A Systematic Analysis To Identify, Mitigate, Quantify, And Measure Risk Factors Contributing To Falls In Nasa Ground Support Ope

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A SYSTEMATIC ANALYSIS TO IDENTIFY, MITIGATE, QUANTIFY, AND MEASURE RISK FACTORS CONTRIBUTING TO FALLS IN NASA GROUND SUPPORT OPERATIONS

by

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ABSTRACT

The objective of the research was to develop and validate a multifaceted model such as a fuzzy Analytical Hierarchy Process (AHP) model that considers both qualitative and quantitative elements with relative significance in assessing the likelihood of falls and aid in the design of NASA Ground Support Operations in aerospace environments. The model represented linguistic variables that quantified significant risk factor levels. Multiple risk factors that contribute to falls in NASA Ground Support Operations are task related, human/personal, environmental, and organizational. Six subject matter experts were asked to participate in a voting system involving a survey where they judge risk factors using the fundamental pairwise comparison scale. The results were analyzed and synthesize using Expert Choice Software, which produced the relative weights for the risk factors. The following are relative weights for these risk factors: Task Related (0.314), Human/Personal (0.307), Environmental (0.248), and Organizational (0.130). The overall inconsistency ratio for all risk factors was 0.07, which indicates the model results were acceptable. The results show that task related risk factors are the highest cause for falls and the organizational risk are the lowest cause for falls in NASA Ground Support Operations. The multiple risk factors weights were validated by having two teams of subject matter experts create priority vectors separately and confirm the weights are valid. The fuzzy AHP model usability was utilizing fifteen subjects in a repeated measures analysis. The subjects were asked to evaluate three scenarios in NASA KSC Ground Support Operations regarding various case studies and historical data. The three scenarios were Shuttle Landing Facility (SLF), Launch Complex Payloads (LCP), and Vehicle Assembly Building (VAB). The Kendall Coefficient of

Concordance for assessment agreement between and within the subjects was 1.00. Therefore, the appraisers are applying essentially the same standard when evaluating the scenarios. In addition, a NASA subject matter expert was requested to evaluate the three scenarios also. The predicted value was compared to accepted value. The results from the subject matter expert for the model usability confirmed that the predicted value and accepted value for the likelihood rating were similar. The percentage error for the three scenarios was 0%, 33%, 0% respectively. Multiple descriptive statistics for a 95% confidence interval and t-test are the following: coefficient of variation (21.36), variance (0.251), mean (2.34), and standard deviation (0.501). Model validation was the guarantee of agreement with the NASA standard. Model validation process was partitioned into three components: reliability, objectivity, and consistency. The model was validated by comparing the fuzzy AHP model to NASA accepted model. The results indicate there was minimal variability with fuzzy AHP modeling. As a result, the fuzzy AHP model is confirmed valid. Future research includes developing fall protection guidelines.

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LIST OF ACRONYMS/ABBREVIATIONS

AHP (Analytical Hierarchy Process)

BLS (Bureau of Labor Statistics)

CR (Comprehensive Risk)

FST (Fuzzy Set Theory)

GSE (Ground Support Equipment)

GSO (Ground Support Operations)

IAPA (Industrial Accident Prevention Association)

KCC (Kendall Coefficient of Concordance)

KSC (Kennedy Space Center)

LCP (Launch Complex Payloads)

MF (Membership Function)

NAICS (North American Industry Classification System)

NASA (National Aeronautics and Space Administration)

NIOSH (National Institute for Occupational Safety and Health)

OSHA (Occupational Safety and Health Administration)

PPE (Personal Protection Equipment)

SHEA (Safety, Health, and Environmental Affairs)

SLF (Shuttle Landing Facility)

VAB (Vehicle Assembly Building)

CHAPTER I: INTRODUCTION

Objectives of Study

A research study will be performed at a NASA/KSC to quantify and describe the exposure-response relationships of the primary task-related, human/personal, organizational, and environmental risk factors that contribute to falls. These relationships will be studied and quantified utilizing methodologies. Analysis of various job tasks within an aerospace environment will allow for a comparison of different exposure levels to aid in quantifying the exposure-response relationship for each primary risk factor. To accomplish this goal, the aim of the research is to develop a quantifiable, aggregate approach for quantifying risk of falls by considering broad categories of risk factors. The research objectives are:

1) Identify and classify risk factors that contribute to falls in an aerospace environment.
2) Develop a conceptual model that includes multiple risk factors that contribute to falls (i.e. human/personal, task related, environmental, organizational)
3) Develop and validate a fuzzy analytical hierarchy process (AHP) model to predict the likelihood of falls and aid in the design of work areas in NASA ground support operations.

In closing, the intent of the research is to develop and validate the model to alleviate falls.

Significance of Research

As evidenced by the literature review presented in Chapter II, there is a significant amount of research in the area of falls however; many of the exposure-response relationships are ambiguous. This is mainly due to differences in exposure measurement techniques, differences in research experimental designs, and unexamined interactions between the various risk factors.

Knowledge about risk factors leading to falls is essential for fall prevention (Hongwei Hsiao a; Petre Simeonova, 2001). Specifically knowledge of extrinsic and intrinsic factors that contribute to falls secure planning and occupational conditions for employers (Gauchard, G., 2001). Safety of work systems needs a holistic approach because it is a combination of many factors that affect the whole system simultaneously (Dagdeviren, M., 2008). The current literature is narrow and the focus needs to be on the causation of workplace falls (Bentley, T., 2009). Therefore, there is a need for research on preventing falls. Thus, this study will address a significant void in the current knowledge base regarding the contributing risk factors that influence falls. The research outcome is to develop a model that will identify, quantify, and validate risk factors that may lead to falls and assist in the design of work environments specifically in an aerospace environment. As result, it will be imperative to propose fall protection guidelines for the workplace.

Aerospace Environment

According to the North American Industry Classification System (NAICS) Code, Aerospace Environment such as NASA/KSC is a multi work environment because NASA performs various industrial tasks such as roofing, construction, NASA ground support operations, space shuttle/rocket operations, launch, and landing; which fall under many codes (e.g. 927110 Space Research & Technology 4789-9902 Space flight operations). In fulfillment of the overall vision for space exploration, NASA continues to explore answers that power the future. NASA uniqueness regarding the Space Shuttle and Expendable Launch Vehicle missions require full process of elements and hardware delivery to the International Space Station. NASA Ground Support Operations is a component of an Aerospace Environment. At NASA/KSC, many employees perform daily tasks from heights in Ground Support Operations. Performing work from an elevation can be detrimental to the success of the vision and ultimately lead to the risk of falls. The types of falls are same level falls and elevated falls. Same-Level Falls are recurring but are less severe. Elevated Falls do not frequently occur, however they are brutal. Falls are among the highest causes of injury and death at NASA/KSC and second only to vehicle accidents as the leading cause of deaths. NASA has developed a fall protection class to educate employees on workplace falls. Figure 1 below shows a United Space Alliance (USA) engineer, a NASA contractor that participates in the fall protection training class.

Figure 1: Engineer at NASA/KSC Fall Protection Training Class
(NASA, 2005)

Research Gaps

There are many gaps that need to be filled regarding fall prevention research. The research gaps are as follow:

- Knowledge and understanding of contributing risk factors that influence falls in NASA Ground Support Operations ((Hongwei Hsiao, 2008; Petre Simeonova, 2001)
- Aggregate impact and interactive nature of risk factors that influence falls (Gauchard, G., 2001)
- Model that quantifies risk factors that influence falls in an aerospace environment and specifically NASA Ground Support Operations (Dagdeviren, M., 2008)

The research gaps will be addressed by the following research objectives in this study. Please see Figure 2 below.

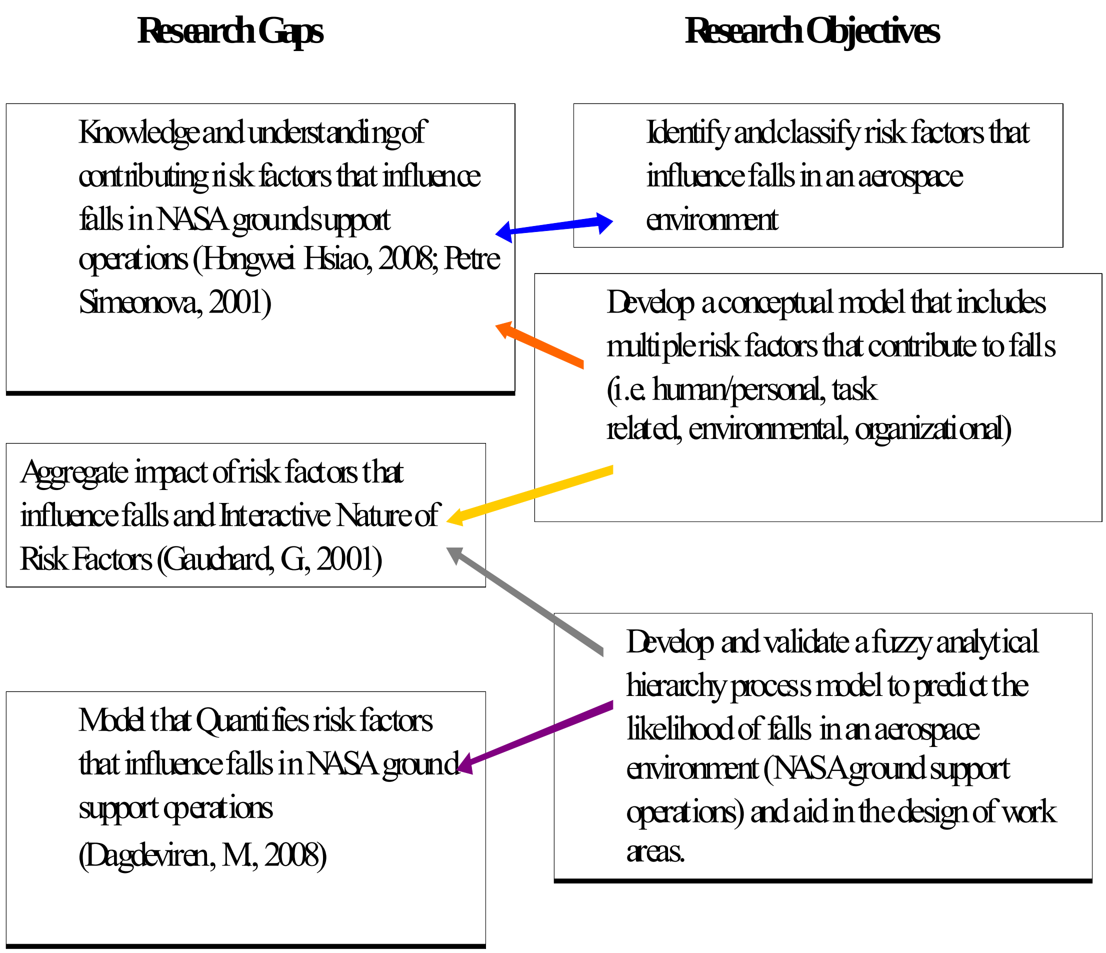

Figure 2: Research Gaps and Objectives

Research Hypotheses

The following are the research hypotheses, which include the null and the alternative.

H0: The development of a conceptual model that characterizes risk factors can be useful
1 in reducing the likelihood of falls in NASA Ground Support Operations.

H1: The development of a conceptual model that characterizes risk factors cannot be useful in reducing the likelihood of falls in NASA Ground Support Operations.

H0: A fuzzy analytical hierarchy process model can be developed and validated to
2 predict the likelihood of falls in NASA Ground Support Operations.

H1: A fuzzy analytical hierarchy process model cannot be developed and validated to predict the likelihood of falls in NASA Ground Support Operations.

Research Questions

1. What are the contributing risk factors that influence falls in the workplace?
2. How do we quantify contributing risk factors that influence falls in NASA ground support operations?
3. What is the aggregate risk value of these risk factors on falls?
4. How we will predict the likelihood of falls?

What is a fall?

Figure 3: Universal Symbol for falls
(Bauer, 2006)

A fall is defined as an event in which a person coming to rest unintentionally on the ground or other lower level, not by the result of a major intrinsic event such as (stroke) or overwhelming hazard (Tinetti, 1988). Falls are generally classified as an acute injury. Acute injury is an injury which occurs immediately after exposure to a hazard. Falls are under the umbrella of System Safety.

In the past, accident models came from operational safety and reflect on factors innately while protecting workers against industrial accidents. Now, these various models were applied to the complexity of work systems called system safety. System Safety is the application of technical and management skills in a systematic approach to identify and control hazards throughout a process or program.

Bureau of Labor Statistics

According to Bureau of Labor Statistics, falls are detrimental to the human body. There are several case studies where the consequences of workplace falls lead to disabling body injury or permanently bodily damage. As the human body hit a lower level, there is a sudden force to the surface. As the result, the body is negatively impacted. Slips, trips, and falls are a major cause of injuries and fatalities in the workplace. About 50% of the workplace injuries at NASA/KSC are falls. According to the textbook, walking and working surfaces are surfaces or devices on which people stand, walk, work, and climb that can cause many accidents. The following diagram shows the number of human body parts affected as result of falls.

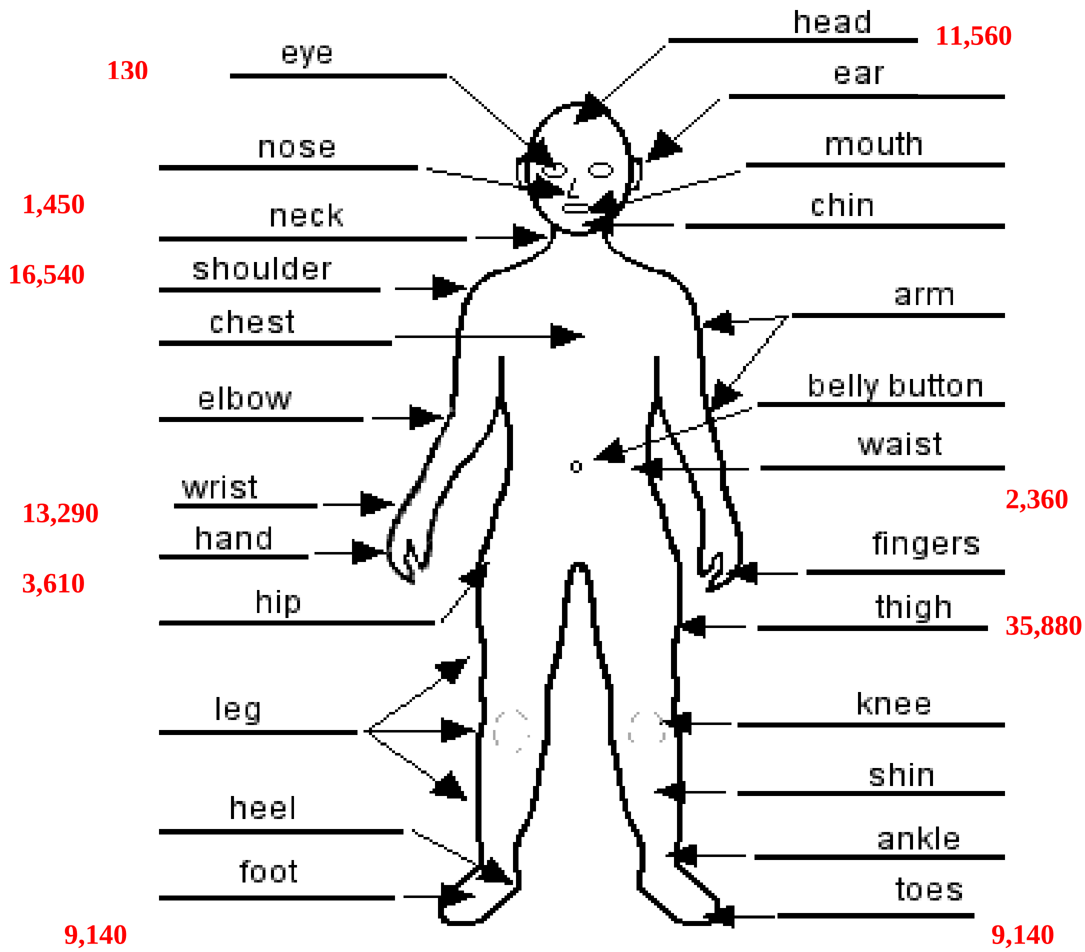

Figure 4: Total Falls on Human Body
(BLS, 2005)

According to BLS, the following table shows that falls (13%) are the second only to highway Fatalities (25%) regarding workplace deaths.

Table 1: BLS Statistics
(BLS, 2005)

Introduction

Workplace Deaths, 2005
(Bureau of Labor Statistics, preliminary)

Highway Fatalities	25%
Falls	13%
"Struck by"	11%
Homicides (mostly robberies)	10%

According to BLS, falls to a lower level is approximately 86 % of all Fall Fatalities. The falls categories are: Fall from ladder, fall from roof, and fall from scaffold.

Table 2: BLS Fall Statistics
(BLS, 2005)

Introduction

Fall Fatalities, 2005
(BLS preliminary)

Fall to lower level	86%
From Ladder	21%
From Roof	17%
From Scaffold	11%

The following figure shows the sources of the most fatal falls. The area that constitutes the most fatal falls are roofing at 36% of all falls. For example, in NASA Ground Support Operations, roofing is high area of concern for fall hazards. Another area of concern is scaffolding, which 17% of all falls. As a result, NASA is offering a fall protection course in scaffolding at Kennedy Space Center.

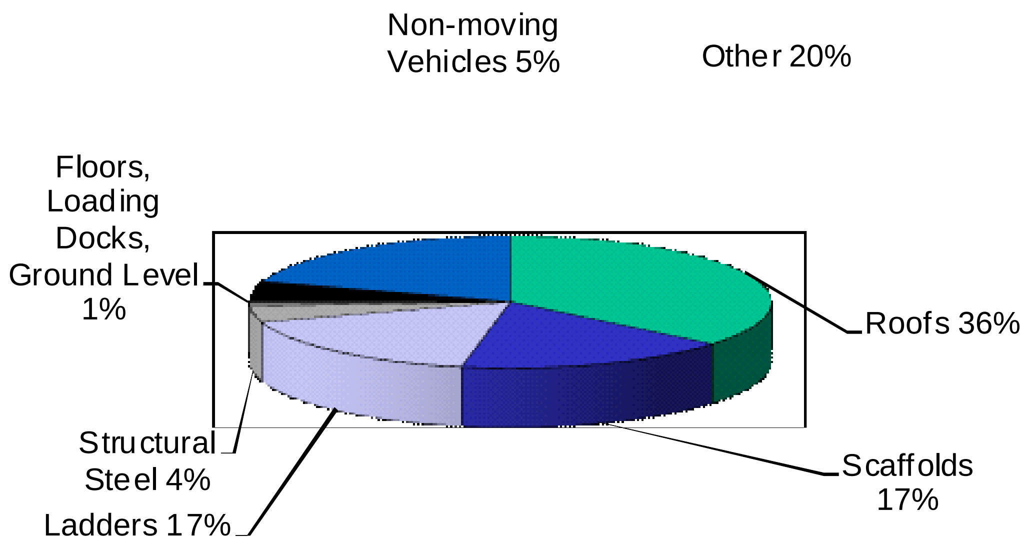

Figure 5: Fatal Falls
(BLS, 2004)

Contribution and Benefits of this research

This dissertation research will offer a contribution to field of fall protection of NASA Safety program. The fuzzy AHP model will be a great asset to the plethora of risk assessment literature and fall prevention studies because it provides granularity and gives insight regarding the fall risks. The contribution to the field of study is the utilization of the valid fuzzy AHP model to predict the likelihood of falls. The model is universal can be applied in any work environment. The benefit of this research will be the application of this model to a safety and risk management course at NASA/KSC.

Overview of Gravitec Study

There are KSC environments where employees are required to perform tasks from various fall distances. To address the issue NASA contracted with Gravitec Systems Inc., a fall-protection engineering firm, who surveyed over 400 elevated work areas and gathered contractor input with respect to fall hazards. Facility maintenance, Space Shuttle operations, payloads, cranes, construction and roofing are areas of concern for fall hazards. A hazard ranking system was developed based on factors that were considered easily measurable, highly relevant, and quantifiable. This ranking system is limited and it fails to include human factors, uncontrollable environmental factors, and working conditions in the evaluation of the workplace. Thus, there is a need for the proposed research.

Influence of Gravitec Study on my research

It was assumed in NASA Gravitec ranking system that multiple risk factors had a uniform influence on falls. The survey goals were to standardize fall protection programs, abate fall hazards across the center, identify existing facilities requiring fall protection systems, establish a baseline current fall protection methods status and benchmark KSC against the fall Protection industry. However, the purpose of this research is to develop and validate model to fulfill these goals. This research portrays the implementation of broad-scale prevention model that can significantly reduce fall injury claims.

Theoretical Framework

A theoretical framework is basically a conceptual model of how one makes logical sense of the relationships among several factors that have been identified as important to the problem. A typical theoretical framework provides a schematic description of relationships between and among independent, dependent, control, and extraneous variables so that a reader can easily comprehend the theorized relationships. What multiple risk factors lead to falls? How to predict the likelihood of falls? Figure 6 is the ergonomics model presented in Bentley's study. The model is about an information processing approach to the role of latent and active failures in workplace regarding slips, trips, and falls. Figure 6 shows that Latent Failures are extrinsic factors and Active Failures are intrinsic factors.

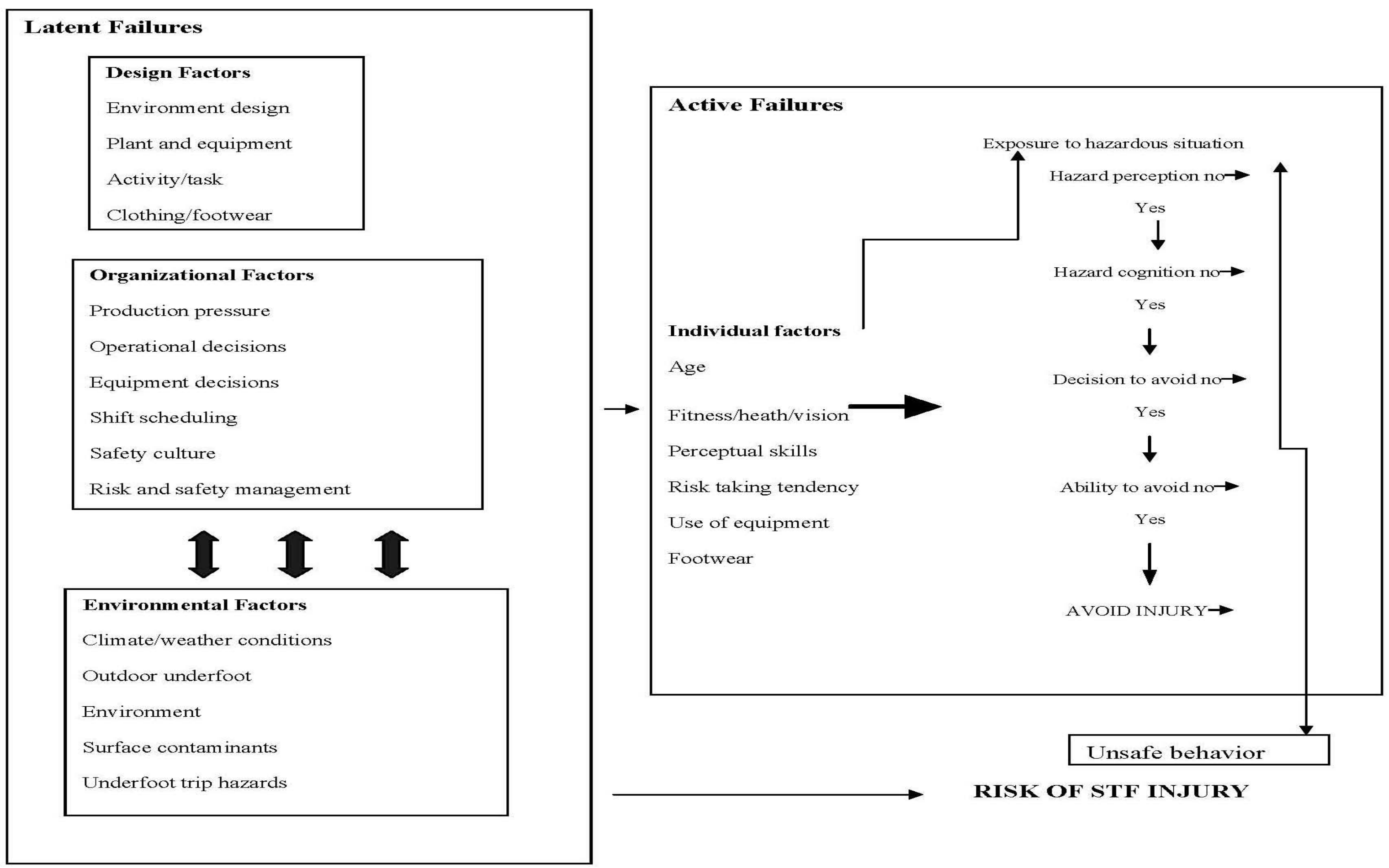

Figure 6: Theoretical Framework Model
(Bentley, T., 2009)

Scope and Limitations of the Study

The scope of this research will be limited to addressing the primary risk factors such as task related (i.e. load handling/carrying, task duration, posture), human/personal (i.e. age, gender, slip/trip, behavior), organizational (i.e. safety culture/climate, job safety and risk training, production pressure) and environmental (i.e. poor lighting, ladder regulation, coefficient of friction) that lead to falls. Also, the interaction of multiple risk factors will not be investigated. This is reserved for future studies. While other factors have been identified that influence falls, many of these factors are often present in combination with the primary risk factors explored in this research. The research will investigate the likelihood of falls in an aerospace environment and particularly NASA ground support operations.

