IMPROVEMENT OF RESEARCH IN CONSTRUCTION SAFETY: A PROPOSAL FOR THE APPLICATION OF QUANTITATIVE APPROACHES

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ABSTRACT

The construction industry is one of the most dangerous industries in the U.S. Some of the incidents leading to construction injuries and fatalities can be attributed to collisions between workers and equipment, workers falling from roofs, scaffolds or trench edges. Traditionally, research conducted in construction safety has focused on the analysis of historical data from federal agencies, such as Occupational Safety and Health Administration (OSHA), the National Institute for Occupational Safety and Health (NIOSH), and the Bureau of Labor Statistics (BLS); interviews with industry practitioners, and qualitative assessments. Even though these research endeavors have identified important trends and issues associated with construction safety, they lack a proactive approach that can take advantage of available quantitative techniques. In this paper, several quantitative approaches are described, based on statistical techniques, design of experiments, and information technology that may assist in the process of identifying the root causes of construction accidents and opportunities for improvement of safety in construction operations. All these approaches are founded on extensive field data collection and data analysis utilizing novel techniques. The techniques presented in this paper should be used as a complement to existing qualitative approaches due to the complex nature of the analysis of safety in the construction industry, which involves the interaction of equipment, human behavior, and risky construction operations.

Keywords: Construction Safety, Information Technology, Simulation, Data Analysis

1. BACKGROUND

In the year 2006, there were 1,226 fatalities associated with the construction industry in the U.S. This accounts for almost 24% of all the fatalities of the private sector (BLS 2007). However, the construction industry accounts for only 5% of the United States' workforce (Abdelhamid and Everett 2000). This high proportion of construction injuries and fatalities is perhaps an indication that the industry needs new approaches in order to improve safety environments for workers on construction sites. Traditionallty, research in construction safety has been conducted based on the analysis of historical data, interviews, and qualitative evaluation of safety initiatives. Although these approaches assist in the process of identifying safety issues on the job site, the authors believe that more quantitative techniques should be utilized in order to identify safety management practices and their success in preventing construction worker injuries. This paper is organized as follows: (1) description of traditional safety research approaches; (2) proposed integrated methodology to conduct safety research, and (3) expected outcomes of the combination of qualitative and quantitative approaches to safety research.

2. TRADITIONAL SAFETY RESEARCH APPROACHES

Qualitative Approaches

Interviews and Focus Groups. Interviews and focus groups have traditionally been used to assist in the process of identifying factors that may affect safety performance. The purpose of the interview is to investigate and/or validate some of the prior knowledge by researchers about safety issues. During the interviews, construction practitioners are asked to describe how a specific set of factors, job site conditions, construction processes, management attitudes, external factors, and human behavior may or may not affect safety performance.. The research hypotheses are stated prior to the start of the field observation, then data is collected in the form of frequencies of accidents or near accidents, work cycles, resource analysis, safety practices, etc. After collecting a representative number of data points in the sample, then each hypothesis is tested using statistics or other tools for data analysis. Statistical validity is important for testing the hypotheses, since the data points collected must be representative of the population being analyzed. Findings from the interviews and the direct observation on the field can assist in the process of refining the original hypotheses, including new factors and/or project attributes.

Safety Behavior Evaluation. Prior research has found that the causes of accidents can be attributed to factors such as human error, unsafe behavior, and the interaction of humans with materials, tools, and environmental factors (Lehto and Salvendy, 1991). Accident reports have been used to find the causes of injuries and fatalities (Abdelhamid and Everett, 2000; Huang and Hinze, 2003; Edwards, 2003; Hide et al., 2003; Arboleda and Abraham, 2004; Chua and Goh, 2004). However, research based on the information obtained from these reports focuses mainly on after-the-fact information and stops at a premature level or ignores important steps to identify the root causes of accidents (Abdelhamid and Everett, 2000). Brown (1995) suggests that accident investigation should be based on theories of accident causation and human error, resulting in a better understanding of the relationship between the "antecedent human behavior" and the accident at a level that enables the root causes to be determined. This could result in more effective accident prevention strategies directed at the root causes of accidents and not at its symptoms.

