02526341	0.305251754	0.220703131	
	Visual Andon	0.466666667	0.182640759	0.472111034	0.333333333	0.163424119	0.333333333	0.260671231
	Audio Andon	0.066666667	0.393487587	0.083615473	0.333333333	0.53961455	0.333333333	0.371113227
	Footprints	0.466666667	0.423871654	0.444273493	0.333333333	0.296961331	0.333333333	0.368215542
2	Criteria	Lighting	Mobility of Entities	Noise Level	Temperature	Type of Entity	Visibility	
	Weight	0.113488393	0.146816543	0.056020996	0.310800764	0.171040252	0.201833052	
	Visual Andon	0.234410916	0.210251555	0.737498402	0.264242056	0.260598386	0.711263763	0.369042702
	Audio Andon	0.685421678	0.694235338	0.085225472	0.665848258	0.656666784	0.226766438	0.549518614
	Footprints	0.080167406	0.095513107	0.177276126	0.069909686	0.08273483	0.061969799	0.081438683
3	Criteria	Lighting	Mobility of Entities	Noise Level	Temperature	Type of Entity	Visibility	
	Weight	0.071428571	0.035714286	0.142857143	0.142857143	0.035714286	0.571428571	
	Visual Andon	0.179925071	0.473684211	0.818181818	0.179925071	0.473684211	0.179925071	0.292087402
	Audio Andon	0.77849057	0.473684211	0.090909091	0.77849057	0.473684211	0.77849057	0.658492762
	Footprints	0.041584359	0.052631579	0.090909091	0.041584359	0.052631579	0.041584359	0.049419836
4	Criteria	Lighting	Mobility of Entities	Noise Level	Temperature	Type of Entity	Visibility	
	Weight	0.310281252	0.065372244	0.03849091	0.131292004	0.069142975	0.385420614	
	Visual Andon	0.077898553	0.218442659	0.766232288	0.249855533	0.229047541	0.06291742	0.140834258
	Audio Andon	0.70775532	0.630097661	0.075896542	0.654806738	0.695523238	0.753110927	0.688041343
	Footprints	0.214346128	0.15145968	0.15787117	0.095337729	0.075429221	0.183971653	0.171124399
5	Criteria	Lighting	Mobility of Entities	Noise Level	Temperature	Type of Entity	Visibility	
	Weight	0.2626567	0.086206528	0.270760532	0.085284223	0.069634277	0.22545774	
	Visual Andon	0.310813683	0.546930565	0.546930565	0.249310525	0.4	0.630097661	0.468049852
	Audio Andon	0.195800351	0.344544666	0.344544666	0.157055789	0.2	0.15145968	0.235888364
	Footprints	0.493385967	0.108524769	0.108524769	0.593633685	0.4	0.218442659	0.296061784

6	Criteria	Lighting	Mobility of Entities	Noise Level	Temperature	Type of Entity	Visibility	
	Weight	0.541572394	0.125168442	0.057706305	0.03016643	0.015769741	0.229616688	
	Visual Andon	0.741864203	0.77849057	0.78700985	0.741864203	0.77849057	0.741864203	0.749631445
	Audio Andon	0.055402202	0.179925071	0.045712851	0.202733595	0.041584359	0.055402202	0.074655957
	Footprints	0.202733595	0.041584359	0.167277298	0.055402202	0.179925071	0.202733595	0.175712598
7	Criteria	Lighting	Mobility of Entities	Noise Level	Temperature	Type of Entity	Visibility	
	Weight	0.36120104	0.142750395	0.045941331	0.13514482	0.033849862	0.281112553	
	Visual Andon	0.333333333	0.333333333	0.747269121	0.333333333	0.333333333	0.111111111	0.289880638
	Audio Andon	0.333333333	0.333333333	0.058748292	0.333333333	0.333333333	0.777777778	0.445657444
	Footprints	0.333333333	0.333333333	0.193982587	0.333333333	0.333333333	0.111111111	0.264461918
8	Criteria	Lighting	Mobility of Entities	Noise Level	Temperature	Type of Entity	Visibility	
	Weight	0.288641925	0.192826769	0.112320923	0.043881208	0.084224849	0.278104325	
	Visual Andon	0.643359719	0.2350621	0.260598386	0.595668188	0.178620449	0.423871654	0.419360965
	Audio Andon	0.255317474	0.113006071	0.08273483	0.308479926	0.112523832	0.182640759	0.178585735
	Footprints	0.101322807	0.651931829	0.656666784	0.095851885	0.70885572	0.393487587	0.4020533
9	Criteria	Lighting	Mobility of Entities	Noise Level	Temperature	Type of Entity	Visibility	
	Weight	0.347214129	0.091066893	0.046841223	0.178593273	0.09553965	0.240744831	
	Visual Andon	0.692773938	0.593633685	0.747269121	0.730161372	0.745006448	0.225535499	0.585480345
	Audio Andon	0.087284047	0.157055789	0.058748292	0.07666214	0.098552002	0.673810571	0.232684057
	Footprints	0.219942016	0.249310525	0.193982587	0.193176488	0.156441551	0.10065393	0.181835598
10	Criteria	Lighting	Mobility of Entities	Noise Level	Temperature	Type of Entity	Visibility	
	Weight	0.25372817	0.013553309	0.028192019	0.062741595	0.114009045	0.527775862	
	Visual Andon	0.041584359	0.179925071	0.179925071	0.77849057	0.179925071	0.179925071	0.18237909
	Audio Andon	0.179925071	0.041584359	0.041584359	0.179925071	0.041584359	0.77849057	0.474286322

	Footprints	0.77849057	0.77849057	0.77849057	0.041584359	0.77849057	0.041584359	0.343334588
AIP	Criteria	Lighting	Mobility of Entities	Noise Level	Temperature	Type of Entity	Visibility	Weights
	Weight	0.222404275	0.090250694	0.068887204	0.087116527	0.073166356	0.295315386	
	Visual Andon	0.271599171	0.327417615	0.548396324	0.390596343	0.320632647	0.274144966	0.266178119
	Audio Andon	0.227108266	0.256722316	0.078769449	0.295690823	0.207678146	0.35015782	0.223467026
	Footprints	0.21307428	0.19003669	0.228891707	0.122801032	0.214060632	0.1290462	0.144776648

Vita

Riddhi Pradeep Shah was born in Bengaluru, India, on January 17, 1993. She is the daughter of Vibha and Pradeep Shah. She completed her Bachelor's degree in Industrial Engineering and Management in year 2015 from M.S.Ramaiah Institute of Technology. She enrolled into the Master's program in the department of Industrial and Systems Engineering at the University of Tennessee, Knoxville. She served as a Graduate Teaching Assistant and a Graduate Research Assistant during her program duration and completed her Master's degree in December 2017.