Conclusion

In conclusion, the research will focus primarily on multiple risk factors that contribute to falls in an aerospace environment. The research will emphasize the importance of system safety with respect to falls and concentrate on interdependence of falls. Ultimately, the result of the research is a methodical examination for fall prevention that lead will to fall protection guidelines.

CHAPTER II: LITERATURE REVIEW

Introduction

To formulate the conceptual and quantitative model development, a comprehensive literature review was conducted. One objective of the literature review was to understand the previous approaches and methods taken by other researchers and thereby identify any gaps in the field.

The literature review will discuss the following topics:

- Description of falls
- Anatomy of a fall
- Impact of falls on industry and workers
- Studies that identified risk factors for falls
- Studies by industry
- Approaches to mitigate falls
- Fuzzy models in risk assessment
- Models and Tools for assessing risks and falls
- Literature Review Summary

Description of falls

Slips, trips and falls are one of the most common causes of injuries and fatalities in the general community (BLS, 2005). The first step to fall prevention is to have cognizance and knowledge of fall etiology. Etiology is origin or cause of an abnormal condition, disease, or injury. Slips and trips are more than just a trivial problem (Maynard, 2002) in the workplace. The control of such incidents involves a complex array of factors. Falls are caused by a slip and trip (Davis, 1983 and Lipscomb, 2006), extrinsic and intrinsic factors (Gauchard, 2001), surface area and footwear (Hanson, 1999). Several fall injuries and fatalities originate multiple risk factors. The intrinsic risk factors among others are physical, behavioral, and apparel. The extrinsic factors include the working surface and managerial factors. The risk factors that increase the severity of fall accidents result from factors such as physical tolerance of bones, body stamina, and harmful materials (Hsiao, 2008).

The main consequences of falls are sprains and fractures (Manning, 1983) that can lead to work interruption due to disability, the length of which varies with age (Kemmlert and Lundholm, 1998), and can have detrimental economic repercussions for the employer. The study of slips and falls are complex, and involves various sciences and disciplines including ergonomics, biomechanics, psychology, and tribology (Maynard, 2002). Biomechanics is the analysis of how individuals walk and surface interface as they walk. Psychology is the perception and response to slippery conditions. Tribology is the study of interaction of sliding surfaces and from the Greek language, "tribos," which means rubbing. It is linked to friction between footwear sole and floor surface. It is imperative to consider the environmental surface and environmental conditions in order to mitigate falls. Multiple factors that contribute to falls are Human/Personal Factors (Davis, 1983), Environmental Factors (Hanson 1999, Hignet and Masud, 2006), Environmental Factors, and Organizational Factors (Gauchard, 2001 and Lipscomb 2006), and Task Related Factors (Maynard, 2002 and Gauchard, 2001).

A fall sequence involves the following steps: occurrence of imbalance such as slip or trip, attempt to recover equilibrium or in case of recovery failure, a fall occurs when the body impacts the surface (Gauchard, 2001). The fall sequence is based on prioprioception in the human body. Prioprioception is an automatic sensitivity mechanism in the body that sends messages through the central nervous system (CNS). Prioprioception is the ability to sense the position, location, orientation, and movement of the human body.

Anatomy of a fall

The anatomy of a fall is the sudden, unanticipated descent in space driven by gravity. The consequences are often permanently disabling or even deadly. It takes most people about 1/3 of a second to become aware. It takes another 1/3 of a second for the body to react. A body can fall up to 7 feet in 2/3 of a second. It is essential to understand the detailed analysis for the anatomy of a fall in order to prevent and mitigate falls.

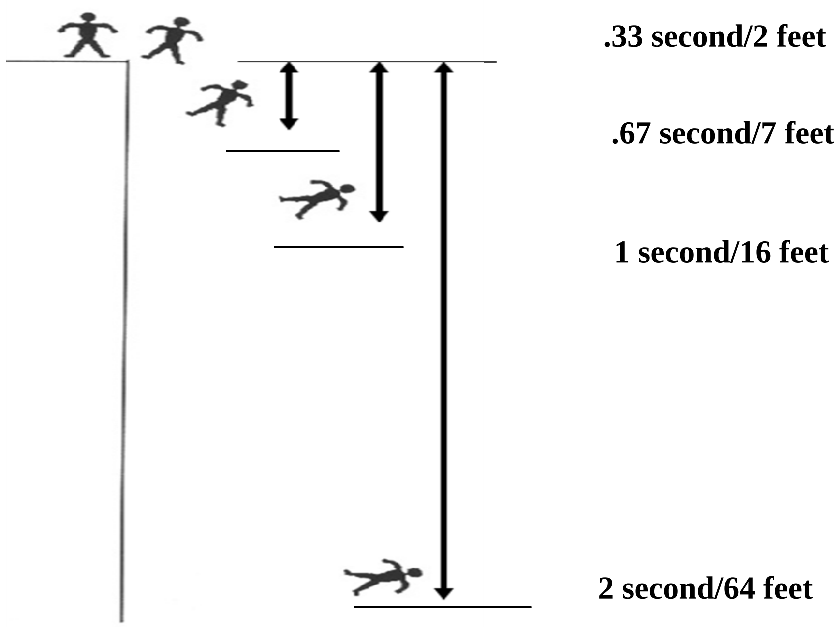

Figure 7: Anatomy of a fall
(BLS, 2004)

Impact of falls on industry and workers

Work-related falls from heights remain a significant problem for workers in industry. An extensive literature review identified a number of environmental, task-related, and personal factors that degrade the control of balance and cause falls. These factors include visual exposure to elevation, unstable visual cues, visual impairment, confined and inclined support surfaces, unexpected changes in working surface, load handling/coupling, physical exertion, fatigue, personal differences, task complexity, work experience, training, and the proper use of personal protective equipment (PPE). In many instances, these procedures are not practical for the industry and current regulations allow the use of alternative means of fall protection, such as slide guards. The prevention of falls should consider the main effects and interactions of the environmental factors, task-related factors, and personal factors that affect the balance control of workers. After the model development and validation, the multiple risk factors that influence falls will also be examined to prevent falls.

Studies that identified risk factors for falls

There are several factors that contribute to task performance such as age, weight, height, foot size, gender, sex or even race may contribute to a fall. The other factors that are involved in task performance are locomotors, visual factors, and fatigue affects (Davis, 1983) that lead to falls. It attempts to prevent injuries and illnesses by reducing or eliminating human exposure to occupational hazards. In addition, it seeks to improve the match between the job and worker's physical abilities, information management, and workload capacities.

A literature review has shown that multiple risk factors lead to falls. These risk factors can be broadly categorized as:

- Task Factors are factors related to the job, occupation, or workplace.
- Environmental Factors are extrinsic influences or factors from the surrounding systems that affect growth and development.
- Human/Personal Factors are characteristics and intrinsic factors related to the psychological, social, physical, biological, and safety characteristics of a user and the system the user is in.
- Organizational Factors are characteristics regarding safety climate and culture of the company, business, or association.

Factors that affect safety, health, and may influence falls

The objective of the research is to identify the various factors influencing safety in the workplace (Sawacha, E., 1999)**.** The health and safety of individuals are influenced by factors such as environmental, human, task, and organizational. The impacts of human, economical, psychological, technical, procedural, organizational, and the environmental issues are considered in terms of how these factors are linked with the level of safety. The human factor is characterized by the background and characteristics of the individual, such as age and experience. The economic factor is determined by the monetary values which are associated with safety such as, hazard pay. The psychological factor is assessed by the safety behavior of fellow workers on site including supervisors. The technical and procedural factors are assessed by the provision of training and handling of safety equipment on site.

The organizational and environmental factors are portrayed as the type of policy that the management adapts to the specific site safety. Information regarding these factors was correlated with accidents' records in a sample of 120 operatives. Results of the factor analysis suggest that variables related to the ‘organization policy' are the most dominant group of factors influencing safety performance in the United Kingdom Construction Industry (Sawacha et al., 1999). The following table portrays various risk factors that affect safety, health, and could possibly lead to falls.

Factors affecting health and safety at work

Table 3: Risk Factors affecting safety and health
(Sawacha et al., 1999)

Environmental Factors

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1. Heating: heat stroke, cramps, low temperature
2. Poor lighting: headache, eye strains
3. Dust: Pneumoconiosis, silicosis
4. Noise: deafness, affects concentration

Occupational Factors

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1. Butchers and carpenters - risk of cutting
2. Cleaners and food handlers - risk of contact dermatitis
3. Store keepers and health careers - risk of back strain

Note: When hazards are not obvious for certain jobs the risks are still there.

Human Factors

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1. Need for proper training and supervision
2. Risk to health and safety - untrained, unwell, carelessness
3. Employees - responsible for own behavior

Environmental Factors

The objective of the study is to examine the characteristics of patient falls during hospitalization in 1998 and compare them with those in the period 1978-1981 (Kerzman et al., 2004). The occurrence of patient falls in a hospital environment is a major concern in any health care system. Research findings have reported the risk factors for these falls are age, gender, certain medications, mental status, chronic diseases, and environmental factors. Falls may lead to fear, pain, slight or severe injuries, increase the duration of hospital stay, cause patient discomfort, and affect quality of life. A retrospective study was performed in a large, 2000-bed medical center in Israel. Reports of 711 fall incidents in 1998 were compared with 328 reports in 1978-1981. Information gathered included age, gender, department, work schedules, severity of injury, tests and treatment after injury. This information is used a risk factors to used in a tool for fall mitigation. The results showed that the rates of falls per 1000 admissions in psychiatric, elder care and rehabilitation departments in 1998 were significantly higher than in the earlier period. Rates of 115, 91, 85, respectively, per 1000 admissions were reported in 1998 compared with 34, 9, 19, respectively, in the period 1978-1981. The percentage of reported falls in the younger age group (under 50) was higher in the later survey (1998), and a higher proportion occurred outside the patient's room. Most of the reported falls in 1998 occurred during the morning shift. In conclusion, the increased number of falls could be an outcome of increased environmental awareness (Kerzman et al, 2004).

Human Factors

Age is a human factor that that may lead to falls. Falling itself is not a diagnosis but a symptom of multiple risk factors and the effect of certain medications of homeostasis and environmental hazards that hinder safe mobility. Preventing falls requires a systematic diagnostic approach focused on identifying and reducing risk factors. Specific preventive strategies include treating underlying medical conditions, establishing a risk assessment, prescribing an exercise program to improve mobility, or removing fall hazards in the workplace (Tideikssar, R., 1996).

Human factors included age, gender, experience, and the use of personal protective equipment (PPE). Accident scenarios were extracted from accident reporting system. Scenarios in NASA Ground Support Operations A trend was found between causes for the falls and accident events. Falls from scaffold staging were associated with a lack of complying scaffolds and bodily action. Falls through existing floor openings were associated with unguarded openings, inappropriate protections, or the removal of protections. Falls from building girders or other structural steel were associated with bodily actions and improper use of PPE. Falls from ladders were associated with overexertion and unusual control of tools. Falls down stairs were associated with unguarded openings. Falls while jumping to a lower floor and falls through existing roof openings were associated with poor work practices. Primary and secondary prevention measures can be used to prevent falls or to mitigate the consequences of falls and are suggested for each type of accident. Primary prevention measures would include fixed barriers, such as handrails, guardrails, surface opening protections, and strong roofing materials. As a result, protection measures would include travel restraint systems, fall arrest systems, and fall containment systems (Chi et al., 2005).

Human factors research in other high-risk fields such as patient care has demonstrated the rigorous study of risk factors effect on task performance. The research can lead to improved outcome and reduced errors after redesign system of tasks. These methods have been applied to the anesthesia work environment. The data obtained in the experiment utilize task analysis, workload assessment during actual patient care, and the use of cognitive task analysis to study clinical decision making. A novel concept of "non-routine events" is introduced and pilot data are presented. In concluding, the awareness of human factors that affect system safety and falls can lead to fall mitigation.

Organizational Factors

Managing Dynamic Nuclear Power Plants (NPP) and maintaining a safe environment must be simultaneous efforts to produce a successful organization. The objective of the NPP study was to develop a system dynamics model to assess the organizational and human factors which contribute to nuclear safety. The dynamic model portrays cause and effect relationships among factors and quantifies these factors. The variables in the model are degree of leadership, human resources, number of employees, workload and not just hardware in each department. The universal user can simulate various situations in nuclear power plant organization. The simulation is so intuitive that it assists with the improvements to safety and provides managerial tools for the organizational and human factors. In concluding, the model can portray how organizational and management policies affect individual performance such as productivity, quality of work, and ultimately NPP safety (Ahn, N., Jae, M., Yu, J., 2004).

System Safety

The NPP environment is very similar to NASA environment. Both organizations are dynamic because of the type of tasks that need to accomplish. Safety is very important to both organizations. The work environments are characterized by continuous change, progress, and activity. For example, at NASA Ground Support Operations, there are several workers involved to complete a task. These human factors can lead to falls because the demand is high and supply is low. These kinds of organizations are schedule driven and leadership influenced.

System Safety refers to the extent to which individuals and group will commit to personal responsibility for safety, learn from mistakes, modify behavior, and be rewarded in these efforts. Safety Climate," is the temporal state measure of safety culture, subject to commonalities among individual perceptions of the organization." It refers to the perception about safety at a particular place and time. The climate is subject to change depending on the current environment.

The NASA Agency and the organizational structure are dynamic. System safety includes the total range of risk management. High risks are detrimental to NASA success. When considering communication and leadership, it was stated, "In an interview shortly after he became Center Director at KSC, Jim Kennedy suggested that most important cultural issue the Shuttle program is establishing a feeling of openness and honesty with all employees where everybody's voice is valued (CAIB, ibid, p. 108)." NASA employees need to feel secure about reporting concerns and taking the appropriate action. Ultimately, employees should be given respect. There is a gap between vision and reality. The first priority at NASA is safety. However, the operational practices have deviated from the standards due to political stress, social factors, cultural factors, and organizational factors. Each center, program, projects, group, division, and various engineering disciplines have their own subculture. This may negatively impact the overall culture of the organization. “If eternal vigilance is the price of liberty, then chronic unease is the price of safety." stated James Reason, Managing the Risk of Organizational Accidents (Leveson, N., 2004).

Safety risk: NASA Scorecard

The NASA Safety Risk Scorecard is a tool to assess risks at NASA. The NASA risk scorecard includes a 5 x 5 matrix in Figure 29. The research involves assessing risk factors that lead to falls in NASA ground support operations. Falls are part of system safety at NASA. The NASA Safety scorecard will be conveyed and compared to the fuzzy AHP model in this research. Showing a correlation between the fuzzy AHP model and the NASA Safety Risk scorecard is the quantitative approach to the research. The fuzzy AHP model and the NASA risk Scorecard has five levels associated with the risk assessment.

Table 4: Risk Factors affecting the organization
(Ahn et al., 2004)

Level of Hierarchy	Attributes			
	Organizational Culture	**Staff Capacity**	**Plant Condition**	**Workload**
Top Managers	Attitude Leadership Morale			
Middle Managers	Attitude			
	Supervision			
	Time allocation			
	Number of MM	Productivity	Number of Defects	Spent time to dealt with work
	Education Etc.	Quality of work	Defect generation rate	Administration task
Employees		Skill level	Parts	Maintenance task
(Operation Engineering Maintenance Coordination)		Spent time to dispose of task	Etc.	Etc.

Task Factors

Task-delineated safety (TDS) is a behavior-based safety management program developed in order to address the significant problems of slip, trip and fall accidents (Quintana, R, 1999). The hypothesis of this approach is that hazards can be minimized if personnel are held directly accountable with clear task delineation for keeping an area safe. Role ambiguity would be minimized which lead to a safe environment. Management's role in providing feedback and enforcement is imperative to the success of the safety management program. This hypothesis was analyzed by focusing on slip, trip and fall hazards at used-clothes sorting facility, with a history of slip, trip and fall accidents costing the company approximately two million US dollars in the past 3 years. The slip, trip and fall hazard density was significantly lower using this TDS approach (Quintana, R., 1999).

There are some implications in the literature regarding risk factors that contribute to falls. A faulty assumption is if a worker slips or trips, they will automatically fall. This is not always the case. According to the literature, the premise is that a cause of fall is a slip and trip. However, a fallacy is that slips, trips, and falls are in the same category, have similar causes and effects, and can be mitigated in the same manner. According to literature and technical reports, each incident is different and should be treated accordingly.

The following table contains multiple risk factors that contribute to the falls in General work environment and specifically in the aerospace environment. The following risk factors were observed multiple times (reoccurrence or three or more) in the literature. According to the literature, the following table contains significant risk factors that lead to falls. The studies show there are multiple sources for falls. It has been observed that causes for falls are dependent on the work environment. There similar trends and information in the Bureau of Labor Statistics (BLS) Data, Liberty Mutual Data, Mishap Data, Incident Reporting Information System (IRIS), Empirical Studies, and NASA/Gravitec Fall Hazard Analysis Report. A general concern is a combination of the risk factors that contribute to falls. Table 5 is a comparative analysis of multiple risk factors that contribute to falls in the workplace. The list is not conclusive but it is a sample of the many risk factors that contribute to falls.

Table 5: Multiple risk factors that contribute to falls

General Work Environment	Aerospace Environment (NASA Ground Support Operations)
• Experience (OF) • Job and Safety Program (OF) • Type of Task/Activity (TF) • Sex/Gender (HF) • Load weight (TF) • Environmental Conditions (EF) • Task Duration (TF) • Slip and Trip (HF) • Environmental Surface (EF) • Slip and Trip (HF) • Poor Lighting (EF) • Day of the week (EF) • Occupation/Industry sector (OF) • Coefficient of Friction (EF) • Time of Day for the fall (EF) • Coefficient of Friction (EF) • Fall Distance (EF) • Age (HF)	• Worker Interference (HF) • Number of Workers (HF) • Age (HF) • Fall Distance (EF) • Environmental Conditions (EF) • Environmental Surface (EF) • Task Duration (TF) • Task Frequency (TF) • Task Proximity (TF) • Fall Hazard Severity (OF) • Fall Hazard Protection (OF) • Fall Hazard Occurrence (OF) **Legend** **OF-Organizational Factor** **EF-Environmental Factor** **TF-Task Related Factor** **HF-Human/Personal Factor**

The focus of this research will be on multiple risk factors that contribute to falls in NASA Ground Support Operations. The following are the multiple risk factors that lead to falls in a dynamic aerospace environment. The benchmark for risk factor selection was by strategically observing three or more occurrences of the each risk factor in the NASA Fall Hazard Report and NASA Mishap Data. The following are the risk factors' definitions that contribute to falls in NASA Ground Support Operations.

Human/Personal Factors

- Worker Interference: the effect multiple workers at the same location have on each other and the interference of each worker's movements in the work environment.
- Number of workers: the number of workers at the location
- Age: the (average) age of the workers at the location

Environmental Factors

- Fall Distance: height of fall
- Environmental Surface: the security of the platform, structure, or surface that supports the worker
- Environmental Conditions: measurement of work being performed in an inside or outside work environment

Organizational Factors

- Fall Hazard Severity: severity and consequence of the fall hazard that is related to the height of the fall in the organization being analyzed
- Fall Hazard Protection: measurement of the existing fall protection quality at the facility/organization being analyzed

- Fall Hazard Occurrence: how often the particular fall hazard is found at the facility/organization being analyzed

Task Factors

- Task Frequency: how frequently workers perform the task and exposed to a fall hazard

- Task Duration: how long workers spend at the location performing the task and the number of man hours exposed to the fall hazard

- Task Proximity: measurement of how close the workers normally get to the fall hazard while performing the task

The Ishikawa "Fishbone" Diagram was used as the conceptual model to represent falls. The following conceptual model is a graphic tool that helps identify, sort, and display possible causes of a problem or quality characteristic. The cause and effect diagram display the number of errors for the various risk factors that contribute to falls. There are extrinsic and intrinsic factors that contribute to falls. Extrinsic factors are characteristics from the outside. Intrinsic factors are original causes and characteristics within the human body. The extrinsic factors are organizational and environmental. The intrinsic factors are human/personal and task related.

Conceptual Model

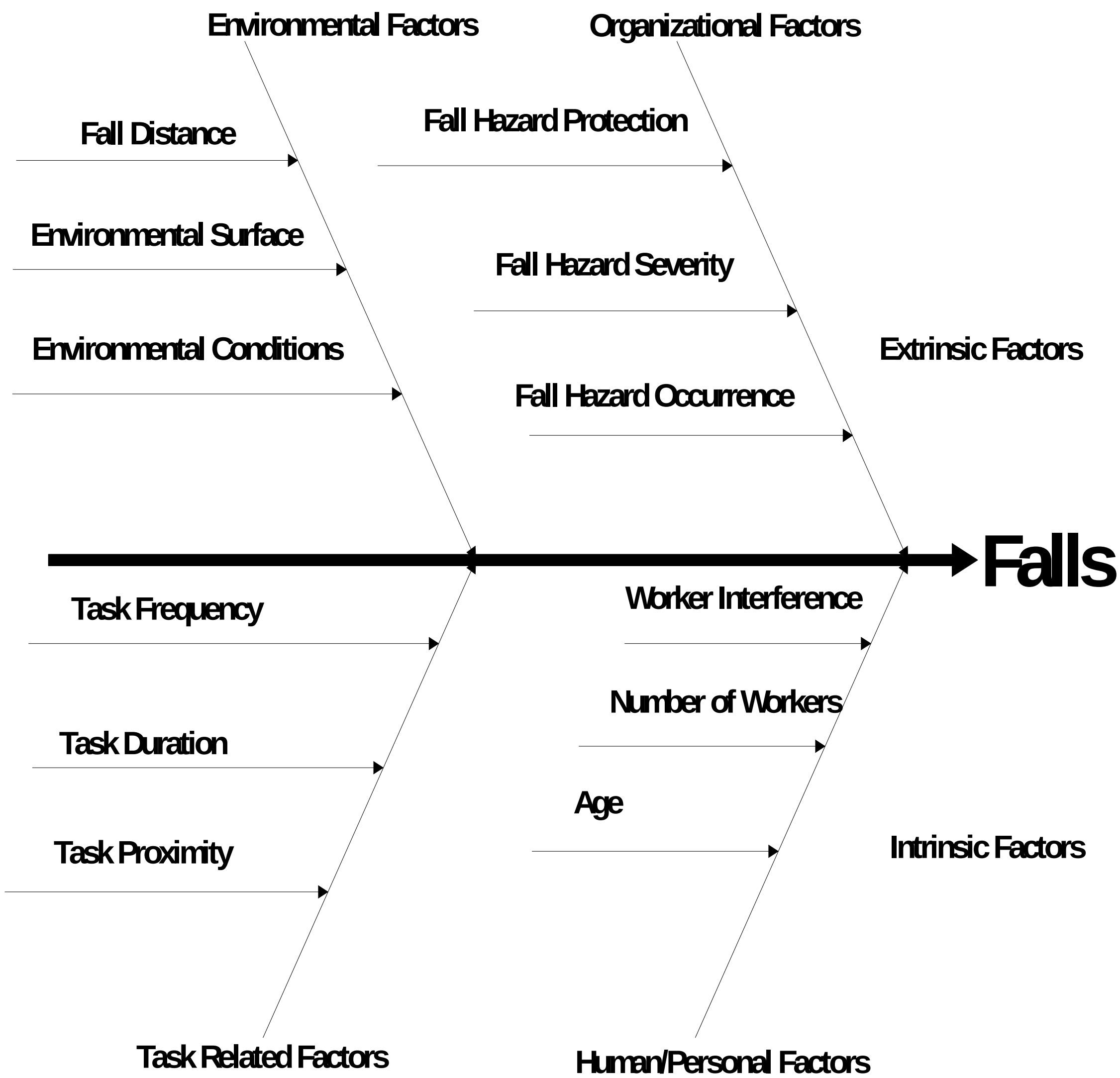

Figure 8: Conceptual Model

Fall Studies by industry

Falls in Healthcare

The objective of the study is to examine how risk factors influence the satisfaction, health, safety, and well-being of health care workers (Lundstrom et al., 2002). Ultimately, these factors affect the satisfaction, safety, and quality of care for patients. In addition, the impact of the work environment on tasks and the effects on health care workers and patients. Studies have shown where falls are major concern in healthcare because medical facilities are dynamic work environments just like an aerospace environment. Therefore, people are performing high risk tasks such as doctors and nurses handling and lifting disabled patients. Studies focusing on worker health and safety concerns affected by the organization and the physical work environment provide evidence of direct positive and/or adverse effects on performance and suggest indirect effects on the quality of patient care. An increasing number of studies are reviewing the relationship between improvement in organizational factors and changes in patient outcomes. Characteristics or risks in hospitals are observed as one model for improving safety. In conclusion, the observance of characteristics of fall is important to fall mitigation (Lundstrom et al., 2002).