Quantitative Approaches

Historical Data Analysis. The analysis of fatality and injury reports has been utilized by safety researchers to identify the major causes of construction injuries and fatalities. For example, Arboleda and Abraham (2004), Suruda et al. (2002), and Hinze (1997) analyzed fatality reports from federal agencies such as the Occupational Safety and Health Administration (OSHA) to determine the major causes of trenching fatalities. Based on these analyses, the major causes of fatalities were identified and safety practices were suggested. These suggestions were not evaluated in a systematic mode to determine the effectiveness and success of the different strategies. This means that the analysis of historical data should be followed by a comprehensive experiment to verify whether the proposed strategies to reduce injuries and fatalities have been successful. There are difficulties that may hinder experimental research in construction safety, such as cost of conducting the experiments, access to the construction site, and ethical issues. However, these difficulties are also present in the experimental research of other domains, constituting a challenge that may be overcome with novel ideas, collaboration from the industry, and a robust design of experiments.

Field Data Collection. Site layout organization is an important part of the planning process and can help make this process more effective. Tawfik and Fernando (1999) developed a simulation tool for organization of the site layout that considered productivity and safety. This tool could help productivity and safety by minimizing travel times for activities such as material delivery, movement of equipment and materials, and movement of labor. Also, safety could be improved by minimizing risks associated with hazard areas near equipment and work processes. Various methods, such as genetic algorithms, isovists, space syntax, and Virtual Reality (VR), were used in the development of the simulation tool. Genetic algorithms can perform a fast and efficient search through a very large number of possible solutions for enhanced site layouts according to multiple criteria that would otherwise be computationally too expensive. Virtual Reality uses computer graphics technology to produce realistic and interactive representations of buildings. Space syntax are techniques for analyzing the spatial patterns of access and visibility that are used in design decision support. It is an approach for mathematically representing and analyzing spatial patterns and properties. Isovists, or fields of vision, are used to analyze the space layout of the site. The isovist of a point in space is the visible field from that space and can be thought of as the geometry obtained by casting light rays in all directions from that point (Tawfik and Fernando 1999). The result of the analysis using isovists is the identification of regions in the site that offer higher visibility than others.

Tools like the one developed by Tawfik and Fernando (1999) could be used to assess environmental impacts on productivity and safety by taking into consideration the environmental characteristics of the job site when planning the job site layout. Computer-aided software is available to assist in the layout and visualization of construction sites. However, the lack of a layout evaluation technique that works in sufficient detail to search for good layout solutions prevents the integration between visualization modeling technologies and the layout evaluation procedure. Other approaches, such as the simulation of project environments (weather, elevation, etc.), could be used to assess the impact of project characteristics on the productivity of workers. In such simulated environments, workers would perform various tasks under a predetermined set of conditions and then be evaluated on their performance. Simulation of construction operations, including factors that affect productivity, could be employed to evaluate the impact of the factors selected.

Practices with Potential Applications in Safety Research

Risk-taking behavior and accident causation. There are many definitions of risk, including the following: the existence of threats to life or health (Fischhoff et. al, 1981), exposure to the chance of injury or loss (Hertz and Thomas, 1983), and the likelihood that harm will occur (Health and Safety Commission, 1995). Risk- taking can be defined as following a course of action selected at the end of a probabilistic process. Risk-taking behavior has been identified as a leading cause of accidents (Wagenaar, 1990). In many accident reports, the causes of accidents are attributed to irresponsible underestimation or acceptance of risk. This fact leads to the hypothesis that a misperceived risk, or a consciously accepted risk, constitutes a major cause of accidents.

Two risk theories that have been used in the study of safety issues in steel erection work (Irizarry, 2005) are the risk homeostasis theory (Wilde, 1982) and the zero-risk theory (Näätanen and Summala, 1974, 1976). The risk homeostasis theory states that an individual's behavior in risky situations is determined by a desire for cost minimization. It explains how behavior can be in accordance with risks, even subjectively perceived risks, without an ever-repeated process of conscious risk evaluation. This theory suggests that no safety measure will ever help to reduce risk and that risk control measures should be replaced by cost control measures. The zero-risk theory states that people seek situations in which there is no risk. Forces that play a role in this model are perceptual, experimental, and motivational. Perception of risk involves individual differences that cause someone to consider a situation to be risky or not risky. The aspects of skill and chance play an important role in risk perception. People who think that their skills can control the risk involved in a given situation may perceive less risk in that situation and completely ignore the chance of being injured. A person's experience is a factor that can influence the risk perceived in a situation; for example, a person who has had an auto accident while driving on wet pavement would perceive a higher risk in driving on a rainy day. Atkinson (1957) argued that the motivation to perform an act combines one's motivations to approach and to avoid the situation. The motivation to achieve success or avoid failure can influence a person's decision to engage or not in an action that has a high level of risk. These theories are important to the study of risk perception of construction workers because they relate the different dimensions of the risk perception with resulting behaviors in risky situations. Understanding these relationships can contribute to the development of safety training programs that target worker risk perception as a method of hazard prevention and avoidance.

There are many research aprocahes for the evaluation of risk on construction sites. An example is a study by Zimolong (1985), which found that accepted risk levels are established as a result of previous experiences and cognition. This study used information about accident-causing factors obtained by investigating the working conditions and personal behavior in harzardous situations. Zimolong concluded that workers are more likely to underestimate high-risk situations if they have had a long-term experience with these hazards.

Another example is a study by Huang and Hinze (2003), which used accident reports to find that approximately 33.3% of fall accidents are caused by the misjudgment of workers about hazardous situations. Huang and Hinze concluded that worker risk taking behavior may be influenced by their perception of what is safe or unsafe, and their subsequent decisions as to when adopt or not adopt required safety precautions are based on this perception.

All the analysis approaches described make use of experiential information or concepts that relate human behavior and accident causation. These are important since accidents are often the cause of risky behavior and the lessons learned from accident experiences can contribute to the reduction of situations that contributed to such accidents. Next, quantitative approaches that can be used in the study of construction accidents and their causes are discussed. Quantitative approaches make extensive use of data ranging from historical accident data to simulated project data to designed experiments.

Assessment of Job-Site Conditions. Another example of the use of quantitative data in construction safety research is related to data used in the planning for safety and the identification of hazards in the construcion activity. This approach has been used to help prevent accidents and costly delays (Burkart, 2002). By practicing good safety habits, a contractor can eliminate the undesirable costs of accidents. Less obvious and more advantageous to the contractor is the elimination of the uninsured costs that result from accidents, which result from delays caused by clearing an accident, damaged equipment, lost time while employees are interviewed for accident reports, cost of filling accident reports, etc. These costs have been estimated by various industry groups, including owners of construction projects, as being between four to 17 times the medical costs of the accident (Burkart, 2002).

Injuries can occur as a consequence of unsafe physical conditions, unsafe work practices, or a combination of the two (Hinze, 1997). Unsafe physical conditions are present when the construction site environment presents difficulties to performing the required tasks. For example, high winds can affect the movement of materials when a crane is used. Unsafe work practices are those that put the worker at risk because specified procedures are not followed. For example, a worker on an elevated structure who does not wear protective equipment is at an increased risk of experiencing a fall.

Job safety analysis consists of considering the various elements that comprise the project and evaluating the existing or possible hazards related to those elements. Not only is it important to conduct such an analysis before the start of the project, but also during the construction process. This kind of analysis is especially important when the work is unusual (i.e., work on irregularly-shaped surfaces or work on complexly-shaped structures), or when the methods used have not been tested before (i.e., use of new tools recently introduced to the market or use of recently developed construction methods).