Falls in the construction industry

Fall-related occupational injuries and fatalities are a major problem in the U.S. construction industry. Two Bureau of Labor Statistics databases-Censuses of Fatal Occupational Injuries and Survey of Occupational Injuries and Illnesses-were examined for 1992-2000. A total of 605 fall-through fatalities occurred during 1992-2000. The costs estimates were in a range of

$55,000-$76,000 for the total cost of a 1998 fall injuries. Current work practices and fall protection equipment have reduced the frequency and costs of fall-through incidents. Researchers can use a systems approach on these incidents to identify contributing risk factors. Employers and practitioners can alert managers and work crews about these dangerous locations to eliminate the fall hazards that are often obvious and easy to rectify (Bobick, T., 2004).

The construction industry is highly subject to occupational accidents. In Norway there is little research-based knowledge on accident pattern and risk factors (Gravseth, et al., 2006). The main objective of the study was to examine studies of accidents in this industry, leading to injuries registered by the health services, could identify preventable risk factors and preventive measures. Fifty accidents in the construction industry led to serious personal injuries. Patients were interviewed after treatment in emergency wards and hospitals. Inspections of the accident sites were performed. Subject matter experts (SMEs) discussed the accidents in order to identify risk factors and suggest preventive measures. The accident reports in the study were compared to reports from the Labor Inspectorate on the same accidents. The investigation identified several risk factors. Several detailed preventive measures were proposed. Results showed that more than one third of the respondents said that time pressure had contributed to the accident. Accident risk caused by time pressure can be reduced by avoiding fragmented contracts, unrealistic time limits, and the use of day penalties for breach of contract. Possible preventive measures for electric injuries imply modification of the reporting system and of the work organization so that workers can comply with the regulations more easily (Gravseth et al., 2006).

The Occupational Safety and Health Administration (OSHA) investigate most worker-related fatalities. A research study was conducted that focused on the data OSHA accumulated on construction worker accidents involving falls. In the construction industry, falls are the major sources of accidents resulting in fatalities (Huang et al., 2003). The purpose of the study was to identify the root causes of fall accidents and to identify any additional information that might be helpful in reducing the incidence of construction worker falls in the future. Data used in the study was from January 1990 through October 2001. However, the last 5 years of this time interval was important because this is a period when more data was accumulated and recorded in the OSHA investigation reports. Results show that most fall accidents take place at elevations of less than 9.15 m (30 ft), occurring primarily on new construction projects of commercial buildings and residential projects of relatively low construction cost. In addition, experience does not seem to diminish accident occurrence. Workers often misjudge fall hazards. Most of all, the results show that fall accidents account for a growing proportion of the total number of construction worker fatalities (Huang X. and Hinze, J., 2003).

The purpose of the study was to develop a method to evaluate the relationship between slip resistance measurements and slips and falls (Hanson et al, 1999). The prediction of falls was based on the surface area. There were five subjects wearing a safety harnesses walked down a ramp at various angles such as 0º, 10º, and 20º. The different surface areas were tile or carpeted surface under dry, wet, or soapy conditions. The coefficient of friction of footwear, floor surface, and contaminant interfaces were measured. The friction was assessed by examining the foot forces during walking trials when no slips occurred. The results showed that the number of slip and fall incidents increased as the difference between the required coefficient of friction (COF) and the measured dynamic coefficient of friction increased. The developed regression model was developed to show the significant factors contributing to slips and falls. This type of model can be used to evaluate various work environments and assist in the design of safer work environments (Hanson et al., 1999).

Figure 9 is the adjustable platform used to set the ramp angle known as the optical data collection trigger (ODCT). The subject is wearing a harness system to prevent fall injury during the experiment. A video camera was used to capture the motion of the markers on the foot.

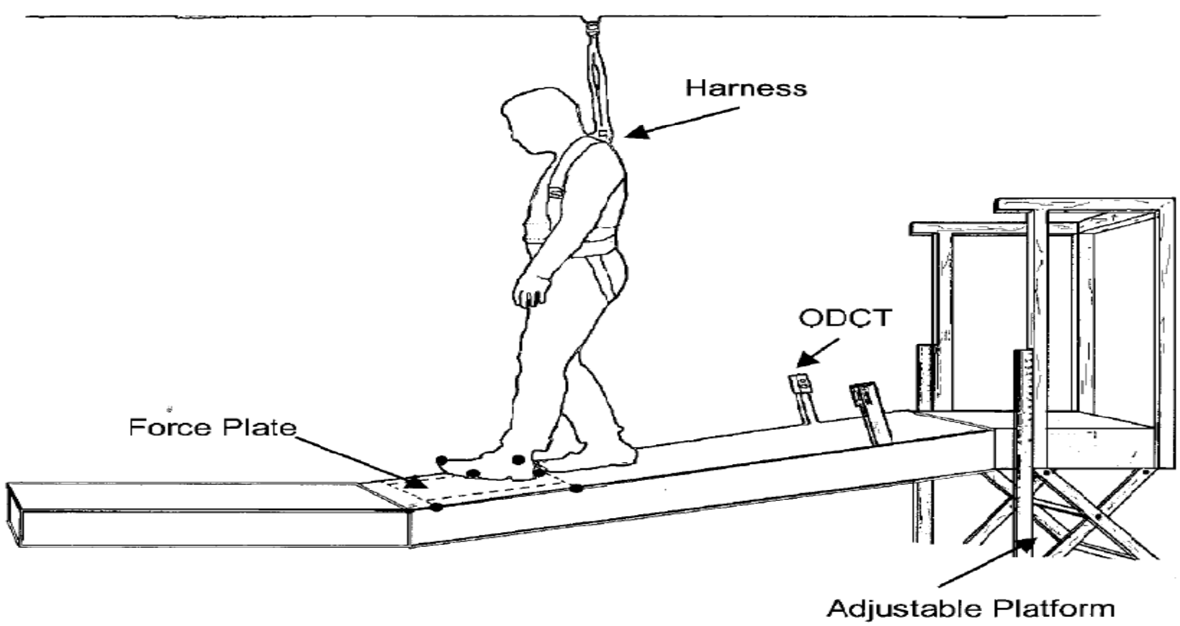

Figure 9: Coefficient of Friction
(Hanson et al., 1999)

The purpose of the study was to identify the factors that contribute to slips, trips, and falls occurring during the delivery of mail. Previous analysis of data consists of approximately 1700 fall incidents. About one-fifth of falls occurred on steps. The experimental methods include interviews with safety management, group discussion with delivery employees, and survey for employee and managers. The results showed that risk factors related to task, behavior, footwear, and equipment contribute to falls. In addition, working practices such as reading the mailing address while walking caused falls. Figure 10 shows that some of the organizational factors that contribute to falls were management safety activities, adverse weather conditions, management factors, employee training, and equipment provision (Bentley, T., 1998).

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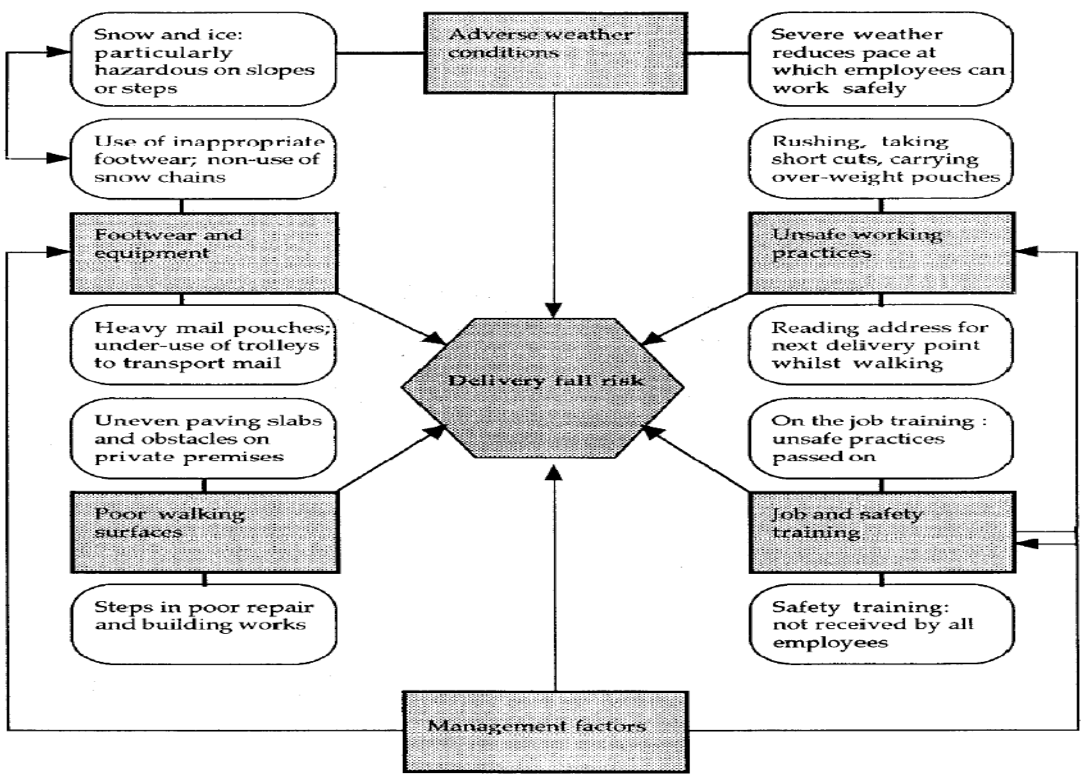


Figure 10: Fall Risk factors during Mail Delivery
(Bentley et al, 1998)

Falls cause important and financial costs, as regards workers (Leamon and Murphy, 1995). The mechanism of a fall can be described as follows: imbalance (slips, trips, etc.), attempt at equilibrium recovery and, in the event of failure, fall with eventual injuries (Leclercq, 1997). Falls are reoccurring occupational incidents in the workplace.

The falls lead to imperative social and economic issues for the employee and employer. Various factors such as environmental and personal factors that affect the balance control of an individual. The factors involved in the study focus on environmental, task, and personal. Having knowledge of intrinsic and extrinsic factors contributing to falls could be beneficial to environmental plan, safer occupational conditions for employees and use of balance rehabilitation procedures to reduce fall hazards (Gauchard et al., 2001).

Fall Hazards in the aircraft maintenance industry

Falls are significant occupational hazards, particularly in industries with dynamic work environments. The following study describes rates of noncompliance with fall hazard prevention requirements, perceived safety climate, employee knowledge, beliefs, and the association between fall exposure and safety climate measures in commercial aircraft maintenance activities. The method includes walkthrough observations on aircraft mechanics at two participating sites. The methods involve asserting the degree of noncompliance and completing questionnaires concerning fall hazard knowledge, personal safety beliefs, and safety climate. The survey results were summarized into safety climate and belief scores by workgroup and site. Noncompliance rates observed during walkthroughs were compared to the climate-belief scores, and were expected to be inversely proportional. As a result, important differences were seen in fall safety performance between the sites. The study provided a characterization of aircraft maintenance fall hazards. Noncompliance varied by height, equipment used, location of work on the aircraft, shift, and by safety system. Employees with higher safety climate scores had greater observed noncompliance within each site. Ultimately, the use of engineered safety systems had a significant impact on working safely. The results of this study indicated that safety systems are very important in reducing noncompliance with fall protection requirements in aircraft maintenance facilities. Site-level fall safety compliance was found to be related to safety climate (Nietzel et al., 2008).

Approaches to mitigate falls

The purpose of this perspective article is to describe the use of a physiological profile approach to falls risk assessment and prevention that has been developed by the Falls and Balance Research Group of the Prince of Wales Medical Research Institute, Sydney, Australia (Lord, S., 2003). The profile's use for people with a variety of factors that put them at risk for falls is discussed. The Physiological Profile Assessment (PPA) involves a series of simple tests of vision, peripheral sensation, muscle force, reaction time, and postural sway. The tests can be administered with the proper portable equipment. The results can be used to differentiate people who are at risk for falls ("fallers") from people who are not at risk for falls ("nonfallers"). A computer program using data from the PPA can be used to assess an individual's performance in relation to a normative database so that deficits can be targeted for intervention. The PPA provides valid, numerical, and reliable measurements that can be used for assessing falls risk and evaluating the effectiveness of interventions and is suitable for use in a range of physical therapy and health care settings (Lord et al., 2003).

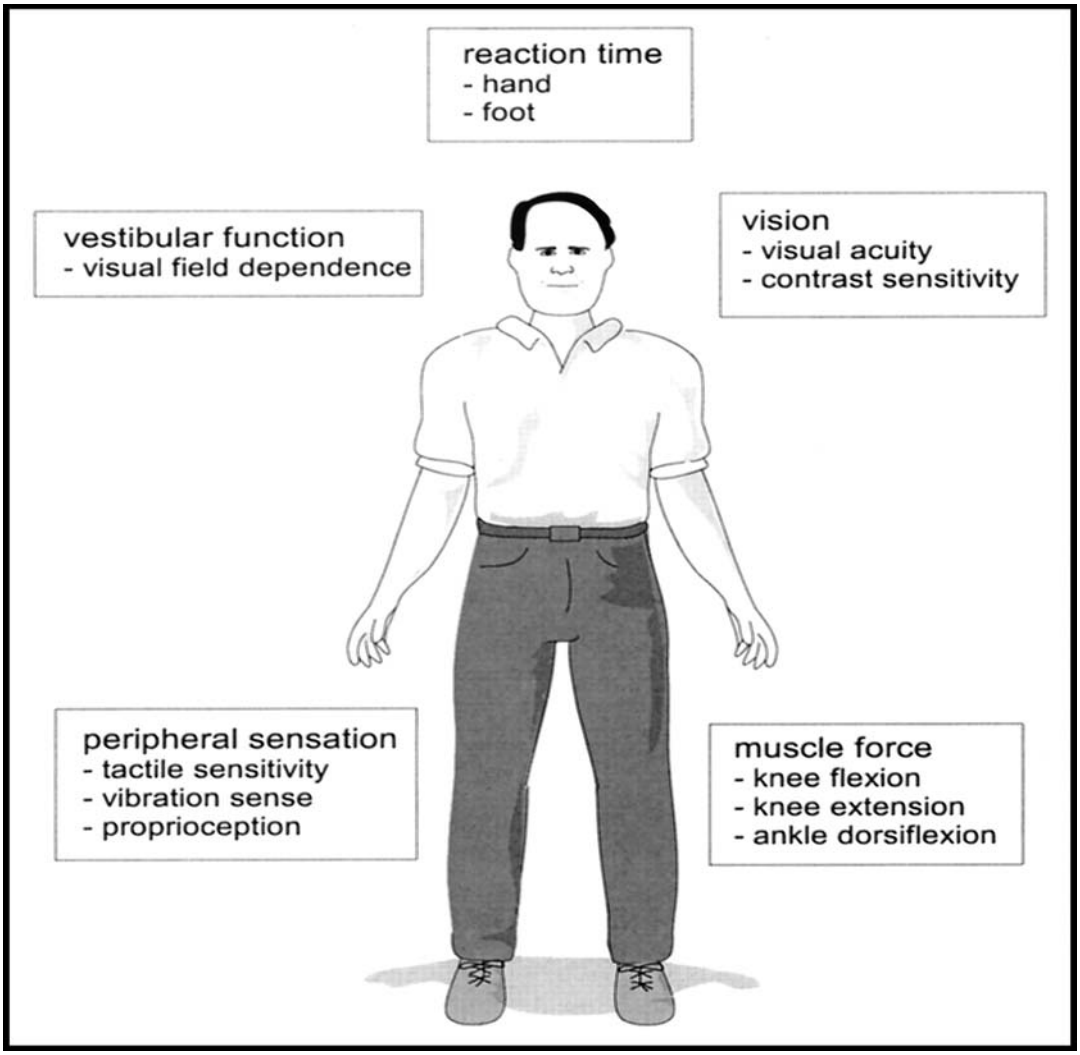


Figure 11: Physiological Profile Assessment
(Lord et al., 2003)

The following risk graph is for a 79 year old woman. It is confirmed that for a 79 year old woman, the fall risk is mild. The normal age range is 20 to 99 years. The graphs shows that falls are the effect (y) and age is the cause (x). Therefore, falls are dependent on age. The PPA output is the following: graph of the overall risk score, profile of the individual's test performances, table of the test performances versus age, and the written report containing results and recommendations.

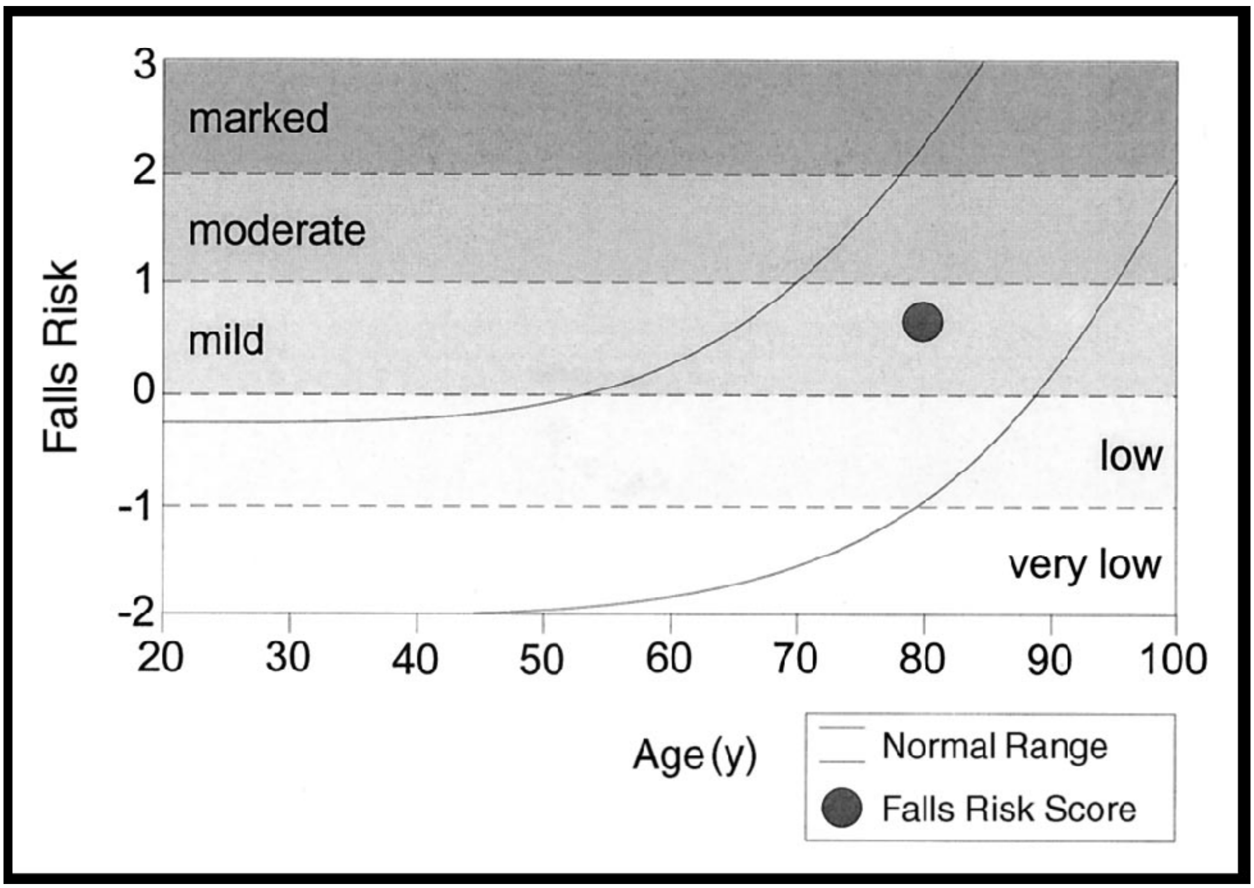


Figure 12: Fall Risk versus Age
(Lord, S et al, 2003)

Fuzzy Models in Risk Assessment

The objective of the research was to develop a fuzzy analytic hierarchy process (AHP) model for behavior-based safety management. Safety management (SM) is a very important element within an effective manufacturing organization. One of the most important components of SM is to maintain the safety of work systems in the workplace. Safety of work systems is a function of many factors which affect the system. Numerous factors affect the safety of work systems simultaneously. As a result, measuring work system safety needs a comprehensive approach. In this study, the work safety issue is studied through the analytic hierarchy process (AHP) approach which allows both multi-faceted and simultaneous assessment. The real problem can be represented in a more compatible way by using fuzzy numbers instead of crisp numbers to evaluate the risk factors. A fuzzy AHP approach is proposed to determine the level of faulty behavior risk (FBR) in work systems. The proposed method is applied in a real manufacturing company. Risk factors causing faulty behavior are weighted with triangular fuzzy numbers in pairwise comparisons. The risk factors are evaluated based on the work system by using the relative weights and fuzzy linguistic variables. As a result of this evaluation, FBR levels of work systems are determined. Finally, faulty behavior is prevented before occurrence and work system safety is improved (Dagdeviren, M., 2008).

The object of the study was the development of the global economy and the ease of air transportation have flight safety (Hsia, T., 2008). There are exact specifications and procedures in the operation and maintenance of aircraft. Human errors and mechanical disorders are two key risk factors of flight safety. The employees need to follow an outlined procedure to avoid human errors and ensure flight safety. Readability of aircraft maintenance technical orders can affect the quality and reliability of aircraft maintenance. To ensure the editing quality of technical orders, monitoring the number of unreadable sentences is important and necessary. The number of unreadable sentences found in a technical order was used as the measure of readability performance (RP) as well as a readability performance index was provided to evaluate whether the RP of individual readability characteristics of technical orders was adequate Different readability characteristics make different grade of RP loss. Based on fuzzy multiple criteria decision-making (Fuzzy MCDM) approaches, the SMES ranked and calculated the weights of all factors. Simultaneously, the experts proposed the upper limits of unreadable sentences according to the weights of individual readability characteristics. The technical orders issued by Taiwan Aerospace Industrial Development Corporation was used as an example to evaluate the readability of the technical orders and total RP losses for individual readability characteristics. Finally, an improved way of editing quality for technical orders was recommended (Hsia, T., 2008).