General Conditions Hazards can be identified from the safety records of previous projects. The OSHA log of previous projects can be used to identify trends in injuries or illnesses, which in turn can assist in determining the root safety problems on various types of projects and operations. Hinze (1997) presents a sample list of questions that could be asked to identify the General Condition Hazards in order to develop strategies to mitigate those risks. These questions can be divided into groups of important factors to assist in the job site safety analysis. The major groups are:

- Physical obstructions (utilities, existing structures)
- Adjacent activities (existing neighbors, traffic)
- Environment (temperature, wind, lighting, ventilation, weather, noise, topography)
- Equipment (type, operational condition)

Specific Operations Hazards is the evaluation of specific procedures that will be used during the project. It is a more detailed and focused analysis of the work operations. An effective approach to this analysis is to use the construction schedule to determine the operations involved in the project. As with the General Condition Hazard identification procedure, Hinze (1997) presented an extensive list of factors that are more specific to the tasks.

- Type of exposure to hazards (falling, being struck by object, being caught in or between collapsing materials or objects, etc.)
- Availability of safety equipment for the task
- Trained workers
- Environmental hazards

Conducting the General Conditions Hazards and the Specific Operations Hazards analyses can increase the safety awareness of the workers on the construction site. By identifying the hazards before the operation starts, steps can be taken to mitigate the possible impacts on safety and productivity.

Designing for safety. Hendrickson (2000) referred to the importance of designing for construction safety. Some designs can be difficult to implement while others may provide for safer construction, thereby reducing the risks of accidents. Safety depends largely upon education, and then upon vigilance and cooperation during the construction process. Education involves training workers and managers in proper procedures and identification of hazards. Vigilance and cooperation is needed when considering the risks of different work practices and implementing strategies that mitigate the risks. This also involves maintaining temporary physical safeguards such as barricades, braces, guylines, railings, etc. Various measures can be taken to improve safety on the jobsite, including design, choice of technology, and education. An example given by Hendrickson (2000) is that parapets could be designed to appropriate heights for construction worker safety, rather than the minimum height required by building codes. Also, modifications to equipment can improve safety on the job site. Controls could be developed to prevent equipment to function under high risk conditions; for example, workers could be provided with sensors that would activate a warning signal to the operators of equipment if the worker is closer than a specified safe distance. Another example is a system to determine the stability (horizontal level) of a crane in order to permit its operation only if the position meets predetermined stability criteria.

Coble and Blatter (1999) discussed the implications of safety on design/build contracts. They focused on the role of the design firm during the design and construction process regarding their liability for safety. Various court cases are cited in which the designer was found liable for safety in the construction stage. In "United States Ex Rel Los Angeles Testing Laboratory v. Rodgers and Rodgers,"[3] it was ruled that "the power of the architect to stop the work alone is tantamount to a power of economic life or death over the contractor." In "W.H. Lyman Construction v. Village of Gurnes,"[4] it was ruled that "the relationship of the supervising engineer and the general contractor gives rise to a duty of care on the part of each party to each other". Designers can become embroiled in liability that in prior years was the responsibility of the contractor. Designers must meet the requirements of the American National Standards Institute (ANSI) and the National Fire Protection Association (NFPA) in order to ensure the safety of the end users of the constructed facility, which implies that designers must have knowledge about safety and constructability when they design structures. This knowledge could be applied to the design of structures considering the safety of the end users and the safety of the workers who will build the structures. Constructability is related to the safety of the end user because the model used to connect design documentation with construction sequence and assembly details would store important information that may be useful for HVAC, or even for considering modifications to the current building physical appearance and layout. The United States Corps of Engineers (USCOE) has stated that jobsite safety is part of the quality control function that many times is the responsibility of the designer (Coble and Blatter 1999). The selection of safe contractors has been shown to have rewards beyond jobsite safety, including increased productivity and better quality construction. The design/build concept allows the firm to give appropriate consideration to safety and other factors according to Coble and Blatter (1999).