There is similar approach used to predict Cumulative Trauma Disorders (CTDs). The objective of the research was used to develop a prediction equation using fuzzy quantification theory following categorical risk factors: task, personal, and organizational. Fuzzy set theory provided a quantitative method for analyzing vague and imprecise information. A three part methodology was used including the identification of risk factors, analytical hierarchy process (AHP), risk factor qualification and quantification. Subject Matter Experts were asked to identify and classify risk factors as well as identify exposure limits. Also, they were asked to rank levels of each factor as minimal, mild, moderate, strong, and very strong risk. AHP was utilized to assign relative weight to each risk factor and each risk factor category. Using a population of diagnosed CTDS and non-CTDS hands, the developed model was used to determine its reliability and sensitivity. The results found the model to be a good predictor of CTDS because it quantified the risk factors that lead to CTDs. Therefore, CTDS could be mitigated and prevented (McBell P, Crumpton-Young L, 1997). The model was comprehensive and holistic approach that included several characteristics of CTDS. The subject matter experts have tested the model and it was confirmed a valid approach for CTDs analysis. A similar approach will be used to quantify and evaluate risk factors that influence falls in this current study.

Fuzzy Set Theory (FST) is a modeling technique frequently used where vague concepts and imprecise data are handled, and it is capable of managing both imprecision and uncertainty data (Bonisson, 1980). FST has been used for the development of the linguistic approach where any variable is treated as a linguistic variable (i.e. Low, Medium, and High). FST can be used to translate linguistic terms into numeric values to be used to get aggregate measures when given several inputs. FST characterizes the concept of approximation based on membership functions with a range between 0 and 1, which provides the lower and upper approximations of a concept (Yao et al., 1992). Zimmerman identifies the necessity to use mathematical language to map several membership functions and develop FST models.

On the contrary, the use of mathematical modeling techniques brings some limitations. Real situations are not often precise, and the description of a real system often requires more detailed data than a human being could ever recognize simultaneously (Schwartz, 1962 and Zimmermann, 1991). FST provides a good starting point in the development of a conceptual basis and can be utilized in the field of pattern classification (Zadeh, 1965). FST also provides a rigorous mathematical framework in which ambiguous data can be precisely studied (Zimmermann, 1991).

Probability theory has been traditionally used for describing the phenomenon of uncertainty; it deals with the expectation of future events based on something known. However, the uncertainty represented by fuzziness is not the expectation of uncertainty; rather it is the uncertainty resulting from the imprecision of a concept expressed by a linguistic term. Probability is the theory of random events and the likelihood of events (Klir, G. J et al., 1997).

Traditional modeling techniques tend to eliminate factors which cannot be explained. This process leads to inaccurate models caused by lost data. In order to develop a model that displays factors that contribute to falls, FST was selected as the most feasible technique to quantify these factors. Furthermore, linguistic approaches have been previously applied and developed for use in FST, allowing factor variables to be represented as numerical values. One of the most important advantages of using this technique is the opportunity to create a scale to measure the factors that contribute to falls. The method is compatible with the current research because the final results involve a qualitative and quantitative multifaceted model; that will be used to predict falls in an aerospace environment. The technique will be used to quantify risk factors that contribute to falls in NASA Ground Support Operations.

Subject Matter Experts (SMEs)

SMEs can be used to determine the relative weights of factor variables and assist in the development of FST models. There are different ways to develop membership functions that include direct methods (experts giving answers to various kinds of questions) and indirect methods (experts are more general and less biased questions). This approach is beneficial for multi-faceted models. The use of SMEs can assist in the quantification of qualitative performance measures (Klir, Y., 1995; Terrano et al., 1992)..

Models and tools for assessing risks and falls

The majority of fatal accidents in the construction industry are caused by falling from heights. Investigators emphasize the importance of safety control, carried out systematically and based on real-time data collection, as the most important element of accident prevention. An automated model to monitor and control fall hazards was developed (Navon, R, Kolton, O, 2007). The model identifies the activities associated with risk of falls from heights and protective measure such as guardrails. The model is designed to follow up the existing guardrails and constantly compare their locations and lengths to the planned ones. Based on this comparison, the model issues warnings whenever guardrails are missing, or temporarily removed. The model provides reports and warnings. The reports are used for planning the materials, or employees, needed to establish the protective measures. The model's main algorithms portray dangerous activities and areas that were identified. But the proposed model was developed only to improve safety during the construction stage. However, including safety in the design stage can improve safety culture during the actual construction (Navon, R., Kolton, O., 2007).

The method of engineering risk analysis is based on a functional analysis of systems and on the probabilities of the events and random variables that affect their performances. These methods allow identification of a system's failure modes, computation of its probability of failure or performance deterioration per time unit or operation, and the contribution of each component to the probabilities and consequences of failures. The model includes the human decisions and actions that affect components' performances and the management factors that affect behaviors. Therefore, these factors are the root causes of system failures. By computing the risk with and without proposed measures, one can then set priorities among different risk management options under resource constraints. In this study, the engineering risk analysis method is used to identify a system's weaknesses and the most cost-effective way to fix them. The first example concerns the heat shield of the space shuttle orbiter and shows the relative risk contribution of the tiles in different areas of the orbiter's surface. The second application is to patient risk in anesthesia and demonstrates how the engineering risk analysis method can be used in the medical domain to rank the benefits of risk mitigation measures, in that case, mostly organizational. The third application is a model of seismic risk analysis and mitigation, with application to the San Francisco Bay area for the assessment of the costs and benefits of different seismic provisions of building codes. The probabilistic risk analysis (PRA) method allowed identifying system weaknesses and the most cost-effective way to fix them (Pate- Cornell, E., 2002).

The objective of the research is to establish fall prevention procedures (Navon, R., and Kolton, O., 2006). The construction industry is very dynamic and prone to risks. As a result, not enough time and effort are invested in safety issues. Fall from heights is the main cause for fatalities and injuries in construction projects. The automated model developed identifies the dangerous activities in the project's schedule. Additionally, it constantly compares the planned guardrails (location and time) and the ones actually used oil site. The model provides textual/graphical reports and warns when guardrails are missing, are incomplete or have been misplaced. The model was implemented, tested in a real time project, and presented to 14 experts who were asked to evaluate and validate it. The main conclusions were the model is accurate, enables early detection of fall hazards before and during design and construction stage, the model is an important managerial, monitoring, and control tool keeping track of all fall hazards and protective measures, and warns when a safety problem (Navon, R., and Kolton, O., 2006).

Decision analysis is a useful tool for risk management. There are several methods used such as probabilistic techniques to assess the accident risk. Decisions made by organizational leadership may affect the likelihood of an accident. Therefore, managerial and organizational factors should be included in the risk modeling process. However, various analytic techniques are not commonly used to understand the decisions that are made by these individuals. A framework of value-focused thinking is used in order to understand the safety decisions made within the research partner organization. The research describes the results of interviews held with managers and employees from this organization. Through these interviews, we sought to understand the values these experts apply in their roles within the organization and the objectives they seek to achieve and contribute to its overall safety performance. The final analysis is a framework that portrays the fundamental objectives of safe operations for various roles in the organization and connects these different decisions (Merrick et al., 2005). Decision analysis is essential to fall mitigation. For example, the leaders and subject matter experts play a major role by making decisions for employee in regards to fall prevention. In addition, the management enforces and requires safety best practices within an organization and specifically at NASA.

Analytical Hierarchy Process (AHP)

Hierarchical classifications can help show relationships among categories. This research has created a hierarchical category system where taxonomies were developed by organizing data into different levels. In order to evaluate the feasibility of the categories and ratings, subject matter experts were asked to review the relative weights obtained through AHP. Pair-wise comparisons are frequently used to determine the relative importance of each factor. Comparisons are made within modules to determine the relationship between the factors identified by the experts (Saaty, 1990). A rating scale was developed and utilized for comparisons where each pair wise comparison is rated on a scale from 1 to 9. In an AHP analysis, the rating is used to define the degree of preference of one factor over another. The value 1 represents equal importance of the two factors, X and Y, and the value 9 suggests X is more important than Y. The inverse of the values is used if the expert considers that an inverse relationship exists among the factors. Once the pair-wise matrix is developed, the relative weights are obtained from the estimate of the maximum eigenvector of the matrix. The normalized average weighting indicates the relative significance of each factor.

The AHP approach, which consists of a series of goals, criteria, and alternatives, simplifies a complex problem into simple pair-wise comparisons. AHP is very useful in complex decision-making, and plethora of software have been developed which assists with the development of AHP, such as Expert Choice (Saaty, 1990). Pair-wise comparison is a problem-solving technique used to determine the relative order or ranking of a group of items resulting in a specific point value. Expert Choice was selected for this research. The following ratings were used to develop the forms to be sent to all the SME.

Inconsistency Ratio

Furthermore, research performed by McCauley-Bell and Badiru used knowledge acquisition to obtain factor relevance (McCauley-Bell et al., 1996). The scale to develop membership functions was developed using the described approach in this research.

The inconsistency ratio is used to evaluate the SMEs' ability to make consistent judgments. The ratio identifies if the SMEs are cognizant or forget previous assessments across the activity. The presence of inconsistency indicates that a SME is not coherent or that he or she does not understand the assessment tool. The inconsistency ratio that is smaller than 0.1 reflects a coherent SME. Therefore, inconsistency ratios those are greater than 0.1 represent a concern (Hallowell, 2007). A series of pair-wise ratio-based comparisons were performed to evaluate SMEs' understanding of falls. This ratio was calculated by evaluating if the whole set of pair-wise comparisons was done consistently.

Conclusion

The literature review identified the research need to develop a fuzzy analytical hierarchy process model to evaluate factors that contribute to falls in NASA Ground Support Operations. The need to develop a holistic model capable of evaluating a large number of key factors that lead to falls is essential for all work environments. Therefore, a series of tools, methods, and techniques are in conjunction with the development of fuzzy AHP model that has been identified. The following sections cover in detail the proposed approach to solve the complex mathematical modeling problem including qualitative and quantitative data. There was a plethora of literature on falls. The literature was partitioned into subcomponents such as system safety, falls, fall risk assessments, risk factors, AHP, and fuzzy models. Table 6 gives a synopsis of the literature.

Table 6: Literature Review Summary

Topics	System Safety	Falls	Task Related	Organizational	*Environmental*	Human/Personal	Fall Risk Assessments and Models	AHP	Fuzzy Models
Authors									
Tinetti, 1988		X					X		
Leamon & Murphy, 1995		X					X		
Maynard, 2002		X							
Nietzel, 2008		X							
Bobick, TG., 2004		X							
Leveson, N, 2005	X	X							
Bentley, T., 2009		X	X	X			X		
Gauchard, 1999		X			*X*		X		
Hanson, 2001		X			*X*				
Bentley & Haslam, 1998		X		X					
Ahn, Jae, 2003		X		X					
Salazar, M., 2005		X		X					
Hisao, 2008		X				X			
Davis, 1983		X				X	X		
Lord, S., 2003		X				X	X		
Dagdeviren, M., 2008								X	X
McCauley-Bell, C-Y, Baidur, 1997								X	X
Saaty, 1990								X	
Hallowell, 2007								X	
Schwartz, 1962									X
Terrano, 1994									X
Zimmermann, 1991									X

CHAPTER III: METHODOLOGY

Experiment Overview

The purpose of the experiment is to develop a model that represents linguistic variables to quantify and rank risk factors that contribute to falls. The variables are quantified using fuzzy set theory. As a result, the model will evaluate the qualitative and quantitative data. (Zimmermann, 1991).

Research Variables

- **Dependent Variable:** Fall (Effect)
- **Independent Variable:** Risk factors that contribute to falls such as task related, human/personal, environmental, organizational (Multiple Causes)

Research Hypothesis

The following are research hypotheses, which include the null and the alternative.

1

H0: The development of a conceptual model that characterizes risk factors can be useful in reducing the likelihood of falls in NASA Ground Support Operations.

H1: The development of a conceptual model that characterizes risk factors cannot be useful in reducing the likelihood of falls in NASA Ground Support Operations.

2

H0: A fuzzy analytical hierarchy process model can be developed to predict the likelihood of falls in NASA Ground Support Operations.

H1: A fuzzy analytical hierarchy process model cannot be developed to predict the likelihood of falls in NASA Ground Support Operations.

Research Questions

1. What are the contributing risk factors that influence falls in the workplace?
2. How do we quantify contributing risk factors that influence falls in NASA ground support operations?
3. What is the total effect of these risk factors on falls?
4. How we will predict the likelihood of falls?

Research Phases

The following are the twelve major research phases:

1. **Knowledge Acquisition:** risk factors that contribute to falls are identified and classified. The first phase is to the development of taxonomy for multiple risk factors that contribute to fall (human/personal, task related, organizational, and environmental) to be evaluated. The taxonomies characterize categorical risk factors, sub risk factors, and factor variables affecting falls in the aerospace environment. The benchmark was to identify the significant factors by observing the repeatability three or more occurrences of risk factors in the literature review and compare it to the NASA/KSC Fall Hazard Report and NASA/KSC Incident Report Information System (McCauley-Bell, Baidur, 1996).
2. **Data Collection:** the following data including scenarios characteristics were collected from NASA/Kennedy Space Center Ground Support Operations Fall Hazard Report. The three scenarios are Shuttle Landing Facility (SLF), Launch Complex Payloads (LCP), and the Vehicle Assembly Building (VAB). The definition of categorical factors have been was developed in order to avoid any misunderstanding of the key factors to

enhance the success and accuracy of the data collection process. NASA/KSC partnered with Gravitec, Inc. to facilitate the data collection process within NASA Ground Support Operations (NASA, 2005). The multiple risk factors in the following table that contribute to falls will be assessed by using the surveys and the NASA Safety Index in APPENDIX F. A taxonomy characterization has been developed for multiple risk factors that contribute to falls, which include sub factors and factors variables identified after performing an intensive literature review and fall hazard reports review. Table 7 represents multiple risk factors that contribute to falls, factor variables, and metrics to be used for data collection in the research.

Table 7: Taxonomy

Conceptual Model Factors	Key variable	Data Collection	Equipment or Instrument Used
Task Related Factors			
Task Frequency	Rating	visual observation	index
Task Duration	Rating	visual observation	index
Task Proximity	Rating	tape measure/meter stick reading	meter stick/tape measure/index
Environmental Factors			
Fall Distance	feet/inches	tape measure/meter stick reading	meter stick/tape measure/index
Environmental Surface	Rating	visual observation	index
Environmental Conditions	Rating	visual observation	index
Human/Personal Factors			
Worker Interference	Rating	visual observation	index
Number of workers	Rating	visual observation	index
Age	Birth date	Birth date/Driver's License	Survey
Organizational Factors			
Fall Hazard Severity	Rating	visual observation	index
Fall Hazard Protection	Rating	visual observation	index
Fall Hazard Occurrence	Rating	counting/visual observation	index

The data in the following table which includes the scenarios characteristics were collected from NASA/Kennedy Space Center Ground Support Operations and Gravitec Fall Hazard Report.

Table 8: Scenario Characteristics

Work Area	**SLF**	**LCP**	**VAB**
Factor			
Task Duration	1.2-Medium	1.2-Medium	1.2 Medium
Task Frequency	1.1-Monthly	1.3-Daily	1.4-Shift
Task Proximity	1.2-Very close	1.2-Very close	1.2-Very close
Fall Distance	100 ft.	60 ft.	500 ft.
Environmental Conditions	1.2-Extreme	1.0-Good	1.1 –Variable
Environmental Surface	1.1-Poor	0.9-Excellent	0.9 Excellent
Age	32	47	25
# of workers	1 worker	1 worker	3 workers
Worker Interference	1.0-Independent	1.0 Independent	1.2-Multiple
Fall Occurrence	1.0-Unique	1.2-Common	1.2-Common
Fall Severity	5.0-Extreme	5.0-Extreme	5.0-Extreme
Fall Protection	0.75-Poor	1.0-None	0.75-Poor

3. **SMEs interviews:** The SMEs are representative of the environment being analyzed (pool of subjects). The SMES were selected based on the ability to answer the questions on the survey. The SMEs were selected based on experience/background and education (e.g. B.S. in Engineering/Technical/Safety Related Field and/or minimum of five years experience in Engineering/Technical/Safety Related Field). The SMEs were divided in teams that are evenly distributed for model validation. Six Subject Matters completed surveys using a voting system in NASA Expert Choice Team version. The SMES consisted of 2 Fall Protection Experts, 2 Human Factors Expert, and 2 Safety Engineer Experts. The voting system allows the SMES to make judgments simultaneously on risk factors using the fundamental pairwise scale (Saaty, 1990).
4. **Analytical Hierarchy Process (AHP):** Structure the decision model. AHP is a Process to analyze and structure a decision problem by prioritizing factors and alternatives (Saaty, 1990)
5. **Weight Validation:** Testing the validity of the developed AHP model will be done by comparing the priority vectors. The weight validation is justified by using the priority vector to validate the model by having two different sets of experts/decision makers create priority vectors separately. There will be three evenly distributed SMEs in each group. If the resulting priority vectors of the two different sets of experts are similar and that will validate the weights in the model. Priority vector is average weight of each factor. If the results of both vectors are the same or close to each other, then the model is confirmed valid. The ratings in AHP are subjective; which can lead to inconsistencies. To level the discrepancies, a priority vector is calculated (Dagdeviren, M., 2008).

6. **Fuzzification of Variables:** Fuzzy Set Theory (FST) has been used for the development of the linguistic approach where any variable is treated as a linguistic variable. In this research, the linguistic variables are Low, Medium, and High. FST can be used to translate linguistic terminology into numeric values to be used to get aggregate measures when given many inputs (Bonisson, 1980).
7. **Membership Function Development:** FST characterizes the concept of approximation based on membership functions with a range between 0 and 1, which provides the lower and upper approximations of a concept (Yao, Y.Y & Wong, S. K. M, 1992).
8. **Factor Qualification using Fuzzy Set Theory:** In order to develop a model that displays risk factors that contribute to falls, FST was selected as the most feasible technique to quantify these risk factors (Zimmermann, 1991).
9. **Factor Quantification using Fuzzy Set Theory:** Linguistic methods have been previously applied and developed for use in FST, allowing factor variables to be represented as numerical values (Zimmermann, 1991).
10. **Model Development:** FST provided a basis for development of a conceptual model and can be utilized in the field of pattern classification (Zadeh, 1965). Fuzzy Set Theory offered a mathematical framework in which unclear data can be accurately studied (Zimmermann, 1991).
11. **Model Usability:** Usability testing or usability practice is a technique used to evaluate a product, system, or even model by testing it on users. It is gives direct input on how real users use the system. Fifteen subjects were asked to apply fuzzy analytical hierarchy process model to three scenarios in NASA Ground Support Operations. The subjects

were fifteen engineers selected from UCF and NASA/KSC. The design of the experiment was a repeated measures analysis. Therefore, the subjects' responses (ratings of the three scenarios) were analyzed (Siegel, S., 1988).

12. **Model Validation:** In addition, the subjects were asked to evaluate the scenarios for the model validation. These predicted values from the SME regarding the scenarios were compared to the NASA accepted Scale for fall hazards. If the results of both models are the same or close to each other, then the model is confirmed valid (Siegel, S., 1988).

Scenarios

The following three scenarios were used in the model validation: Shuttle Landing Facility (SLF), Launch Complex Payloads (LCP), and Vehicle Assembly Building (VAB).

SLF Scenario: Shuttle Landing Facility Mate/De-mate Device

Mate / De-mate Device Camera

Figure 13: Scenario 1 (Shuttle Landing Facility)

Case Study: One worker at the age of 32 is required to conduct routine maintenance on the camera pictured in the red circle outside the Shuttle Landing Facility (SLF). At this site, there is no personal protection equipment. The maintenance includes lens cleaning, adjusting, focusing, etc. Once outside the guardrail railing, workers are exposed to a fall distance is approximately 100 ft. to the ground.

LCP Scenario: Launch Complex Payload 39 A & B (Launch Pad)

LC 39 A & B - Payload Platforms

Figure 14: Scenario 2 (Launch Complex Payload)

Case Study: A 47 year old is working off of the Launch Complex Payload (LCP) platforms at any level in this NASA/KSC facility on the orbiter payloads. There is minimal lighting in the facility for the worker. The fall distance is 60 + ft off platforms. All edges of platforms are unguarded. There is no fall protection equipment present.

VAB Scenario: Vehicle Assembly Building Roof

Building Roof

Figure 15: Scenario 3 (Vehicle Assembly Building)

Case Study: During construction, up to approximately three workers with an average age of 25 replace and repair roof material near the edge of the Vehicle Assembly Building (VAB) roof. Temporary Horizontal lifeline is installed (solid yellow line). A vertical line lifeline (dotted yellow line) is mounted to adjust the system to the proper length. The fall distance is in excess of 500 ft and contingent upon what location or perimeter of the roof where the fall may occur.

Schematic Diagram

The following schematic diagram represents the proposed fuzzy analytical hierarchy process model.

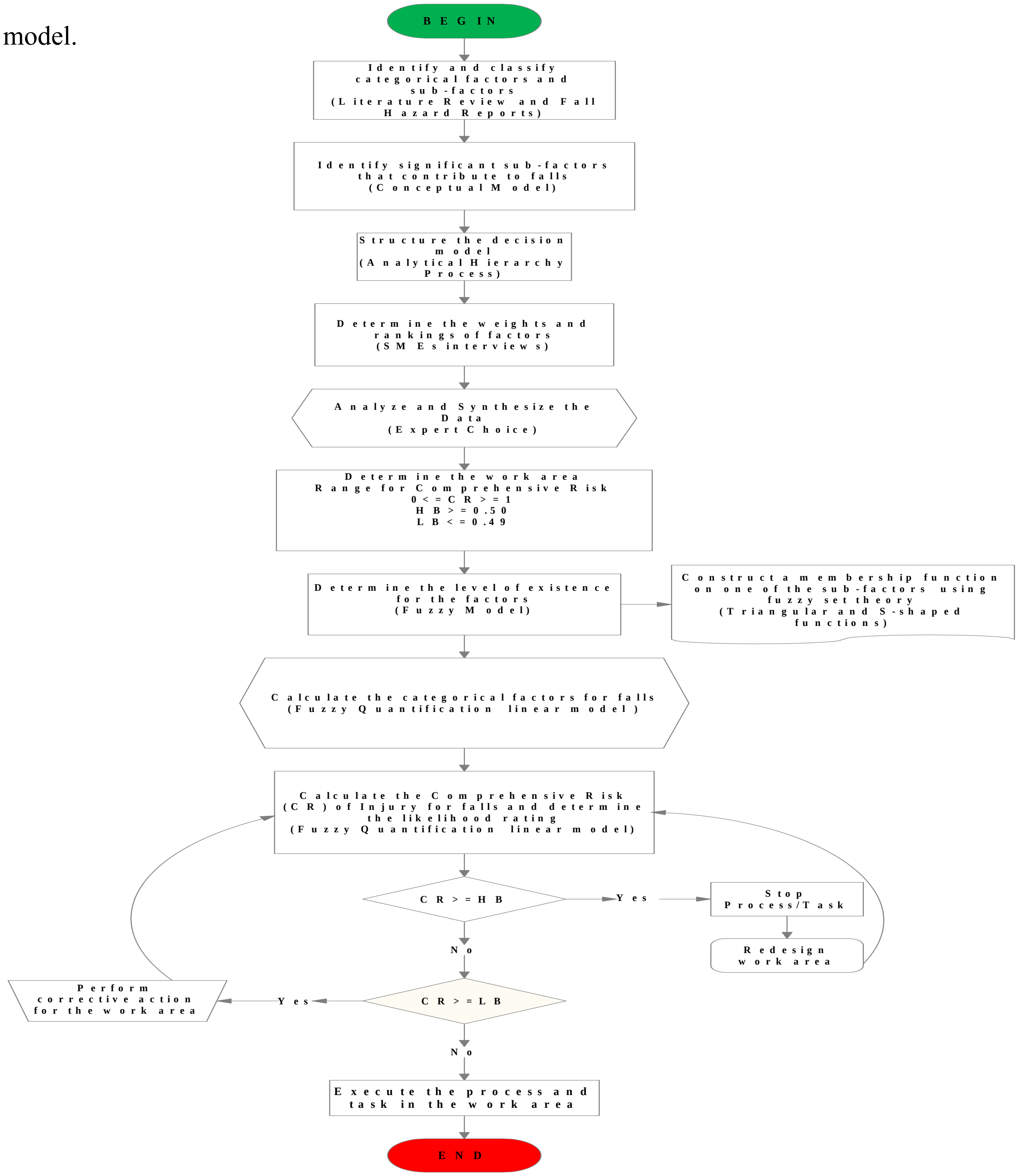


Figure 16: Schematic Diagram
(Dagdeviren, M., 2008; McCauley-Bell and Badiru, 1996)

Fuzzy Model Algorithm

The following Algorithm was adopted from the previous (Dagdeviren, 2008) study regarding a fuzzy AHP model (schematic diagram) for a faulty system in a work safety environment. The method was emulated because falls are under the umbrella system safety and is a hazard in the workplace.