In a CII report on the relationship between the designer and construction safety, over 400 design suggestions were identified that could be used to increase worker safety during the design process. Three ways in which the designer can contribute to the safety of the worker are:

1. Reviewing high risk areas in the construction process to determine safety implications.

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[3] 161 F. Supp. 132 (S.D. Cal. 1958)

[4] 84 III. App. 3d 28, 403 N.E. 2d 1325, 1328 (1980)

2. Designing for less worker exposure to hazards.
3. Consulting with contractors and possibly safety consultants to understand the safety implications of their designs (Hinze and Gambatese 1996).

Two important concepts were introduced. First, in design/build contracts the role of the designer is expanded to eliminate by design potential construction safety hazards during the actual construction process. Second, designers should consider the building process in their designs. This could include the incorporation of safety devices such as fall protection (higher parapets and connections for safety lines) and a design that would facilitate the construction sequence (use of similar shapes in steel structures). No methodology is presented in the study to assess the impact of a designer's efforts to improve worker safety by implementing modifications to the design, and the implications of designing for safety in other contract strategies are not addressed. The ability of the designer to influence safety in the construction process is reduced when there is no direct relationship between the designer and the contractor.

3. A DIFFERENT APPROACH TO SAFETY RESEARCH

Linking the two methodologies: Qualitative data and Quantitative Data. Previous sections described methodologies utilized to identify the major causes of construction injuries and fatalities and some of the techniques to prevent these events. In this section we propose the combination of qualitative and quantitave methodologies to determine the best safety management practices in order to anticipate and minimize construction safety injuries and fatalities (Figure 1).

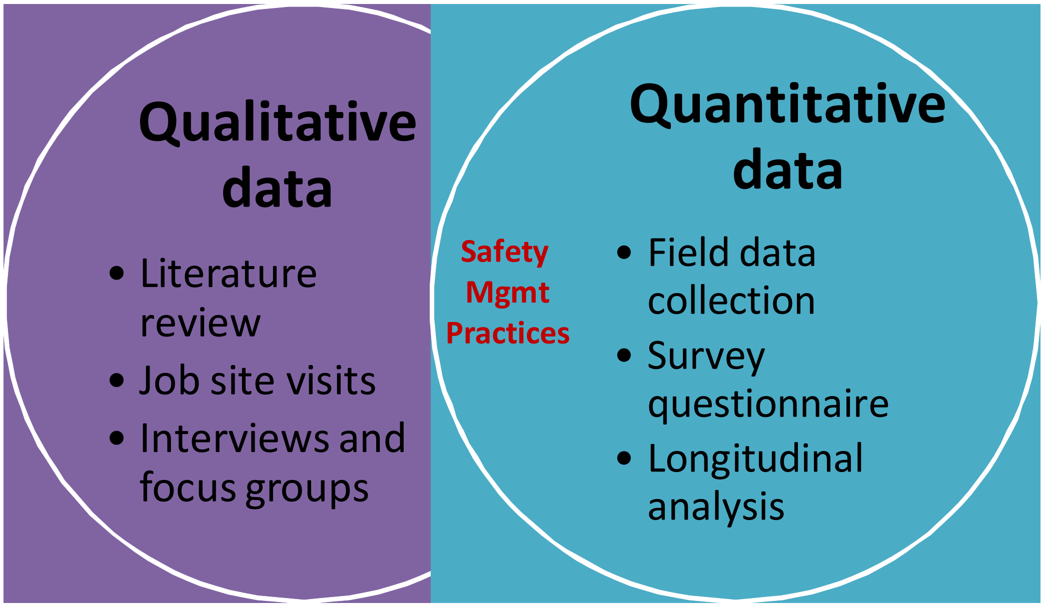

Figure 1. Combination of qualitative and quantitative approaches in safety research

Integrated Approach. A brief description of the major components of the integrated approach are as follows (Figure 2):

a) ***Assessment of safety factors***. The purpose of this phase is to identify the most relevant safety factors related to construction operations. This assessment will be performed evaluating previous studies in construction safety, focus groups with construction workers and managers, and a qualitative assessment based on job site visits.