BEGIN

Identify and classify the categorical risk factors and sub factors

(Conceptual Model)

Identify the significant factors that contribute to falls

(Literature Review and Other Sources)

Identification of significant categorical and sub-factors is conducting by observing the repeatability of three or more of same risk factors in the literature, Fall Hazard Report (2005), and current IRIS (NASA Mishap Data 2005-2008), etc. until the list was completely exhausted. The following list is a sample of 40 risk factors observed in the literature from a list of approximately 150 risk factors. For instance, age showed up approximately four times and environmental surface showed up three times. The benchmark for determining the final risk factors in the model was observing the reoccurrence of the same risk factor in the literature and NASA Fall Hazard Report. The multiple risk factors that contribute to falls in a general environment were compared to an aerospace environment such as NASA Ground Support Operations.

Source of fall:

1. Slip and Trip (Davis, 1983)
2. Slip and Trip (Maynard, 2002)
3. Slip and Trips (Holmes, N., 1999)
4. Prioproception (Gauchard, 2001)
5. Prioprioception (S.Lord, 2003)
6. Poor lighting (Hanson, 1999)
7. Poor Lighting (Maynard, 2002)
8. Management (Salazar, M., 2005)
9. Leadership/Management (Bentley & Haslam, 1998)
10. Age (Lockhart, 1998)
11. Age (Bentley, 2009)
12. Age (Agnew, 1993)
13. Age (Webster, 2000)
14. Sex/Gender (Webster, 2000)
15. Sex (BLS, 2007)
16. Sex/Gender (Bentley, 2009 and Masud & Morris, 2001)
17. Behavior (Maynard, 2002)
18. Behavior (Salazar, M., 2005)
19. Heights (Maynard, 2002)
20. Heights (Holmes, N., 1999)
21. Heights (Maynard, 2002)
22. Surface Contaminants (Bentley, 2009)
23. Environmental Contaminants (Gauchard, 2001)
24. Floor Contaminants (Maynard, 2002)
25. Nonmoving vehicles (BLS, 2007)
26. Nonmoving vehicles: trucks (Jones, D. 2003)
27. Coefficient of Friction (Maynard, 2002)
28. Friction Variation (Chang, Wen-Ruey, 2008)
29. Posture (Wogalter, 2006)
30. Postural Control or Neuropathy (Kim, B.J., 2005)
31. Task Frequency (NASA Fall Hazard Report, 2005)
32. Task Frequency (IRIS, 2008)
33. Task Duration (NASA Fall Hazard Report, 2005)
34. Task Duration (IRIS, 2008)
35. Fall Hazard Occurrence (NASA Fall Hazard Report, 2005)
36. Fall Hazard Occurrence (IRIS, 2008)
37. Fall Hazard Protection (NASA Fall Hazard Report, 2005)
38. Fall Hazard Protection (IRIS, 2008)
39. Worker Interference (NASA Fall Hazard Report, 2005)
40. Worker Interference (IRIS, 2008)

Table 9: Fall Risk Factors in NASA Ground Support Operations

Task Related Factors	**Human/Personal Factors**
Task Duration	Age
Task Frequency	Number of Workers
Task Proximity	Worker Interference
Organizational Factors	**Environmental Factors**
Fall Hazard Occurrence	Fall Distance/Direction
Fall Hazard Severity	Environmental Surface
Fall Hazard Protection	Environmental Conditions

Structure the decision model

The following figure is the AHP Affinity Diagram. It is the decision model for the research. The diagram displays the goal (objective), criteria (factors), and alternatives (areas of the concern for fall hazards in NASA Ground Support Operations) in the AHP model (Saaty, 1990).

Figure 17: Affinity Diagram

SME Interviews

Analytical Hierarchy Process (AHP) Data Collection

Subject Matter Experts can provide some insight on fall prevention intervention. See example of the voting instrument in the APPENDIX E. The numbers in the fundamental pairwise scale represent the rating for each risk factor. For example, if a task related factor is strongly more important than human/personal factor, then the rating will be five**.** The six subject matter experts will be making pairwise comparisons within and between the risk factors based on the previous fundamental scale. The three steps in AHP process are: perform pairwise comparisons, assess consistency of pairwise judgments, and compute the relative weights.

Table 10: Pairwise Comparison Fundamental Scale
(Saaty, 1990)

The Fundamental Scale for Pairwise Comparisons		
Intensity of Importance	**Definition**	**Explanation**
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another; its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation
Intensities of 2, 4, 6, and 8 can be used to express intermediate values. Intensities 1.1, 1.2, 1.3, etc. can be used for elements that are very close in importance.		

Expert Choice Software

Expert Choice Software was used to synthesize analyzed the SMEs results (Saaty, 1990). The NASA/KSC Expert Choice voting system allows teams (subject matter experts) to vote simultaneously by to making numerical judgments between risk factors that contribute to falls.

Determine the work environment

The areas that of concern for fall hazards in NASA Ground Support Operations are: Facility maintenance, Space Shuttle Operations, Payloads, Cranes, Construction, and Roofing. The model can be applied to any work environment. The higher and low boundaries were determined by the expert team based on the work area and tasks according to the following range for comprehensive Range of Fall Injury.

Determine the level of existence for each risk factor

The level of existence for each risk factor will be determined by using following triangular fuzzy scale. The level of existence for each risk factor is determined from the fuzzy membership functions inputs (the risk factor ranges). The level of existence is the numerical value and linguistic variables for each risk factor that contribute to falls. The range of comprehensive risk (CR) of falls is: $0 \leq CR \leq 1$

Table 11: Triangular Fuzzy Scale
(Dagdeviren, M., 2008)

Linguistic variables	**Meaning of Fuzzy Numbers**
Low	0-.33
Medium	0.34-0.66
High	0.67-1.0

Membership Functions

The next section is about Fuzzy Set Theory membership functions for various risk factors that contribute to falls. A membership functions are used to characterize risk factors or portray the universe of discourse. There are many types of fuzzy membership functions such as linear, triangular, trapezoidal, Gaussian, bell, sigmoid (s-shaped), but two were selected and applied to this research. Triangular membership function was selected to characterize the age (human/personal risk factor) in relation to falls. However, a sigmoid (s-shaped) membership function was selected to characterize the other risk factors such as task duration (task risk factor), fall distance (environmental risk factor), and fall hazard occurrence (organizational risk factor). A membership function *(MF*) is a curve that defines how each point in the input space or the universe of discourse is mapped to a degree of membership between 0 and 1. Examples of fuzzy or linguistic variables are *low, medium,* and *high* in regards to degree of membership for the level of existence in the set.

In general, the triangular membership function can be specified from the formula below:

$$\mu_{triang}(x) = \begin{cases} 0 & x < L \\ 1 - \dfrac{|C - x|}{(R - L)/2} & L < x < R \\ 0 & x > R \end{cases}$$

Equation 1

Where,

L is the left bound

R is the right bound

C is the center of the symmetric triangle

Table 12: Membership Function Variables

$\mu_{triang}(x)$ or $\mu_{sigmoid}(x)$	x-value
Degree of membership for falls	Scalar quantity (risk factor that contribute to falls)

Sigmoid membership functions are also called S-curve MF and are represented by increasing and decreasing nonlinear functions. A growing s-shaped MF goes from the left-hand side which represents no membership to the extreme right-hand side of the graph which represents a complete membership. S-curve MF are represented by three parameters: α which represents zero membership value, β the inflection point or the 50% membership point, and γ which represents complete membership value. S-curve MF represents continuous cumulative distribution functions and is commonly used to model population dynamics.

In general, the sigmoid membership function can be specified from the formula below:

$$\boldsymbol{S(x, \alpha, \beta, \gamma)} \quad \left\{ \begin{array}{l} \mathbf{0 \rightarrow x \leq \alpha} \\ 2(x-\alpha)/(\gamma-\alpha)^2 \rightarrow \alpha \leq x \leq \beta \\ 1-2(x-\gamma)/(\gamma-\alpha)^2 \rightarrow \beta \leq x \leq \gamma \\ 1 \rightarrow x \geq \gamma \end{array} \right\} \quad \textbf{Equation 2}$$

Where,
α= 0 degree of membership

β= 0.5 degree of membership or inflection point

γ= 1 degree of membership

`

The following fuzzy model is representative of McCauley-Bell and Baiduru fuzzy model (1996) by using the Fuzzy Quantification Linear Models (Terrano, 1994).

Calculate the Categorical Risk Factors for falls

Fuzzy Quantification Linear Models

Task Related Risk:

$X_1 = F(TR) = a_1 w_1 + a_2 w_2 + a_3 w_3 + \ldots\ldots + a_n w_n$ **Equation 3**

Human/Personal Risk:

$X_2 = F(HP) = b_1 z_1 + b_2 z_2 + b_3 z_3 + \ldots\ldots + b_n z_n$ **Equation 4**

Organizational Risk:

$X_3 = F(O) = c_1 u_1 + c_2 u_2 + c_3 u_3 + \ldots\ldots + c_n u_n$ **Equation 5**

Environmental Risk:

$X_4 = F(E) = d_1 v_1 + d_2 v_2 + d_3 v_3 + \ldots\ldots + d_n v_n$ **Equation 6**

where,

a= task related risk sub-factors relative weight

b=human/personal risk sub-factors relative weight

c=organizational risk sub-factors relative weight

d=environmental risk sub-factors relative weight

w=task related risk sub-factors level of existence

z=human/personal risk sub-factors level of existence

u=organizational risk sub-factors level of existence

v=environmental risk sub-factors level of existence

Calculate the Comprehensive Risk (CR) for falls

Fuzzy Quantification linear models

The following equation was used to quantify the comprehensive risk of a fall is a result of all three categories:

$$Y= e_1X_1 + e_2X_2 + e_3XR_3 +e_4X_4 \qquad \textbf{Equation 7}$$

where,

Y = comprehensive risk for the given condition

X_1 = the risk associated with the task related factors

e_1 = weighting factor for the task related factors

X_2 = the risk associated with the human/personal factors

e_2 = weighting factor for the human/personal factors

X_3 = the risk associated with the organizational factors

e_3 = weighting factor for the organizational factors

X_4 = the risk associated with the environmental factors

e_4 = weighting factor for the environmental factors

The weighting factors (e_1, e_2, e_3, e_4) represent the relative significance of the given risk factor category's contribution to the likelihood of injury.

The comprehensive risk is the aggregate value for the prediction of a fall; which is equal to the product of relative weight respective to the categorical risk factors.

Determine the likelihood rating for the associate risk for falls

The following table represents the aggregate risk value based on the comprehensive risk number and the rating associated with the fall injury in a work environment.

Table 13: Aggregate Risk Value Table
(McCauley-Bell & Baiduru, 1996)

Aggregate Risk Value	**Risk Association**	**Likelihood Rating**
0.00 - 0.20	Very Low risk: Falls are very unlikely to occur. Strong Controls are in place.	1
0.21 - 0.40	Low risk: Falls are not likely to occur. Controls have minor limitations and uncertainties.	2
0.41 - 0.60	Moderate risk: Falls may occur. Controls exist with some uncertainties.	3
0.61 - 0.80	High risk: Falls are highly likely to occur. Controls have significant uncertainties.	4
0.81 - 1.00	Very high risk: Falls are nearly certain to occur. Controls have little or no effect.	5

Model Application

Based on the comprehensive risk range, the boundaries were set by the SMEs. The High and Low Bounds are contingent upon the range for Comprehensive Risk (CR) of Injury.

Where,

CR=Y

High Bound (HB)

HB>=0.50

Low Bound (LB)

LB<=0.49

Apply the If and Then Rule followed by then the Loop process. Verify the high boundary (HB). If $CR \geq HB$, **YES** then stop process/task and redesign the work area and recalculate the CR again. If **NO,** then verify the low boundary (LB). If $CR \geq LB$, **YES,** then perform corrective action for the work area. If **NO,** execute the process/task in the work area and end the procedure.

END

CHAPTER IV: RESULTS AND DISCUSSION

The following chapter discusses the research findings. The model was developed by combining and defining multiple risk factors that contribute to falls in NASA Ground Support Operations.

AHP Analysis

The following weights in Figure 18 were obtained from the Expert Choice Software after entering the six SMEs judgments of the multiple risk factors that contribute to falls. The following are relative weights for these risk factors: Task Related (0.314), Human/Personal (0.307), Environmental (0.248), and Organizational (0.130). The overall inconsistency ratio for all the risk factors was 0.07, which indicates the model results were acceptable. The results show that task related risk factors are the highest cause for falls and the organizational risk are the lowest cause for falls in NASA Ground Support Operations.

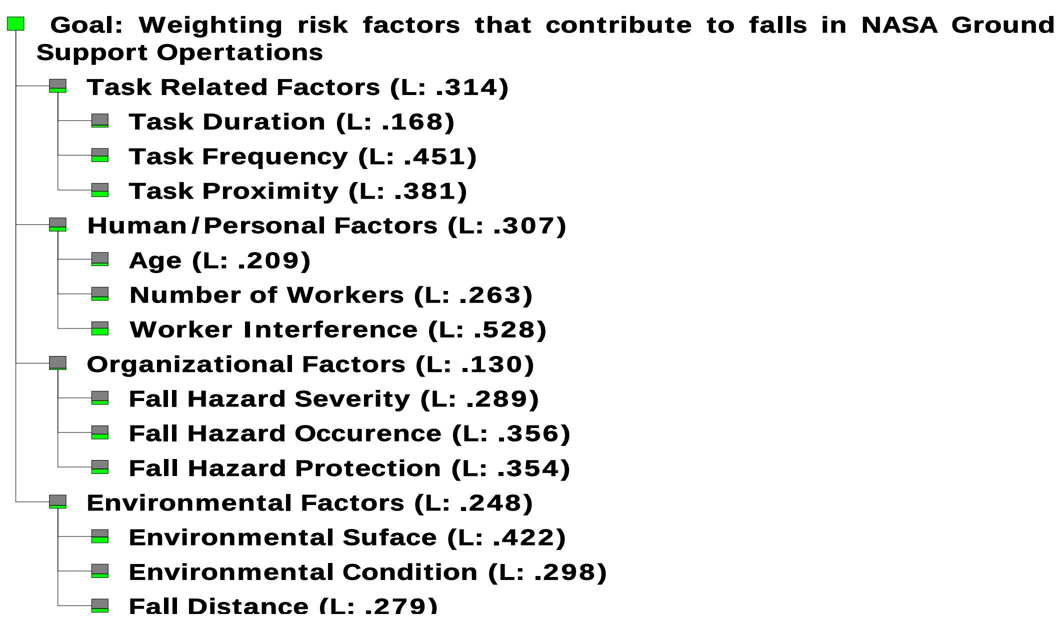


Figure 18: AHP Weights

AHP for Groups

AHP can be especially useful with groups. Each member's assessments can, of course, be evaluated for priorities and inconsistency, and then the group rollup (group segments) can be synthesized and viewed the same way. This can be a powerful way to build consensus, as each constituent can see where they stand and compare it to the group as a whole. If the group has a high inconsistency ratio (more than 0.1, or so) segmenting might reveal where the differences in agreement are and why they exist. That, too, can help lead to better understanding and consensus. Figure 19 shows the weights for the categorical risk factors where Task Related is 0.314, Human/Personal is 0.307, Environmental is 0.248, and Organizational is 0.130. Therefore, task is highest contributing factor to falls and organizational factors are the lowest contributing factor to falls. The inconsistency ratio was 0.01, which is acceptable.

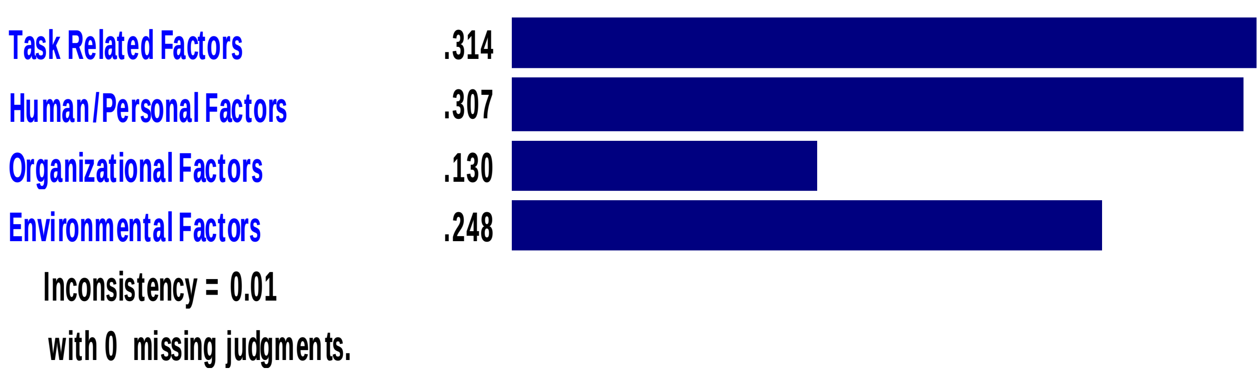


Figure 19: Categorical Risk Factors Weights

The relative weights for the task related risk factors are as follows: task frequency (0.451), task proximity (0.381), and task duration (0.168). It can be inferred from Figure 20 that Task Frequency is the highest contributing factors to fall and the task duration is the lowest contributing factor to falls. The inconsistency ratio is 0.11, which is acceptable.

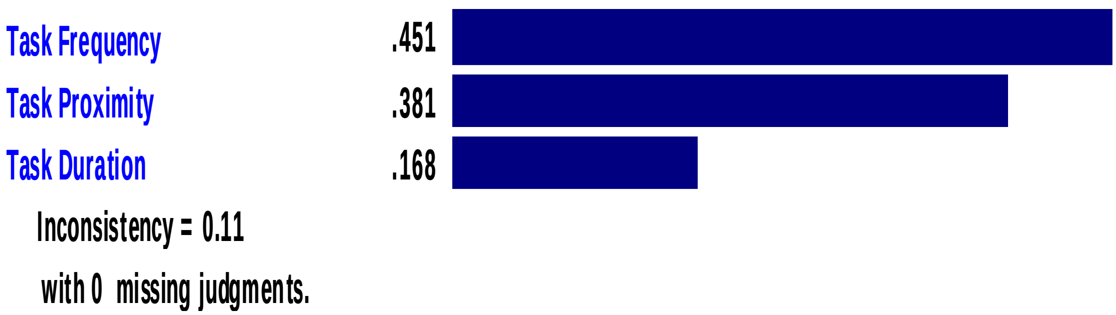


Figure 20: Task Related Risk Factors Weights

The relative weights for the human/personal risk factors are as follows: worker interference (0.528), task proximity (0.263), and task duration (0.209). It can be inferred from Figure 21 that Worker Interference is the highest contributing factor to falls and the age is the lowest contributing factor to falls. The inconsistency ratio is 0.01, which is acceptable.

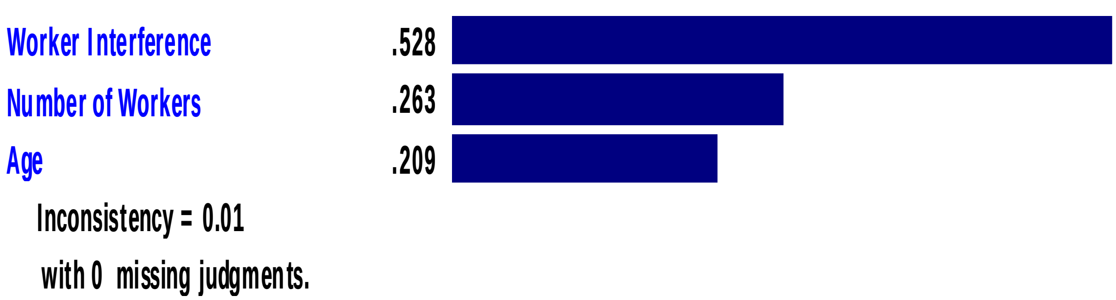


Figure 21: Human/Personal Risk Factors Weights

The relative weights for the organizational risk factors are as follows: fall hazard occurrence (0.356), fall hazard protection (0.354), and task duration (0.289). It can be inferred from Figure 22 that fall hazard occurrence is the highest contributing factor to falls and the fall hazard severity is the lowest contributing factor to falls. The inconsistency ratio is 0.00, which indicates there was no inconsistency among the SMEs on these risk factors.

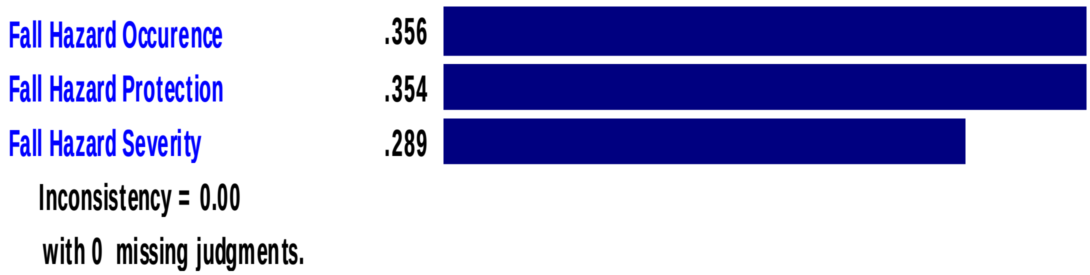


Figure 22: Organizational Risk Factors Weights

The relative weights for the environmental risk factors are as follows: environmental surface (0.422), environmental condition (0.289), and fall distance (0.279). It can be inferred from Figure 20 that environmental surface is the highest contributing factor to falls and the fall distance is the lowest contributing factor to falls. The inconsistency ratio is 0.11, which is acceptable.

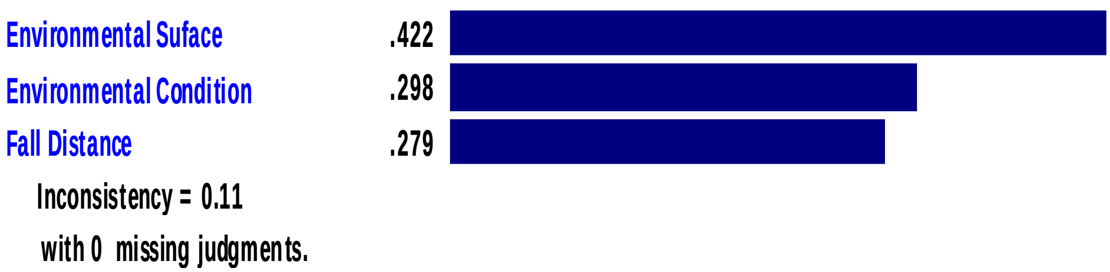


Figure 23: Environmental Risk Factor Weights

The following figure shows the synthesis and global weight with respect to the primary goal. It is inferred from the table that worker interference, task frequency, and task proximity are the highest risk factors leading to falls. The global weights are 0.162, 0.142, and 0.120 respectively. Therefore, task related factors are the leading risk factors that contribute to falls. From employee perspective, it is important to be cognizant of task related risk factors that lead to falls. It is observed from the research, the task related risk factors are the most relevant. NASA/Kennedy Space Center is a unique aerospace environment where specific tasks are performed from excessive heights. In this aerospace environment, tasks are schedule driven. It is imperative that the employee understands that task being performed, aware of the fall hazards and others while performing the task, and performs the task with safety measures in order to mitigate falls.

In addition, the inconsistency ratios for the individual SMES were all 0.3 and below, which indicates little discrepancy within and between the SMEs. For example, the safety experts inconsistency ratio was approximately 0.2, which indicates there is an agreement among the experts. The overall inconsistency for the model is 0.07. Therefore, the results are acceptable because the value is 0.1 or less.