b) ***Identification of safety practices***. The purpose of this phase is to identify the most relevant safety practices related to risky construction operations. Survey questionnaires can be deployed in order to categorize practices implemented by construction companies and their success in reducing safety incidents.

c) ***Design of experiment***. Once the most relevant practices have been identified, an experiment will be designed and conducted in order to assess whether these practices are effectively reducing near-misses, injuries, and fatalities in trenching and roofing operations. Different "treatments" can be studied to verify whether safety practice is succesful in reducing safety incidents and the variation of the safety metrics through time (longitudinal analysis) There are important challentes associated with this approach, mainly related with the complexity and variability of construction operations. However, we do consider these challenges can be overcome with a rigourous design of experiments and collaboration with the industry.

d) ***Safety practices recommendation***. The "best" practices to improve safety will be identified as a result of the comparisson of the results of the experiment in the previous phase. This comparisson will also provide information regarding the combination of practices that can be implemented on the job site.

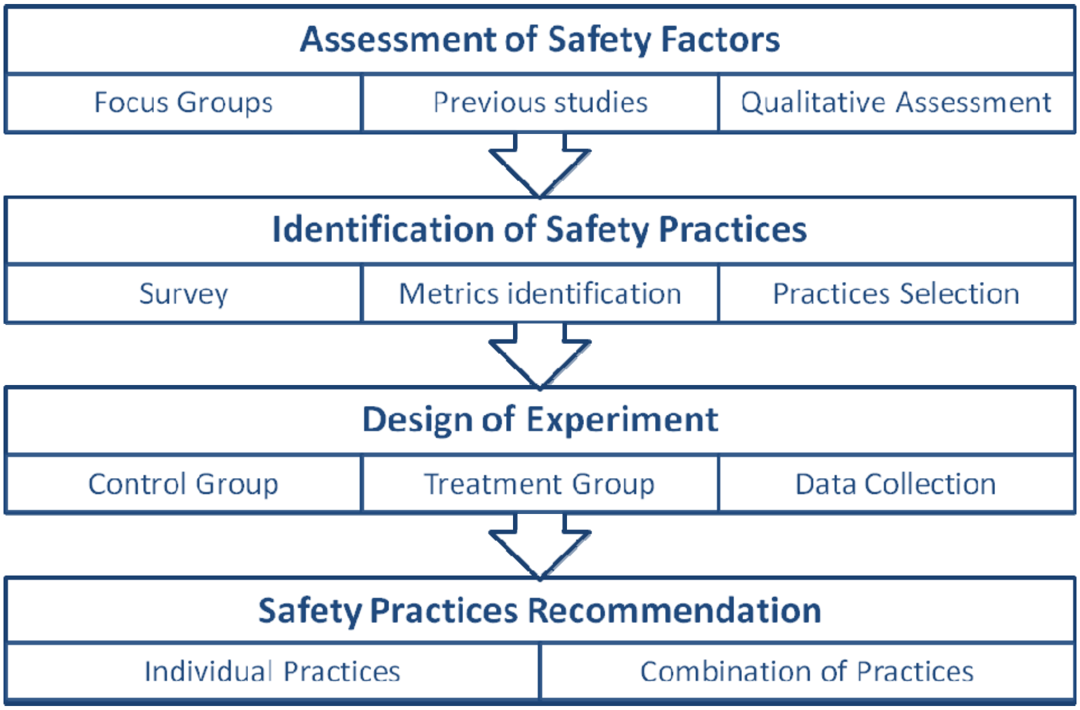

Figure 2. Integrated Approach for Construction Safety Research

Automated Safety Surveillance (iSafety). Information technologies provide the opportunity to collect very accurate data regarding jobsite safety issues. The model for automated safety survailance consists of an automated safety assessment and management system for construction workers in building construction sites using UWB and Bluetooth technologies. In this proactive safety approach, the system can be designed to monitor the location of workers in reference to equipment and work face areas and automatically determine if the workers are at risk of injury by using several decision rules related to the safety hazards previously identified in the project and the proximity of the workers to the hazard. The system can then notify the workers via Bluetooth, alerting them to be aware and remove themselves from the dangerous situation. This concept is innovative because it protects construction workers on building construction sites by automatically detecting exposure to possible hazards and alerting them of the hazard before an accident can occur. The application of this concept can be through safety specifications in construction contracts or possibly as safety requirements of government safety standards such as OSHA. The requirement for use of a system such as this could be similar to the requirements for use of personal protective equipment (PPE). Currently, protection for building construction workers is limited to the use of PPE (e.g., protective footwear, reflective vest, hard hat, fall restraint harness, etc.) and delimitation of hazard areas with tape or signs for visibility of the worker in the building site. Workers would carry a UWB tag the size of a 36 mm watch case attached to their vests. The UWB system would pinpoint the location of every tag and display it on a CAD drawing that can be seen by project participants on their computer screens. Autonomous software agents would determine whether a particular worker is too close to a hazard zone which has been previously identified by the resident engineer and/or safety competent person and entered in the CAD drawing, or to a piece of equipment that also has an attached UWB tag. If this is the case, the worker would immediately receive a warning message using Bluetooth. The message would be received by the worker’s warning device, which would be programmed for communication with the server. The system, dubbed i-safe-T (Integrated Surveillance and Automated Frequency Estimation of Threats system), would continuously estimate the proximity of workers to safety threats in the job site and automatically determine if the worker is at