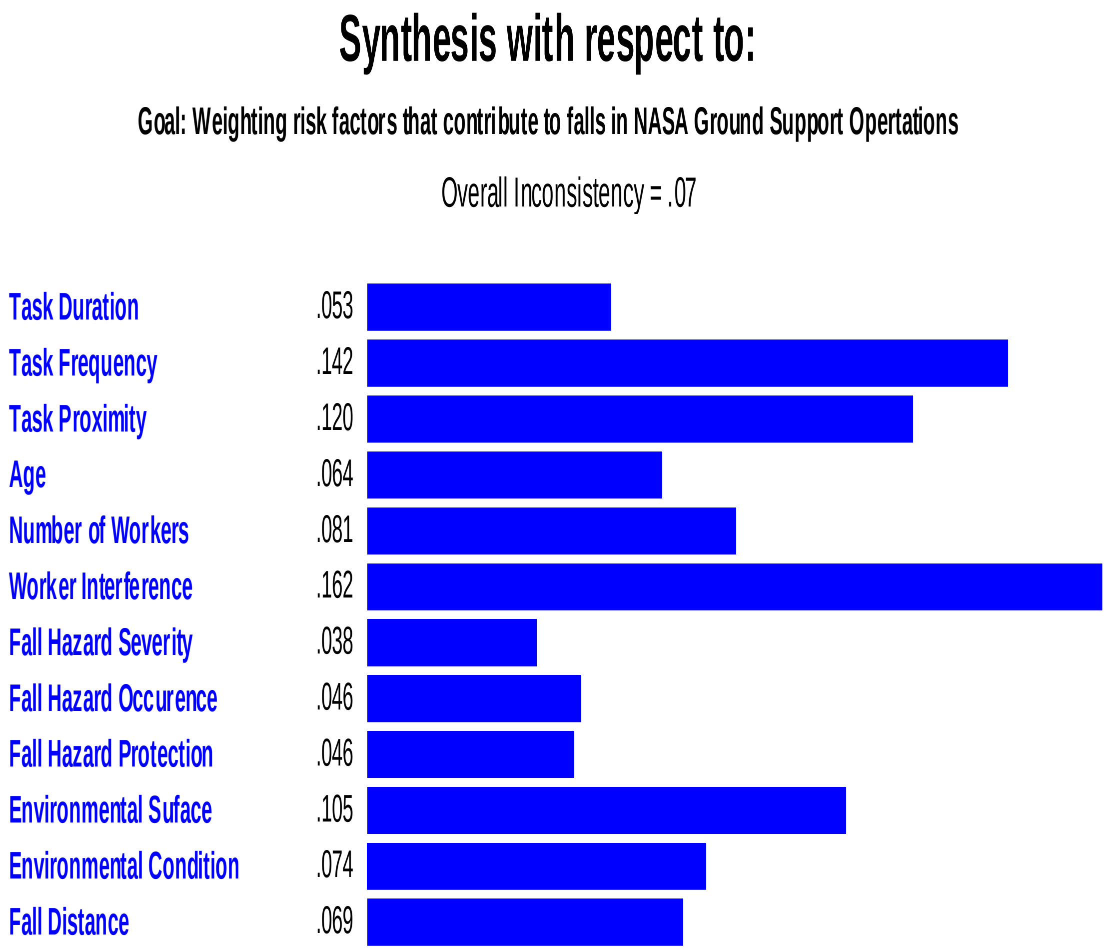


Figure 24: Synthesis with respect to the goal

Weight Validation

The ratings in AHP are subjective; which can lead to inconsistencies. There are several ways to validate the weights from the AHP. Please see the following table that displays a few alternative ways to validate relative weights in a model. The method that involves creating priority vectors among teams (Dagdeviren, M, 2008) will be used in this research.

Table 14: Alternative Methods for Weight Validation

Method	Reference
Estimation of overall workloads using physiological and epidemiological viewpoints and compared to NASA TLX results. (Risk Assessment)	(Jung and Jung, 2001)
Expert Opinions and Consistency Index (CI) of a matrix. (SWOT-ANP Model)	(Yuksel I. and Dagdeviren, M., 2007)
Comparison of priority vector from the studies using AHP with the actual relative weight vector to analyze validation. (AHP model)	(Whitaker, R., 2007)
Using the priority vector to validate the model by having two to three different team of subject matter experts create priority vectors separately and compare results. (AHP model)	(Dagdeviren, M., 2008)

To level the discrepancies, a priority vector is calculated. Testing the validity of the developed model will be done by comparing the priority vectors to actual weights. As indicated in the methodology, the model will be validated by having two teams of subject matter experts create priority vectors separately. There will be three evenly distributed SMEs in each group including a human factors expert, fall protection expert, and a safety expert. If the resulting priority vectors of the two different sets of experts are similar and that will validate the weights in the model. Priority vector is average weight of each factor. If the results of both vectors are the same or close to risk factors' relative weights, then the model is confirm valid.

Table 15 is the pairwise comparison matrix from Expert Choice Software for the categorical risk factors that contribute to falls in NASA Ground Support Operations. The values in the table are based on SMEs rankings for the risk factors. The values in the rows are multiples of each other. The values were determined by normalizing the columns. The values in Table 15 are the geometric averages between the judgments of risk factors. The sum is the total value for each column or the categorical risk factor. The diagonal elements of the matrix are all 1's for a consistent matrix.

Table 15: Pairwise Comparison Matrix

	Task Related	**Human/Personal**	**Organizational**	**Environmental**
Task Related	**1**	1	2.5	1.25
Human/Personal	1	**1**	2.84	1
Organizational	0.39	0.35	**1**	1.51
Environmental	0.8	1	0.6	**1**
Sum	**3.19**	**3.35**	**7.3**	**4.76**

The following values in Table 16 were determined by dividing each entry in the pairwise comparison matrix by the sum. The subject matter experts calculated the average of results for each categorical risk factor, which is the priority vector and compared it to the relative weights from Expert Choice Software. The results are similar. Therefore, the weights are confirmed valid.

Table 16: Priority Vector

Risk Factor					Priority Vector	Relative Weight	Rank
Task Related	0.313	0.298	0.342	0.262	**0.304**	**0.314**	**1**
Human/ Personal	0.313	0.298	0.389	0.210	**0.302**	**0.307**	**2**
Environmental	0.2501	0.298	0.0821	0.210	**0.21**	**0.248**	**3**
Organizational	0.122	0.104	0.136	0.317	**0.17**	**0.13**	**4**

The results in table 16 show that task related are the highest contributor risk factors to falls and organizational are the lowest contributor risk factors to falls in NASA Ground Support operations. It can be inferred from the results how a worker can perceive a risk associated with a task. For example, if a worker is performing facility maintenance where the fall hazard is 100 ft. versus 8 ft. in an elevated work area, they may assume a high risk for that task. As result, this situation could lead to a fall. Also, a worker may be schedule driven, influenced by peer pressure, and neglected to wear personal protection equipment. This is a characteristic of a human/personal risk factor that could lead to fall. In addition, environmental risk factors lead to falls. For instance, the environmental conditions concerning the hot or cold weather could lead to a fall. The weather can affect the environmental surface and the worker. If the weather is hot, the worker may prematurely fatigue from heat exhaustion and perspire while performing the task. If the weather is cold specifically snowing; with the change in temperature, the worker may slip on melting ice and lead to a fall. Therefore, it is confirmed that organizational would be least contributor risk factors to falls.

Fuzzy AHP Model

Membership Functions

Membership Functions will be developed for the following risk factors that contribute to falls in NASA Ground Support Operations: Task Duration, Fall Distance, Fall Hazard and Occurrence. The ranges for the membership functions were determined by the subject matter experts (SMEs) and the NASA Safety Index in the APPENDIX F. The linguistic variables in the membership functions are based on the meaning of fuzzy numbers in Table 11 and Table 25.

Human/Personal Factor: Age

Figure 25 is the Age Membership Function. It forms the shape of a triangle. It can be inferred from figure 25 that at the age of 45, there are high instances for falls and there is a high degree of fall injuries.

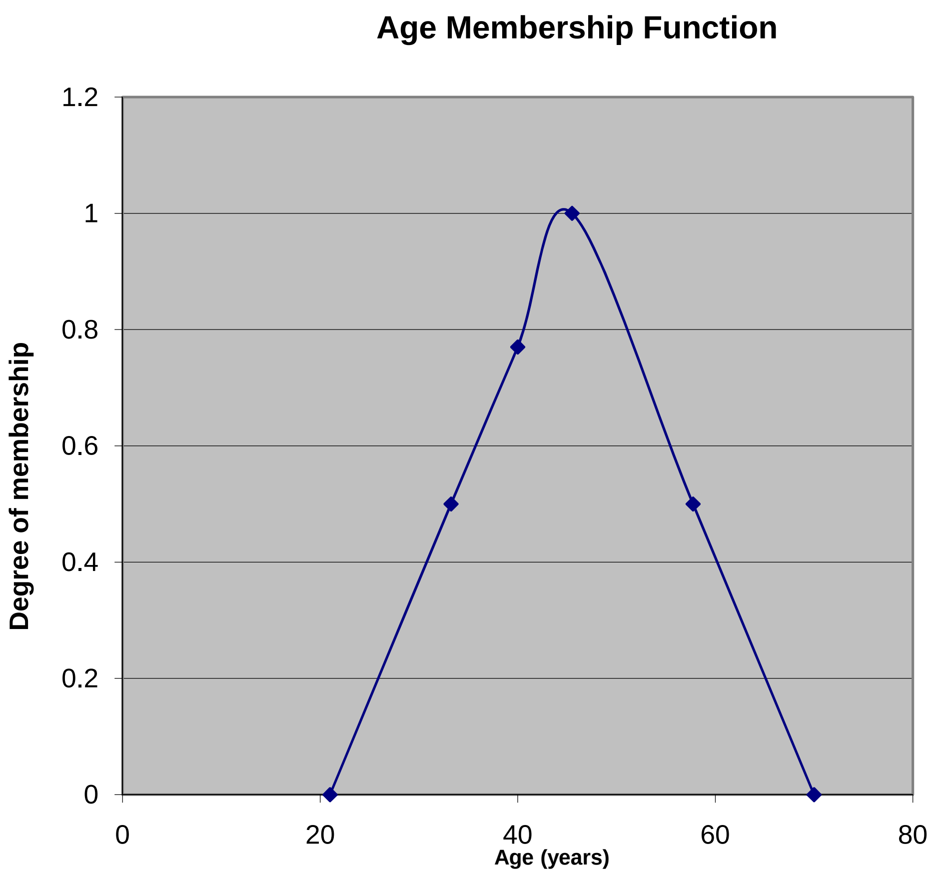


Figure 25: Age Membership Function

Table 17: Age Linguistic Variables

Human/Personal Factor Triangle		
Age (years)	**Degree of Membership**	**Ling. Var.**
21	0	low
33.25	0.5	medium
40	0.77	high
45.5	1	high
57.75	0.5	medium
70	0	low

It can be inferred from Table 17 that during the age range of 40-45, there are high instances for falls and fall injuries. There was a common thread and trends in the fall data and among other studies. For the age range of 40-45, there are high occurrences or instances for falls. There is a parenthetical remark to be made about the observation in the research. It is not scientifically sound to say that there is a high degree of likelihood for falls due to the unknown base population. In decision analysis, there is a concept called base rate neglect or base rate fallacy. The base rate fallacy, also called base rate neglect, is an error that occurs when the conditional probability of some hypothesis H (educated guess) given some evidence E is assessed without taking sufficient account of the "base rate" or "prior probability" of H. In other words, the terminology refers to a decision maker using specific information and neglecting the base rate information. For example, the campus police will say that a Honda Accord is the most stolen on the UCF Campus. Of course, UCF is a large campus and have many cars on campus. It can be inferred that the Honda Accord has a high degree of likelihood of being stolen! The statement is false. Likelihood is state of being probable. The Honda Accord is a popular car and there are more Honda Accord's on campus. The Honda Accord could have a low likelihood of being stolen and still be the most stolen car on campus. The population of cars on UCF campus needs to be investigated before the Honda Accord is declared the car with the highest degree of likelihood for being stolen. Lastly, according the statistics, the population at NASA/KSC consists of majority of employees in the age range of 40-45 years of age. In addition, according to the BLS Data in Table 18, the greatest number of falls occurred in the age range of 45 to 54 in 2005, 2006, and 2007.

Table 18: BLS Data

BLS Age Range	Falls 2005	Falls 2006	Falls 2007
Age:			
25 to 34	48,760	44,310	44,900
35 to 44	60,170	54,280	55,580
45 to 54	63,720	57,990	65,670
55 to 64	41,480	39,540	48,100
65 and over	11,290	10,320	11,210

Task Related Factor: Task Duration

Figure 26 is the Task Duration Membership Function. It forms the s-shape curve. It can be inferred from figure 26 that as the task duration increases, the high instances for the falls increases. Therefore, the variables are directly proportional.

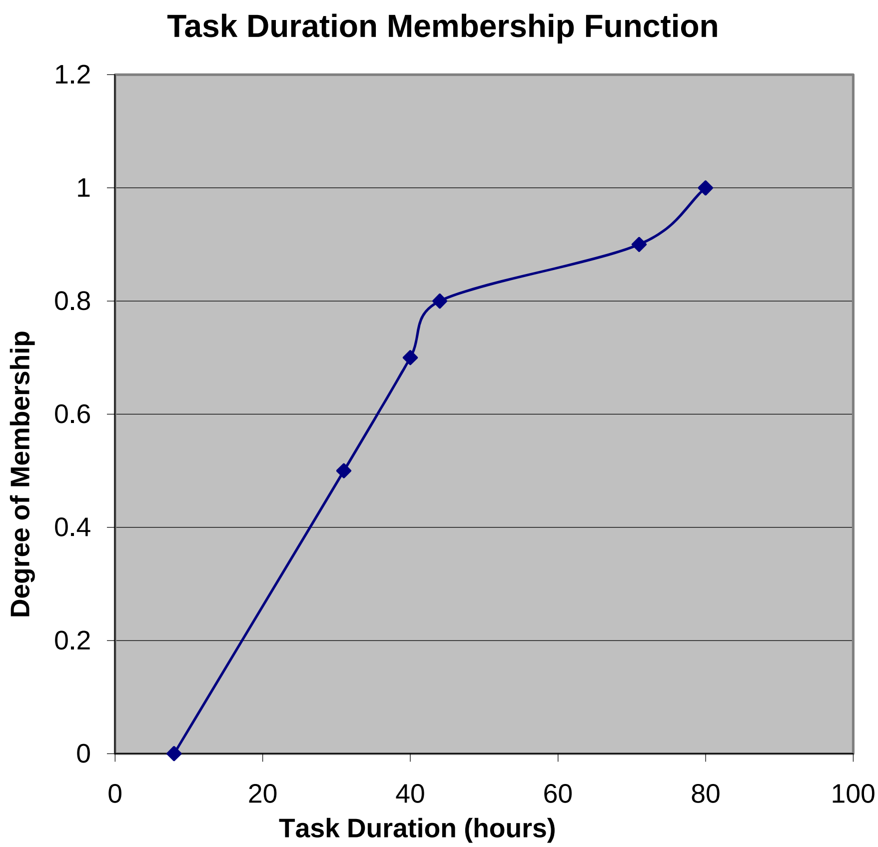


Figure 26: Task Duration Membership Function

Table 19: Task Duration Linguistic Variables

Task Related Factor S-shaped		
Task Duration (hours)	**Degree of Membership**	**Ling. Var.**
8	0	low
31	0.5	medium
40	0.7	high
44	0.8	high
71	0.9	high
80	1	high

It can be inferred from Table 19 that a worker performing a task approximately 40 hours or more are exposed to a high risk for falls and spending a long time in proximity to a fall hazard.

Environmental Factor: Fall Distance

The fall distance membership function was developed based on the Fall Hazard Severity Index. The membership function forms the s-shape curve. It can be interrupted from the figure 27 that as the fall distance increases, the likelihood for falls increases. These variables are also directly proportional.

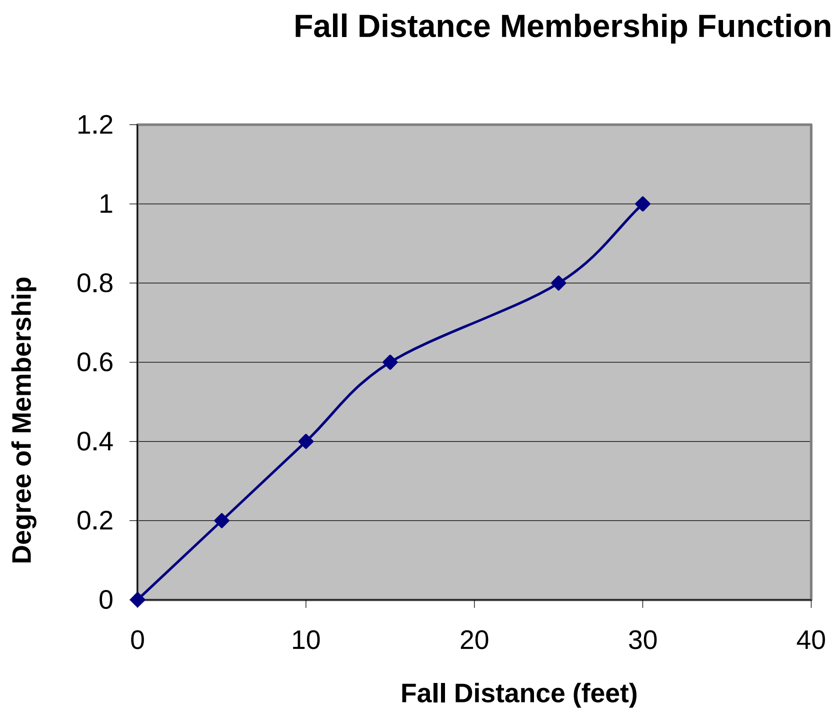


Figure 27: Fall Distance Membership Function

Table 20: Fall Distance Linguistic Variables

Environmental Factor S-shaped		
Fall Distance (feet)	**Degree of Membership**	**Ling. Var.**
0	0	low
5	0.2	low
10	0.4	medium
15	0.6	medium
25	0.8	high
30	1	high

It can be observed from Table 20 that if a fall distance is 25 ft or higher, there are high instances for falls and there is a likelihood of a fall hazard. The fall hazard is likely to cause a critical injury, permanent or temporary disability and in some cases death.

Organizational Factor: Fall Hazard Occurrence

The fall hazard occurrence membership function was developed based on the Fall Hazard Occurrence Index. The membership function forms the s-shape curve. It can be inferred from the Figure 28 that as the fall hazard occurrence increases, the likelihood for falls increases. Thus, the variables are directly proportional.

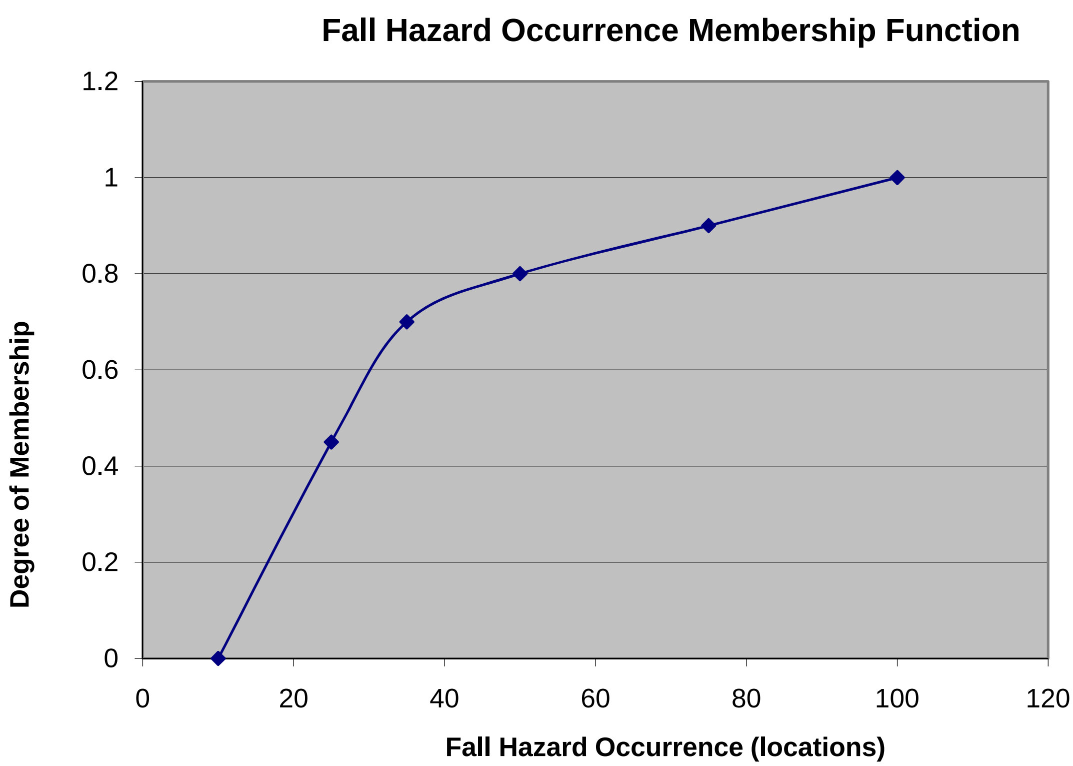


Figure 28: Fall Hazard Occurrence Membership Function

Table 21: Fall Hazard Occurrence Linguistic Variables

Organizational Factor		
S-shaped		
Fall Hazard Occurrence (locations)	**Degree of Membership**	**Ling. Var.**
10	0	low
25	0.45	medium
35	0.7	high
50	0.8	high
75	0.9	high
100	1	high

It can be inferred from Table 21, that if a fall hazard is at 35 or more locations, there is high risk for falls and is considered recurring safety hazard. There number of falls will increase if the fall hazard incidents increase.

Risk Factor Ranges for Existence

Table 22 lists the ranges that were established for each variable. These ranges are based on the NASA Safety Index in the APPENDIX F and in some cases SME input. If the fall hazard occurrence is 50 locations, it is considered a 1.4 in the NASA Safety Index Scale. As a result, the risk factors are associated with a task index for NASA Ground Support Operations.

Table 22: Ranges for Risk Factors

Conceptual Model Factors	Ranges for Fuzzy Model (Left to Right)
Task Related Factors	
Task Frequency	0.1 to 2.0
Task Duration	1.0 to 2.0
Task Proximity	1.0 to 2.0 (in relation to Fall Distance)
Environmental Factors	
Fall Distance	0-10ft= low (0.33), 11-15 ft= medium (0.66), >25 ft, =high (1.0)
Environmental Surface	0.9 to 2.0
Environmental Conditions	0.9 to 2.0
Human/Personal Factors	
Worker Interference	1.0 to 2.0
Number of workers	1 to 5 (dependent on workers)
Age	21-70 (years)
Organizational Factors	
Fall Hazard Severity	1 to 10
Fall Hazard Protection	0.1 to 2.0
Fall Hazard Occurrence	1.0 to 2.0

Mathematical Model

The fuzzy analytical hierarchy process (AHP) model was validated by requesting 15 subjects apply it to three scenarios in NASA Ground Operations. The three scenarios selected for the model validation are: Shuttle Landing Facility (SLF), Launch Complex Payload (LCP), and Vehicle Assembly Building (VAB). The following data including scenario characteristics was collected for each scenario.

The following level of existence listed in Table 24 was based on the ranges for each risk factor and the scenario characteristics listed in Table 23. The data in Table 23 was collected by NASA SMES. The ranges were inputted in the triangular membership function. The output was the level of existence for each risk factor. For example, for SLF, age range is 21-70 and the age for the scenario was 32 years. Therefore, 21 is the left bound and 70 is right bound in the triangular membership function. The inputs are these boundaries and the output is the level of existence for each risk factor.

Table 23: Scenario Characteristics
(NASA Fall Hazard Report, 2005)

Work Area	**SLF**	**LCP**	**VAB**
Factor			
Task Duration	1.2-Medium	1.2-Medium	1.2 Medium
Task Frequency	1.1-Monthly	1.3-Daily	1.4-Shift
Task Proximity	1.2-Very close	1.2-Very close	1.2-Very close
Fall Distance	100 ft.	60 ft.	500 ft.
Environmental Conditions	1.2-Extreme	1.0-Good	1.1 –Variable
Environmental Surface	1.1-Poor	0.9-Excellent	0.9 Excellent
Age	32	47	25
# of workers	1 worker	1 worker	3 workers
Worker Interference	1.0-Independent	1.0 Independent	1.2-Multiple
Fall Occurrence	1.0-Unique	1.2-Common	1.2-Common
Fall Severity	5.0-Extreme	5.0-Extreme	5.0-Extreme
Fall Protection	0.75-Poor	1.0-None	0.75-Poor

Table 24: Risk Factor Level of Existence

Work Area	SLF	LCP	VAB
Factor			
Task Duration	.4	.4	.4
Task Frequency	.95	.74	.63
Task Proximity	.4	.4	.4
Fall Distance	1.0	1.0	1.0
Environmental Conditions	.54	.18	.36
Environmental Surface	.36	0	0
Age	.48	.94	.16
Number of workers	0	0	1
Worker Interference	0	0	.4
Fall Occurrence	0	.4	.4
Fall Severity	.88	.88	.88
Fall Protection	.68	.94	.68

Development of the Linguistic Variables

As indicated in the methodology section, the following table represents the linguistic variables and the meaning of the fuzzy numbers. The following values are based on the triangular membership function where there are three points (e.g. low, medium, high). The meaning of the fuzzy numbers are the ranges for the linguistic variables developed from the subject matter experts and fuzzy AHP study for safety (Dagdeviren, M., 2008).

Table 25: Meaning of Fuzzy Numbers

Linguistic variables	Fuzzy Numbers
Low	0-.33
Medium	0.34-0.66
High	0.67-1.0

Model Usability

Usability testing or usability practice is a technique used to evaluate a product, system, or in this research a model by testing it on users. It gives the direct input on how real users use the system. The model usability involves the application of Fuzzy Quantification Linear Models presented below. The general linear equations were presented in the Methodology section. Using the weights from AHP and the level of existence for each risk factor, the fuzzy linear equations will be solved.

Shuttle Landing Facility (SLF) Scenario

The following are the results for the Shuttle Landing Facility.

$$\mathbf{X_1(\boldsymbol{TR}) = (0.481)(0.95) + (0.168)(0.4) + (0.381)(0.4) = 0.524}$$ **Equation 8**

$$\mathbf{X_2(E) = (0.279)(1) + (0.422)(0.36) + (0.298)(0.54) = 0.591}$$ **Equation 9**

$$\mathbf{X_3(H/P) = (0.528)(0) + (0.236)(0) + (0.209)(0.44) = 0.091}$$ **Equation 10**

$$\mathbf{X_4(O) = (0.289)(0.89) + (0.354)(0.68) + (0.356)(0) = 0.498}$$ **Equation 11**

$$\mathbf{Y = (0.314)(0.524) + (0.248)(0.591) + (0.307)(0.092) + (0.130)(0.498) = 0.404}$$

Equation 12

Launch Complex Payloads (LCP) Scenario

The following are the results for the Launch Complex Payloads.

$$\mathbf{X_1(TR) = (0.481)(0.74) + (0.168)(0.4) + (0.381)(0.4) = 0.423}$$ **Equation 13**

$$\mathbf{X_2(E) = (0.279)(1) + (0.422)(0) + (0.298)(0.2) = 0.339}$$ **Equation 14**

$$\mathbf{X_3(H/P) = (0.528)(0) + (0.236)(0) + (0.209)(0.6) = 0.125}$$ **Equation 15**

$$\mathbf{X_4(O) = (0.289)(0.9) + (0.34)(0.94) + (0.356)(0.4) = 0.735} \quad \textbf{Equation 16}$$

$$\mathbf{Y = (0.314)(0.423) + (0.248)(0.338) + (0.307)(0.125) + (0.130)(0.735) = 0.351} \quad \textbf{Equation 17}$$

Vehicle Assembly Building (VAB) Scenario

The following are the results for the Vehicle Assembly Building.

$$\mathbf{X_1(TR) = (0.481)(0.63) + (0.168)(0.4) + (0.381)(0.4) = 0.370} \quad \textbf{Equation 18}$$

$$\mathbf{X_2(E) = (0.279)(1) + (0.422)(0) + (0.298)(0.36) = 0.386} \quad \textbf{Equation 19}$$

$$\boldsymbol{X_3}\mathbf{(H/P) = (0.528)(0) + (0.236)(1) + (0.209)(0.16) = 0.091} \quad \textbf{Equation 20}$$

$$\mathbf{X_4(O) = (0.289)(0.88) + (0.354)(0.68) + (0.356)(0) = 0.498} \quad \textbf{Equation 21}$$

$$\mathbf{Y = (0.314)(0.370) + (0.248)(0.306) + (0.307)(0.508) + (0.130)(0.637) = 0.451} \quad \textbf{Equation 22}$$

Table 26 is the Aggregate Risk Value table from a previous study with a few modifications (McCauley-Bell and Baiduru, 1996). The ranges in Table 26 were developed by the Subject Matter Experts. The following table was applied in the model usability to determine the aggregate risk values and likelihood rating. The likelihood rating and risk are based on the comprehensive risk value (Y).

Table 26: Aggregate Risk Value and Likelihood Rating

Risk Value	Risk	Likelihood Rating
0.00 - 0.20	Very Low risk: Falls are very unlikely to occur. Strong Controls are in place.	1
0.21 - 0.40	Low risk: Falls are not likely to occur. Controls have minor limitations and uncertainties.	2
0.41 - 0.60	Moderate risk: Falls may occur. Controls exist with some uncertainties.	3
0.61 - 0.80	High risk: Falls are highly likely to occur. Controls have significant uncertainties.	4
0.81 - 1.00	Very high risk: Falls are nearly certain to occur. Controls have little or no effect.	5

The comprehensive risk values for the following scenarios are: Shuttle Landing Facility (0.404), Launch Complex Payloads (0.351), and Vehicle Assembly Building (0.451). The predicted values and accepted values are the likelihood ratings for each scenario. Therefore, the Shuttle Landing Facility and Launch Complex Payloads had a likelihood rating of two; which is a low risk environment for falls. Falls are not likely to occur. The controls in the environment have minor limitations and uncertainties. However, the Vehicle Assembly Building had a likelihood rating of three; which is a moderate risk environment for falls. Falls may occur. Controls exist with some uncertainties in this environment. Thus, predicted value from Table 26 was compared to accepted value in Table 27. Table 27 is the Fall Hazard Accepted Scale from NASA/Kennedy Space Center Safety Report developed by the NASA Contractor and NASA Safety Directorate.

Table 27: NASA Fall Hazard Accepted Table

Risk Value	Risk	Likelihood Rating
0-5	Low Risk Hazards	1
6-10	Medium Risk Hazards	2
10-15	High Risk Hazards	3
15-20	Dangerous Risk Hazards	4
20-25	Extreme Hazards	5

The percentage error was calculated for each scenario by the Subject Matter Expert (NASA Safety Manager) using the following equation:

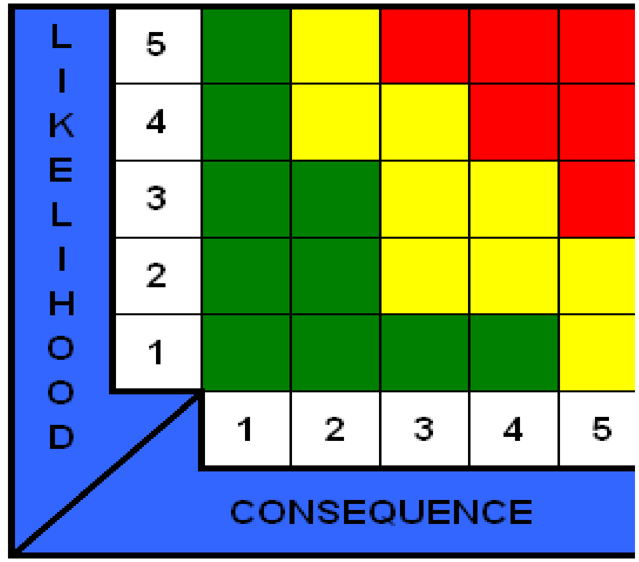
$$\%error = \frac{(predicted - accepted)}{accepted} \qquad \textbf{Equation 23}$$

Percentage error is the estimate minus the true value divided by the true value and multiplied by 100 with the absolute value. In this case, it is predicted value minus the accepted divided by the accepted value multiplied by 100. The final result is the absolute value of the answer. For example, the accepted values for the three scenarios were: SLF:2, LCP:3, VAB:3, and the predicted values were: SLF:2, LCP:2, and VAB:3. The likelihood ratings were very similar. Therefore, the percentage error for the three scenarios was 0%, 33%, and 0% respectively.

NASA Safety Risk Scorecard

The research involves evaluating risk factors that contribute to falls in NASA Ground Support Operations, it is imperative to relate the fuzzy AHP model to the NASA Safety Risk Scorecard. Showing a correlation between the fuzzy AHP model and the NASA Safety Risk scorecard is the empirical approach to the research and the first time being used in the research. Table 26 and Table 27 have 5 ranges associated with the risk and the NASA risk Scorecard has 5 levels associated with the risk assessment. The NASA Safety Risk Scorecard is a method to assess risks at NASA and specifically the future Constellation Program. The NASA risk scorecard includes a 5 x 5 matrix in figure 29. For instance, a worker is performing a task on High Bay 3 area for the Constellation Project at NASA/Kennedy Space Center. The worker does not use pre manufactured fall protection equipment because the fall distance is assumed not to be detrimental to the welfare and safety of the human being. Therefore, in this case the Occupational Safety and Health Administration (OSHA) requirement for a fall hazard is neglected. The subject matter expert evaluates the fall hazard as highly likely to occur. The controls have significant uncertainties in the work environment. Consequently, there may be a loss of life or permanently disabling injury to the worker. The final assessment using the following NASA Scorecard is a 4 x 5 risk. Thus, fall hazard risk is high (Red) and catastrophic.

Likelihood Rating		
5	Very High	Nearly certain to occur. Controls have little or no effect.
4	High	Highly likely to occur. Controls have significant uncertainties.
3	Moderate	May occur. Controls exist with some uncertainties.
2	Low	Not likely to occur. Controls have minor limitations/uncertainties.
1	Very Low	Very unlikely to occur. Strong Controls in Place.



Consequence	Component	1	2	3	4	5
Safety	**Personnel**	Minor Injury	Injury requiring first aid treatment	Injury or illness; medical treatment	Severe injury or hospitalization	Loss of Life or permanently disabling injury
	System Safety	Minor damage or non essential flights assets	Minor damage to the program critical needs	Minor damage to flight, Ground Support assets,	Loss of mission, major damage to flight,	Loss of Flight or Ground Assets or Loss of vehicle prior to completing its mission Catastrophic hazard
	Environmental	Negligible; OSHA/EPA violation non reportable	Minor reportable OSHA/EPA violation; reportable	Moderate OSHA/EPA violation which requires immediate remediation	Major OSHA/EPA violation causing temporary stoppage	Serious or repeat OSHA/EPA violation; termination of project or program

Figure 29: NASA Risk Scorecard

Figure 30 is an example of project where the NASA Safety Risk Scorecard can be applied. NASA/Kennedy Space Center is currently working on the Constellation project for the new vehicle entitled, Orion 606D Ground Operations. Figure 30 displays simulated models are from the NASA/KSC Design Visualization Lab of Human Factors capabilities in Delmia Envision that portrays the tasks being performed in the Aerospace Industry. The tasks contain the physical system with a human. NASA Risk Scorecard can be used evaluate the following work areas and determine the fall hazards in each area. Figure 30 is the models for Launch Pad Operations (Pad 39 B) and Hazardous Servicing; which are considered fall hazards. ***Disclaimer:*** *NASA/KSC Constellation Ground Ops Project is under development and material is subject to update.*

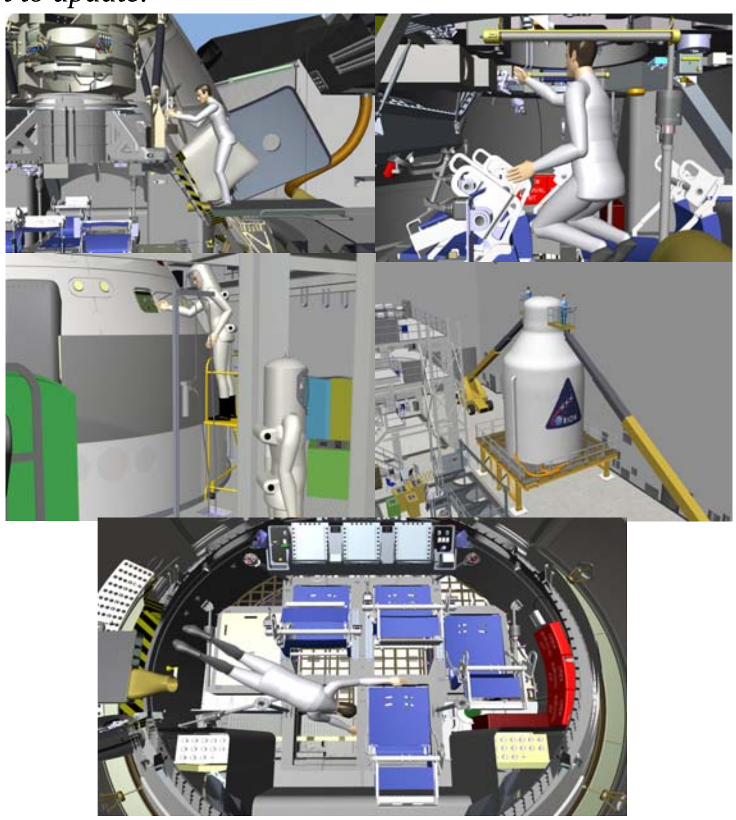


Figure 30: Constellation Orion 606D Models

Statistical Analysis

Repeated Measures Analysis

Repeated measures analysis is a systematic method to validate a model. There are fifteen subjects participating in the model validation. They are applying the fuzzy AHP model to three scenarios. They are repeating the same technique for all three cases. Therefore, design of experiment for the model validation was a repeated measures analysis. Repeated measures are multiple measurements of some kind being made on the same subject. Repeated measures analysis of variance involves two types of factors--between subject factors and within subject factors. The repeated measures make up the levels of the within subjects factor. The objective of the repeated measure analysis is to test for significant differences in means when the same observation appears in multiple levels of a factor.

Repeated Measures Analysis of Variance

The following are the research hypotheses that were tested in the research.

1

H0: The development of a conceptual model that characterizes risk factors can be useful in reducing the likelihood of falls in NASA Ground Support Operations.

H1: The development of a conceptual model that characterizes risk factors cannot be useful in reducing the likelihood of falls in NASA Ground Support Operations.

2

H0: A fuzzy analytical hierarchy process model can be developed and validated to predict the likelihood of falls in NASA Ground Support Operations.

H1: A fuzzy analytical hierarchy process model cannot be developed to predict the likelihood of falls in NASA Ground Support Operations.

A Kendall's Coefficient of Concordance test, Attribute Agreement analysis, t-test, and an analysis of variance test were performed on the data to evaluate the hypothesis.

When several measurements are taken on the same experimental unit (e.g. person, plant, machine, subject etc.), the measurements tend to be correlated with each other. When the measurements represent qualitatively different things, such as weight, length, and width, this correlation is best taken into account by use of multivariate methods, such as multivariate analysis of variance. When the measurements can be thought of as responses to levels of an experimental factor of interest, such as time, treatment, or dose, the correlation can be taken into account by performing a repeated measures analysis of variance.

Agreement of Data

The Attribute Agreement analysis and Kendall's Coefficient of Concordance test was performed to evaluate the agreement of data within and between subjects in the model validation.

Attribute Agreement Analysis

Attribute Agreement Analysis is a quality assessment tool used to evaluate the agreement of subjects while appraising data. This analysis was done using Minitab. The session in Minitab includes the following tables

Within Appraiser: Does each subject rate scenarios consistently?

across trials? In other words, does the appraiser give the same rating to the

same scenario each time?

Between Appraiser: Doe the subjects' ratings agree with each other?

That is, do different appraisers give the same rating to the same scenario?

The following results in Figure 31 are the Minitab output regarding the Attribute Agreement Analysis for the ratings in the model validation. The results show that one subject; which is subject # 2 did not rate the scenario the same as the other subjects. The rationale for subject #2 incorrect rating is that the subject most likely did not understand the scenario. The subjects applied the fuzzy AHP model to the scenarios. The scenarios were evaluated twice. For instance, there were three scenarios inspected and only two matched in the trials. In Figure 31, it shows that all subjects inspected 3 scenarios and the ratings were matched for scenarios except for one subject. For the fourteen subjects, the 95% confidence interval (CI) for percent matched is 36.85% to 100%. For the one subject, the 95% confidence interval (CI) for percent matched is 9.43% to 99.16%. The percent matched for the fourteen subjects was 100%. The percent matched for the one subject was 66.67%. The rationale for this one subject's incorrect rating is due ambiguity and misapprehension of the scenario in the model usability. Therefore, the fuzzy AHP model is precise, intuitive, and applicable for the evaluation of risk factors that lead to falls.

Within Appraisers

Assessment Agreement

Appraiser#	Inspected#	Matched	Percent	95 % CI
Subject 1	3	3	100.00	(36.84, 100.00)
Subject 10	3	3	100.00	(36.84, 100.00)
Subject 11	3	3	100.00	(36.84, 100.00)
Subject 12	3	3	100.00	(36.84, 100.00)
Subject 13	3	3	100.00	(36.84, 100.00)
Subject 14	3	3	100.00	(36.84, 100.00)
Subject 15	3	3	100.00	(36.84, 100.00)
Subject 2	**3**	**2**	**66.67**	**(9.43, 99.16)**
Subject 3	3	3	100.00	(36.84, 100.00)
Subject 4	3	3	100.00	(36.84, 100.00)
Subject 5	3	3	100.00	(36.84, 100.00)
Subject 6	3	3	100.00	(36.84, 100.00)
Subject 7	3	3	100.00	(36.84, 100.00)
Subject 8	3	3	100.00	(36.84, 100.00)
Subject 9	3	3	100.00	(36.84, 100.00)

Matched: Appraiser agrees with him/herself across trials.

Between Appraisers

Assessment Agreement

# Inspected	# Matched	Percent	95 % CI
3	2	66.67	(9.43, 99.16)

Matched: All appraisers' assessments agree with each other.

Figure 31: Attribute Agreement Analysis Data

Kendall's Coefficient of Concordance

Kendall's Coefficient of Concordance is useful in the research because it shows the agreement of data without discrepancies. The Kendall test is one of the many nonparametric measures of correlation in statistics and used for test consistency among the subjects. A coefficient of agreement or concordance is between different sets of rank orderings of the same set of things. The test can be used to interpret quantitative data. In addition, the test indicates the degree of association of ordinal assessments made by multiple appraisers when evaluating the same samples.

Interpreting Kendall's coefficient of concordance

Kendall's coefficient of concordance ranges from 0 to 1. The higher the value of Kendall Coefficient, the stronger the association (Siegel et al, 1988). Generally Kendall's coefficients of 0.9 or above are considered great. A high or significant Kendall's coefficient means that the appraisers are applying essentially the same standard when evaluating the samples. The following results show that the Kendall Coefficient of Concordance is 1.00, which indicates the outstanding high degree of agreement between and within the subjects. The following are the null and alternative hypothesis for the model usability.

1

- **H_0:** The p-value provides the likelihood of obtaining the sample, with its Kendall's coefficient, agreement within subject is due to chance.
- **H_1:** The p-value provides the likelihood of obtaining the sample, with its Kendall's coefficient, agreement within subject is not due to chance.

For a 95% CI, the alpha level is equal to 0.05. Figure 32 shows the p-value for all the subjects is 0.1353. If the p-value is less than or equal to a predetermined level of significance (alpha level), reject the null hypothesis and support the alternative hypothesis. Because the p-values are greater than the alpha level for all subjects, accept the null hypothesis. Therefore, agreement within the subject is due to likelihood of sample. There is a relative agreement among the subjects in the likelihood of falls.

Kendall's Coefficient of Concordance

Appraiser	Coef	Chi - Sq	DF	P
Subject 1	1	4	2	0.1353
Subject 10	1	4	2	0.1353
Subject 11	1	4	2	0.1353
Subject 12	1	4	2	0.1353
Subject 13	1	4	2	0.1353
Subject 14	1	4	2	0.1353
Subject 15	1	4	2	0.1353
Subject 2	1	4	2	0.1353
Subject 3	1	4	2	0.1353
Subject 4	1	4	2	0.1353
Subject 5	1	4	2	0.1353
Subject 6	1	4	2	0.1353
Subject 7	1	4	2	0.1353
Subject 8	1	4	2	0.1353
Subject 9	1	4	2	0.1353

Figure 32: Kendall Coefficient of Concordance

Descriptive Statistics

The statistical variability is data dispersion or spread in a variable or a probability distribution. Common examples of measures of statistical dispersion are the variance, coefficient of variation, and standard deviation. Variability or variance is no significance difference in the data. Figure 33 is the Minitab output for the model validation. Multiple descriptive statistics for a 95% confidence interval and t-test are the following: coefficient of variation (21.36), variance (0.251), mean (2.34), and standard deviation (0.501). The results indicate there is minimal variability with fuzzy AHP modeling. As result, model evaluation and validation indicates that there is no distinction between the current accepted NASA model and developed fuzzy AHP model.

One-Sample T test

Variable	N	Mean	StDev	SE Mean	95% CI
Rating 1	90	2.3444	0.5008	0.0528	(2.2396, 2.4493)

Variable	N	N*	Mean	SE Mean	StDev	Variance	CoefVar	Minimum	Q1
Rating 1	90	0	2.3444	0.0528	0.5008	0.2508	21.36	2.0000	2.0000

Variable	Method	CI for StDev	Variance
Rating 1	Standard	(0.437, 0.587)	(0.191, 0.345)
	Adjusted	(0.444, 0.574)	(0.197, 0.330)

Figure 33: Variability

Model Validation

Model validation is certification of conformance to a standard. There are various ways to validate a model. Model validation was partitioned into three components: reliability, objectivity, and consistency. Reliability is the agreement between and within the subjects. Objectivity is the high performance for complex applications. Consistency is full agreement between the models.

Reliability is the agreement of the data such as the Kendall Coefficient of Concordance for the fifteen test subjects when they applied the fuzzy AHP model to the three scenarios. Objectivity is the statistical analysis such as the variance as a result of the fuzzy AHP model application. There is minimal variability with fuzzy modeling. Consistency is similarity and logical coherence among the Fuzzy AHP model and the NASA Accepted model.

The model was validated by comparing the fuzzy AHP model to NASA accepted model. NASA accepted model for fall hazards is the standard for the research. The comparison involved the comprehensive risk for falls, predicted likelihood rating, and accepted likelihood rating. The fuzzy AHP model is confirmed valid. In addition, there is another way to validate model is to conduct the same statistical analysis on 15 NASA SMES and then compare the results to the 15 test subjects used in this research. Table 28 shows the model validation results for the research.

Table 28: Agreement of Data

Subject	Kendall Coefficient	Inspected	Matched	Percentage (%)	P-value	95% CI
Subject 1	1.00	3	3	100	.1353	(36.84, 100.00)
Subject 2	1.00	3	2	67	.1353	(9.43, 99.16)
Subject 3	1.00	3	3	100	.1353	(36.84, 100.00)
Subject 4	1.00	3	3	100	.1353	(36.84, 100.00)
Subject 5	1.00	3	3	100	.1353	(36.84, 100.00)
Subject 6	1.00	3	3	100	.1353	(36.84, 100.00)
Subject 7	1.00	3	3	100	.1353	(36.84, 100.00)
Subject 8	1.00	3	3	100	.1353	(36.84, 100.00)
Subject 9	1.00	3	3	100	.1353	(36.84, 100.00)
Subject 10	1.00	3	3	100	.1353	(36.84, 100.00)
Subject 11	1.00	3	3	100	.1353	(36.84, 100.00)
Subject 12	1.00	3	3	100	.1353	(36.84, 100.00)
Subject 13	1.00	3	3	100	.1353	(36.84, 100.00)
Subject 14	1.00	3	3	100	.1353	(36.84, 100.00)
Subject 15	1.00	3	3	100	.1353	(36.84, 100.00)
Overall	**1.00**					

The previous results in Table 28 show that the Kendall Coefficient of Concordance is 1.00, which indicates the outstanding high degree of agreement between and within the subjects. Because the p-values are greater than the alpha level for all subjects, accept the null hypothesis. Therefore, agreement within the subject is due to likelihood of sample. As a result, there is a relative agreement among the subjects in the likelihood of falls.