risk of injury, taking the necessary action to reduce the risk of injury to the worker (Figure 3). The research approach for the development of the proposed concept involves several tasks. The first task is the deployment of the UWB system on a building construction site. The second task is to develop the program that will identify the safety hazards in the work zone based on previous experiences by the project management team, a set of defined decision rules, and information from standard safety regulations. The last task of the research is to develop a prototype of the system and to perform field testing that includes construction equipment and several simulated scenarios of building construction activities such as excavation, forming, rebar assembly, concrete pouring, steel erection, etc. (Castro et al, 2007). Several components are part of the proposed i-safe-T system:

UWB receivers. Receiver boards that obtain power from the central processing hub via standard CAT-5 cables, which are also used to carry data back to the hub for subsequent processing. A set of three or more receivers will be positioned at known coordinates within, or about the edge of the area to be monitored. These receivers will be placed at strategic locations around the building construction site where construction activities are being performed. The purpose of the receivers is to assist the Hazard Assessment and Management System (HAMS) to determine the relationship between the location of workers and the hazards they might be exposed to, based on the tasks they are assigned to perform.

Sensor monitored automated resource tracking vest (SMART vest). This will be a reflective safety vest fitted with an UWB tag. Short pulse, radio frequency emissions from the tags are subsequently received by each sensor and processed by the central hub CPU. This information will allow the system to determine the possible safety hazards that the worker wearing the vest can be more frequently exposed to, based on his position and the tasks he is assigned to perform, thus facilitating the calculations and decisions made by the system. The vest will also have a Bluetooth-enabled communication device such as a pager to alert the worker of a dangerous situation and that action must be taken for personal protection.

Processing hub. The hub uses a standard CPU that interprets the data sent from the receivers, and generates the identity and location of each tag within a designated area. The results are made available via the hub LAN interface to client computers for further processing and display.

Computing server running the hazard assessment and management system (HAMS). This unit will analyze the information received and processed by the central hub CPU. It will run a software application that would determine the location of each of the workers fitted with a SMART vest and also the location of the construction equipment and hazard areas within the building construction site. It will then calculate the distance of the workers to possible hazards in the work zone, including equipment. The program will them determine, based on a set of decision rules based on actual safety regulation information and equipment manufacturer's safety information, if the worker is in a risky situation and it will then notify the worker of the danger so actions can be taken for personal protection.

4. SUMMARY AND RECOMMENDATIONS

Historically safety research has being limited to the diagnosis of safety problems and limited to recommendations on how to improve safety on construction sites. More recently, a paradigm shift has occurred in which pre-construction design has been used to reduce safety hazards from construction operations. Other efforts concentrate on the development of training materials and other methods of improving safety. What this paper recommends is a step forward in that direction. It is proposed that traditional qualitative research and quantitavive research be joined in a way that will promote strategies that can be monitored and their effectiveness in reducing safety hazards evaluated.

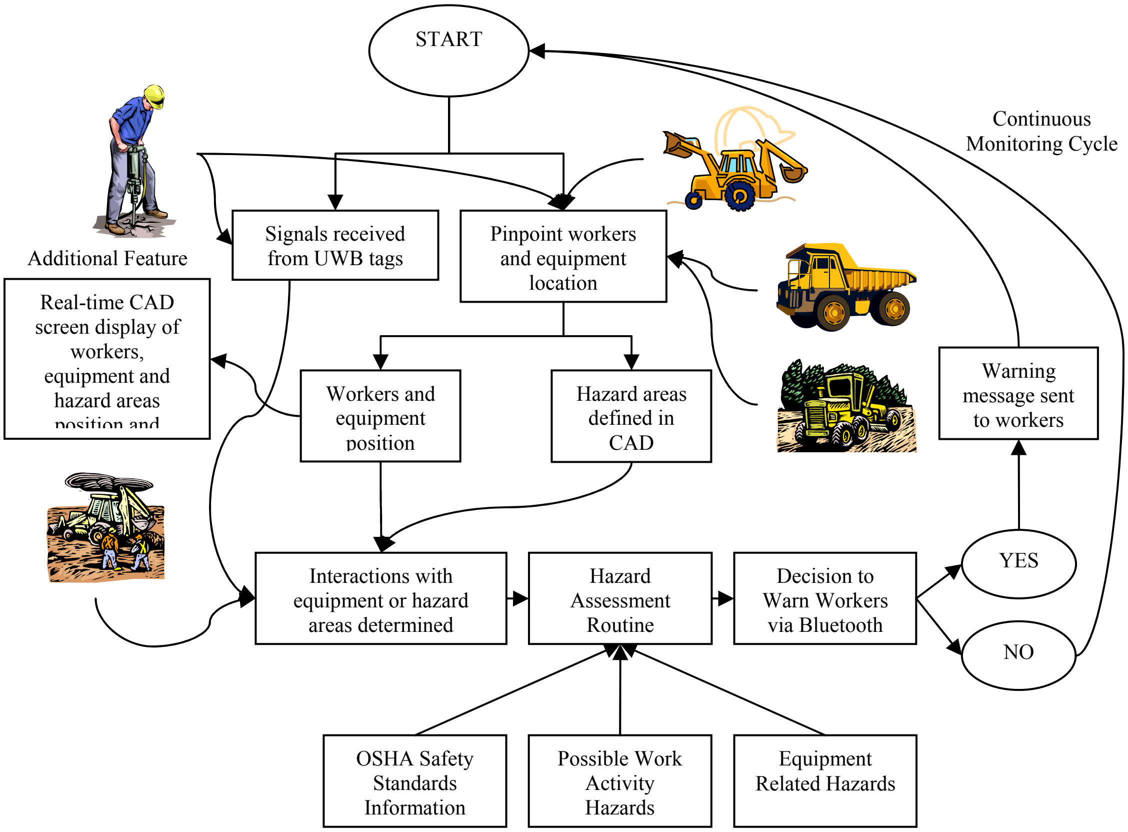

Figure 3. iSafety information processing cycle

The proposed quantitative approach will harmonize the outcomes derived from to the statistical analysis of existing data, interviews with site personnel and the combined output of simulations of different treatments and iSafety monitoring. The identification of the most relevant safety practices will be based on consistent and valid statistical considerations of data from projects completed. These safety practices will be incorporated in the experiment design, simulated using analysis of time and space and monitored using the iSafety methodology. Any perceived discrepancy between the expected behavior of the worker in terms of unnecessary proximity to equipment in motion or to predefined hazardous areas, and the current monitoring, will be reported in real time. This information will allow for a proactive identification of worker behavior, encompassing safety considerations while performing a construction task in real time.

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