Table 29: Variability

Descriptive Statistic Name	Value
Coefficient of Variation	21.36
Variance	0.251
Mean	2.34
Standard deviation	0.501

Multiple descriptive statistics were calculated for a 95% confidence interval and t-test to measure the variability. Table 29 lists the summary of the statistical results where the variance is 0.251. Therefore, there is minimal disparity and discrepancy with the fuzzy AHP modeling.

Table 30: Model Validation

Scenario	Comprehensive Risk for Falls (Y)	Fuzzy AHP model: Predicted Likelihood Rating	NASA/KSC current Model: Accepted Likelihood Rating
Shuttle Landing Facility (SLF)	0.404	2	2
Launch Complex Payloads (LCP)	0.351	2	3
Vehicle Assembly Building (VAB)	0.451	3	3

The results in Table 30 show there is compatibility between the fuzzy AHP and NASA accepted model. Thus, the fuzzy AHP is in full agreement with the NASA standard.

Results/Discussion Summary

The following section is the synopsis of the results in the research. The section includes the AHP Analysis results, range of existence results, mathematical model results, and research hypothesis results.

AHP Analysis Summary

The following is results summary for the AHP analysis. Table 29 lists the categorical risk factors in the research.

Table 31: Categorical Risk Factors

Ranking	Categorical Risk Factor	Relative Weight
1	Task Related	0.314
2	Human/Personal	0.307
3	Environmental	0.248
4	Organizational	0.130

Table 30 lists the task related risk factors in the research.

Table 32: Task Related Risk Factors

Ranking	Categorical Risk Factor	Relative Weight
1	Task Frequency	0.451
2	Task Proximity	0.381
3	Task Duration	0.168

Table 31 lists the environmental risk factors in the research.

Table 33: Environmental Risk Factors

Ranking	Environmental Risk Factor	Relative Weight
1	Environmental Surface	0.422
2	Environmental Condition	0.298
3	Fall Distance	0.279

Table 32 lists the human/personal risk factors in the research.

Table 34: Human/Personal Risk factors

Ranking	Human/Personal Risk Factor	Relative Weight
1	Worker Interference	0.528
2	Number of Workers	0.263
3	Age	0.209

Table 33 lists the organizational risk factors in the research.

Table 35: Organizational Risk Factors

Ranking	Organizational Risk Factor	Relative Weight
1	Fall Hazard Occurrence	0.356
2	Fall Hazard Protection	0.354
3	Fall Hazard Severity	0.289

Table 34 lists the ranges of existence for each risk factor according to the category.

Table 36: Ranges of Existence Summary

Linguistic Variable	Task Related	Human	Environmental	Organizational
High	0.67-1.00	0.67-1.00	0.67-1.00	0.67-1.00
Medium	0.34-0.66	0.34-0.66	0.34-0.66	0.34-0.66
Low	0-0.33	0-0.33	0-0.33	0-0.33

Mathematical Model Summary

The aggregate risk level is determined by applying the following fuzzy AHP model in any organization or case. After the linguistic risk and the relative significance are generated an aggregated numeric value is obtainable. The fuzzy quantification linear models were used in the research.

Research Hypothesis Results

The following are the research hypotheses for this study. Both null hypotheses were accepted and not rejected.

1

H0: The development of a conceptual model that characterizes risk factors can be useful in reducing the likelihood of falls in NASA Ground Support Operations

H1: The development of a conceptual model that characterizes risk factors cannot be useful in reducing the likelihood of falls in NASA Ground Support Operations

2

H0: A fuzzy analytical hierarchy process model can be developed and validated to predict the likelihood of falls in NASA Ground Support Operations.

H1: A fuzzy analytical hierarchy process model cannot be developed and validated to predict the likelihood of falls in NASA Ground Support Operations.

The research hypotheses were validated by conceptual model, mathematical model, and the statistical analysis results. The research findings indicated that having cognizance of risk factors that lead to falls is beneficial and could prevent the likelihoods of falls in NASA Ground

Support Operations. A fuzzy AHP model was developed and validated in the research. The results from the fuzzy AHP model were compared and confirmed with the NASA accepted scale for the prediction of fall hazards.

CHAPTER V: CONCLUSION

The research is consistent with prior literature; which states there are multiple risk factors that contribute to falls in NASA Ground Support Operations. Falls remain a significant problem in an occupational environment. The current literature reviews numerous risk factors that lead to falls in the workplace. These factors can be categorized broadly as environmental, risk, organizational, human/personal, and task-related. Current measures to reduce falls focus mainly on fall protection procedures, such as the use of covers, guard rails, safety nets, safe monitoring systems, etc. But these procedures are not practical for all organizations. However, future research on preventing falls in an industrial environment such should consider the main effects and the interaction of factors that affect the balance control of the worker. Ultimately, safety should be the number one priority of any organization.

Research Gaps Addressed

There are research needs in field of fall mitigation. The following are the gaps indicated in the literature.

- Knowledge and understanding of contributing risk factors that influence falls in NASA Ground Support Operations ((Hongwei Hsiao, 2008; Petre Simeonova, 2001)

  The previous gap was filled by identified and classifying the recurring and significant risk factors that contribute to falls in a general work environment and an aerospace work environment.

- Aggregate impact and interactive nature of risk factors that influence falls (Gauchard, G., 2001)

The previous gap is a growing process. A step in progression was made by developing a conceptual model based on a theoretical basis from previous studies to understand the comprehensive influence of risk factors on falls.

- Model that quantifies risk factors that influence falls in an aerospace environment and specifically NASA Ground Support Operations (Dagdeviren, M., 2008)

  The gap was filled by developing and validating a fuzzy analytical hierarchy process model to predict the likelihood of falls in an aerospace environment (NASA ground support operations) and assist in the task and work design.

Research Questions Addressed

There are research questions that were addressed in the research. The following are the research questions from this study.

- What are the contributing risk factors that influence falls in the workplace?

  The multiple risk factors that lead to falls can be generally categorized in the areas of task related, human/personal, environmental, and organizational.

- How do we quantify contributing risk factors that influence falls in NASA ground support operations? The rationale in the research was to develop and validate a model that represents linguistic variables to quantify and rank risk factors that contribute to falls. The variables were quantified using fuzzy set theory. As a result, the model will evaluate qualitative and quantitative data.

- What is the aggregate risk value of these risk factors on falls?

  The total effect or the aggregate risk value of the risk factors that lead to falls was the comprehensive risk in the fuzzy AHP model.

- How we will predict the likelihood of falls?

  The likelihood of falls was predicted by using the aggregate risk value and likelihood rating for the falls in an aerospace environment such as NASA Ground Support Operations.

Research Limitations

Fall is preventable by multidimensional assessment and targeted intervention. The limitations in the study are not considering the interaction of risk factors in the model that contribute to falls or the global weights of risk factors. The model local weights for the risk factors were used in the research. However, the global weights the model were analyzed. The global weights indicate how the risk factors compare against each other in the whole model.

Model Importance and Applications

It is imperative to understand the cause of the problem in order to prevent the effect. The cause in this model was the risk factor and fall was the effect. A model is not the real world but merely a human development to assist in understanding real world systems. The key features in the model were: assumptions simplified, boundary conditions identified, and applicability of the model understood. The conceptual model is a qualitative model that assists emphasize important connections in real world systems and processes. This is first step in the development of more complex models. The Fuzzy AHP model is a quantitative model that involves solving relevant equations of a system or characterizing a system. This fuzzy AHP model is innovative method for evaluating a problem and specifically falls. This is a step towards fall mitigation and prevention and can be applied to any work environment with regards to falls.

Research Contribution

The fuzzy AHP model was developed and validated by quantifying the risk factors that lead to falls in NASA Ground Support Operations. The multifaceted model is ergonomically and mathematically sound; which can be applied in any work environment. The purpose of the research was to establish another technique to predict and prevent falls in NASA Ground Support Operations. The research will be a great contribution to the prevention of falls and to the NASA Safety program. The model will aid in risk assessment, assist in task design, and fall prevention. It is recommended to use the model in NASA Fall Protection training and Risk Management. The fuzzy AHP model is addition to the body of knowledge in field. For instance, there are hazard analysis, failure mode analysis, physiological assessments, and risk analysis on falls in the literature. However, the fuzzy AHP model can be applied to a Human Performance Assessment, Biomechanics, and Athletic Training. For example, to assess the risks in athletic training, there is need for understanding, identifying, and quantifying the risk factors that may lead to a hazard during that period. Therefore, the fatalities and personal injuries will be prevented. The contribution is the utilization of the valid fuzzy AHP model to predict the likelihood of falls. The fuzzy AHP model is numerical, quantifiable, and it has granularity. Granularity is distribution of parts in a comprehensive approach that has been uniformly exposed and processed. The fuzzy AHP model is a numerical model. The model also gives insight of the risk associated with the fall. The fuzzy AHP model is intuitive because it provides understanding based on identification of relationships and behaviors. For example, the aggregate risk value of 0.69 in the model indicates a high linguistic variable, high risk where falls are highly likely to occur, and a likelihood rating of 4. Controls have significant uncertainties. This is a tool that can be applied to any organization. The benefit of this research is the application of the model for a safety engineering management class. Lastly, this research effort provides, tools, systems, methods, and techniques to measure and assess falls in an aerospace environment such as the NASA Expert Choice voting system, creation of priority vectors, taxonomy development, fall hazard assessment, and the fall risk factors survey. The research produced a reliable fuzzy AHP model that is prepared to be benchmarked by other organizations.

CHAPTER VI: RECOMMENDATIONS AND FUTURE RESEARCH

After completing the research and reviewing literature on falls, here are the following recommendations:

Management

- Establish and implement procedures that significantly reduce the number injuries and deaths due to falls.
- Conduct regular inspections of working and walking surfaces to identify hazards that could lead to slips, trips, and falls followed by immediate corrective action to avoid recurring incidents as indicated in the schematic diagram for the fuzzy AHP model.
- Implement extensive fall protection training or risk management course
- Establish a NASA online course in Satern (Training website) for fall prevention.
- Hold all employees especially high risk areas for falls accountable to take the previous training and course annually.

Employee

- Every employee in NASA Ground Supports Operations and specifically in those areas for the fall hazard concerns should to take the training/course annually.

It is recommended to use the model in this study to predict the likelihood of falls in an aerospace environment and provide recommendations for fall abatement. The table displays the objective or goal and the method of corrective action. For example, objective C is to reduce energy levels. One of the major future goals is to Go green and optimize energy performance. It was observed in the NASA Ground Support Operations, that majority of the work areas had a fall distance of over 100 ft.; which is considered high. This is a fall hazard and may lead to falls.

The following tables are recommended protection methods that can prevent falls and injuries.

As result, using safety measures and protection methods can ultimately save your life.

Table 37: Protection Methods
(Bauer, 2006)

OBJECTIVE	METHOD
A. Prevent falls of people	1. Remove tripping and slipping hazards
	2. Protect edges and openings
	a. Provide barriers (guardrails, covers, cage, etc.
	b. Proved visual and auditory warnings
	3. Provide grab bars, handrails, and handholds
	4. Provide fall-limiting equipment
B. Prevent objects from falling on people	1. Housekeeping (remove objects that could fall)
	2. Barrier (ice boards, guardrail, infill, covers, etc.
	3. Proper stacking and placement
	4. Fall zone
	5. Overheard protection
C. Reduce energy levels	1. Reduce fall distances
	2. Reduce weight of falling objects
	3. Control fall deceleration
D. Reduce injuries from falls and impact	1. Increase area of impact force
	2. Increase energy absorption distance

Future Research

The following section is the proposed future research after completing this dissertation. Some of the proposed future research includes compare and contrasting other fall prediction models to the Fuzzy AHP model in this study, developing a cost and benefit analysis for fall simulated training module vs. fall protection training course. Another future research activity is to develop a statistical model using stepwise regression on the most current BLS Data (e.g. BLS 2007-2008) and observed if there are any other trends in the data. Once of the limitations of this research was evaluating the interaction of multiple risk factors that contribute to falls. In addition, future research includes increasing the number of risk factors in the model to show the interactive nature of other risk factors that contribute to falls. However, it is essential to recognize and comprehend the interactive nature of risk factors that contribute to in order to mitigate falls.

APPENDIX A: NASA IRB APPROVAL

National Aeronautics and
Space Administration

John F. Kennedy Space Center
Kennedy Space Center, FL 32899

Reply to Attn of:

April 30, 2009

TA-B1A

TO: TA-B1C/Joylene Ware

FROM: TA-B1A/Chair, KSC Human Research Institutional Review Board

SUBJECT: Approval of Protocol

As of April 30, 2009, the KSC Human Research Institutional Review Board (IRB) has reviewed (via expedited review) and approved your study entitled "A Systematic Analysis to Identify, Mitigate, Quantify, and Manage Risk Factors Contributing to Falls in NASA Ground Support Operations," which was submitted to the IRB in April 2009. The Board would like to make you aware that you are bound by your protocol as prescribed by the approved proposal and that any changes to it will require notification to the IRB and may or may not require another review. Also, as the Board reviews all KSC related ongoing research involving human subjects on an annual basis, you may be asked to provide an update or overview of your research if it is still being conducted at that time. Please contact me if you have any additional questions.

David A. Tipton, MD
Chief, Aerospace Medicine and Occupational Health Branch

CC:
TA-B1A/Philip J. Scarpa, MD

APPENDIX B: UCF IRB APPROVAL

University of Central Florida

University of Central Florida Institutional Review Board
Office of Research & Commercialization
12201 Research Parkway, Suite 501
Orlando, Florida 32826-3246
Telephone: 407-823-2901, 407-882-2901 or 407-882-2276
www.research.ucf.edu/compliance/irb.html

Not Human Subjects Research

From : **UCF Institutional Review Board**
FWA00000351, Exp. 10/8/11, IRB00001138

To : **Joylene Ware**

Date : **May 01, 2009**

IRB Number: **SBE-09-06252**

Study Title: **A systematic analysis to identify, mitigate, evaluate, and manage risk factors contributing to falls in NASA Ground Support Operations**

Dear Researcher:

After reviewing the materials that you have submitted, the UCF Institutional Review Board has determined that your project does not fit the definition of human subjects research because you will be obtaining expert opinions from the study participants and no gathering information about living individuals.

Therefore, IRB review is not needed.

Thank you for your time in resolving this issue. Please continue to submit applications that involve human subject activities that could potentially involve human subjects as research participants.

On behalf of Tracy Dietz, Ph.D., UCF IRB Chair, this letter is signed by:

Signature applied by Joanne Muratori on 05/01/2009 02:36:00 PM EDT

Joanne Muratori

IRB Coordinator

APPENDIX C: NASA SUBJECT CONSENT FORM

NASA Subject Consent Form

I, the undersigned, do voluntarily give my informed consent for my participation as a test subject in the study: ____________________.

I understand or acknowledge that:

The research procedures were explained to me prior to the execution of this form. I was afforded an opportunity to ask questions, and all questions asked were answered to my satisfaction. A layman's description was provided to me along with this form. I have been medically qualified to participate in the investigation. I can refuse to participate in the tests at any stage of their performance, and my refusal will be honored as promptly as possible. My withdrawal or refusal to participate in this investigation will not result in any penalty or loss of benefits to which I am otherwise entitled. The investigators may discontinue my participation in this study if necessary for safety or other reasons. In the event of an injury requiring immediate treatment during the course of this study, Kennedy Space Center and its contractors will provide or arrange for necessary initial treatment.

If I have further questions I will discuss them with the investigators or contact the Principal Investigator, Joylene Ware, at (321) 861-1196. In addition, if I have concerns about this study or my participation as a subject, I can also contact the KSC Institutional Review Board (IRB) directly through David A. Tipton, MD, at 321-867-6385.

I have read and fully understand the attached study description entitled "__________________________" and will receive a copy of that document and this signed document.

Signature:		Signature:	
______________________		______________________	
Test Subject	Date	Witness	Date

I, the undersigned, the Principal Investigator of the investigation designated above, certify that:

I have thoroughly and accurately described the research investigation and procedures to the test subject and have provided him/her with a layman's description of the same and a copy of this consent form.

This study entails moderate risk to the test subject. All equipment to be used has been inspected and verified to be ready for safe and proper operation.

The test subject is medically qualified to participate.

Except as provided for by Agency-approved routine uses under the Privacy Act, the confidentiality of any data obtained as a result of the test subject's participation in this study shall be maintained so that no data may be linked to him/her as an individual.

The test protocol has not been changed from that approved by the KSC Human Research IRB.

Signature:

____

Principal Investigator Date

APPENDIX D: UCF INFORMED CONSENT

Joylene Ware, PhD Candidate

University of Central Florida

Informed Consent

Researchers at the University of Central Florida (UCF) study many topics. To do this we need the help of people who agree to take part in a research study. You are being invited to take part in a research study which will include about six subject matter experts. You can ask questions about the research. You can read this form and agree to take part right now, or take the form home with you to study before you decide. You will be told if any new information is learned which may affect your willingness to continue taking part in this study. You have been asked to take part in this research study because you are expert in the field of Human Factors/Ergonomics, Safety, and Fall Prevention. You must be 18 years of age or older to be included in the research study and sign this form.

The person doing this research is Joylene Ware, a PhD candidate in the Industrial Engineering Department at the University of Central Florida. Because the researcher is a PhD student she is being guided by Dr. Pamela McCauley-Bush, a UCF faculty supervisor in the department of Industrial Engineering.

Study title: A systematic analysis to identify, mitigates, quantify, and manage risk factors contributing to falls in NASA Ground Support Operations

Purpose of the research study: The purpose of the research is to develop a model that represents linguistic variables to quantify and rank risk factors that contribute to falls. The variables are quantified using fuzzy set theory. As a result, the model will evaluate the qualitative and quantitative data.

What you will be asked to do in the study: After reading the consent form, you will be asked to participate in a live survey (voting system) to vote on risk factors that contribute to falls. Please select the answers that best represent your preference and priorities based on your expertise and experience. The purpose of this study is to participate as a Subject Matter Experts (SMEs) to decide on factors that contribute to falls. You will be given several alternatives or areas where falls are likely to occur. Weighted model designed to enhance the risk assessment of falls.

Voluntary participation: You have been selected to participate in this study as one of six participants with expertise in the fall prediction and prevention research. You should take part in this study only because you want to. There is no penalty for not taking part, and you will not lose any benefits. You have the right to stop at any time. Just tell the researcher or a member of the research team that you want to stop. You will be told if any new information is learned which may affect your willingness to continue taking part in this study.

Location: Study will be conducted by email and at NASA/Kennedy Space Center.

AHP Model (Voting and Validation)-NASA/KSC
Fuzzy Model Validation- NASA/KSC

Time required: The entire study will take approximately 1.5 hours to complete.

Risks: There are no expected risks for taking part in this study. You need to answer every question in the voting system.

Benefits:
As a research participant you will not benefit directly from this research, but learn more about how research is conducted.

Compensation or payment:
There is no compensation or other payment to you for taking part in this study.

Confidentiality: Your identity will be kept confidential. The researcher will make every effort to prevent anyone who is not on the research team from knowing that you gave us information, or what that information is. For example, your name will be kept separate from the information you give, and these two things will be stored in different places.

Your information will be assigned a code number. The list connecting your name to this number will be kept in a locked file cabinet. When the study is done and the data have been analyzed, the list will be destroyed. Your information will be combined with information from other people who took part in this study. When the researcher writes about this study to share what was learned with other researchers, He will write about this combined information. Your name will not be used in any report, so people will not know how you answered or what you did.

There are times when the researcher may have to show your information to other people. For example, the researcher may have to show your identity to people who check to be sure the research was done right. These may be people from the University of Central Florida or state, federal or local agencies.

Study contact for questions about the study or to report a problem:

Joylene Ware, PhD Candidate Industrial Engineering & Mgmt. Systems , College of Engineering and Computer Science at (321) 861-1196 or Joylene.L.Ware@nasa.gov or Dr. Pamela McCauley-Bush, Faculty Supervisor, Department of Industrial Engineering & Mgmt. Systems at (407) 823-6092, by email at mbush@mail.ucf.edu.

IRB contact about your rights in the study or to report a complaint: Research at the University of Central Florida involving human participants is carried out under the oversight of the Institutional Review Board (UCF IRB). For information about the rights of people who take part in research, please contact: Institutional Review Board, University of Central Florida, Office of Research & Commercialization, 12201 Research Parkway, Suite 501, Orlando, FL 32826-3246 or by telephone at (407) 823-2901.

If you are harmed because you take part in this study: If you believe you have been injured during participation in this research project, you may file a claim with UCF Environmental Health & Safety, Risk and Insurance Office, P.O. Box 163500, Orlando, FL 32816-3500 (407) 823-6300. The University of Central Florida is an agency of the State of Florida for purposes of sovereign immunity and the university's and the state's liability for personal injury or property damage is extremely limited under Florida law. Accordingly, the university's and the state's ability to compensate you for any personal injury or property damage suffered during this research project is very limited.

How to return this consent form to the researcher: Please write down your name and check all boxes that apply and return this consent form by email.

□ I have read the procedure described above

□ I voluntarily agree to take part in the procedure

□ I am at least 18 years of age or older

____________________________ ____________________________ __________

Signature of participant Printed name of participant Date

______________________________________ _____________

Principal Investigator Date

APPENDIX E: SURVEY/VOTING INSTRUMENT

Joylene Ware Dissertation Research Survey
Exit this survey

1. Default Section

1. Which Categorical Risk Factor (Factor A or B) is more important that contribute to falls? What is the intensity of the importance? (i.e. 1=equal importance, 2=moderate importance, 3=moderate importance, 5=strong importance, 7=very strong importance, 9=extreme importance)

	More Important	Intensity
Human/Personal or Environmental	Which Categorical Risk Factor (Factor A or B) is more important that contribute to falls? What is the intensity of the importance? (i.e. 1=equal importance, 2=moderate importance, 3=moderate importance, 5=strong importance, 7=very strong importance, 9=extreme importance) Human/Personal or Environmental More Important	Intensity
Human/Personal or Organizational	Human/Personal or Organizational More Important	Intensity
Human/Personal or Task Related	Human/Personal or Task Related More Important	Intensity
Environmental or Organizational	Environmental or Organizational More Important	Intensity
Environmental or Task Related	Environmental or Task Related More Important	Intensity
Organizational or Task Related	Organizational or Task Related More Important	Intensity

2. Which Task Related Risk Factor (Factor A or B) is more important that contribute to falls? What is the intensity of the importance? (i.e. 1=equal importance, 2=moderate importance, 3=moderate importance, 5=strong importance, 7=very strong importance, 9=extreme importance)

	More Important	Intensity
Task Frequency or Task Duration	Which Task Related Risk Factor (Factor A or B) is more important that contribute to falls? What is the intensity of the importance? (i.e. 1=equal importance, 2=moderate importance, 3=moderate importance, 5=strong importance, 7=very strong importance, 9=extreme importance) Task Frequency or Task Duration More Important	Intensity
Task Frequency or Task Proximity	Task Frequency or Task Proximity More Important	Intensity
Task Duration or Task Proximity	Task Duration or Task Proximity More Important	Intensity

3. Which Human/Personal Factor Risk Factor (Factor A or B) is more important that contribute to falls? What is the intensity of the importance? (i.e. 1=equal importance, 2=moderate importance, 3=moderate importance, 5=strong importance, 7=very strong importance, 9=extreme importance)

	More Important	Intensity
Age or Number of Workers	Which Human/Personal Factor Risk Factor (Factor A or B) is more important that contribute to falls? What is the intensity of the importance? (i.e. 1=equal importance, 2=moderate importance, 3=moderate importance,	Intensity

	More Important	Intensity
	5=strong importance, 7=very strong importance, 9=extreme importance) Age or Number of Workers More Important	
Age or Work Interference	Age or Work Interference More Important	Intensity
Number of Workers or Work Interference	Number of Workers or Work Interference More Important	Intensity

4. Which Environmental Risk Factor (Factor A or B) is more important that contribute to falls? What is the intensity of the importance? (i.e. 1=equal importance, 2=moderate importance, 3=moderate importance, 5=strong importance, 7=very strong importance, 9=extreme importance)

	More Important	Intensity
Fall Distance or Environmental Condition	Which Environmental Risk Factor (Factor A or B) is more important that contribute to falls? What is the intensity of the importance? (i.e. 1=equal importance, 2=moderate importance, 3=moderate importance, 5=strong importance, 7=very strong importance, 9=extreme importance) Fall Distance or Environmental Condition More Important	Intensity
Fall Distance or Environmental Surface	Fall Distance or Environmental Surface More Important	Intensity
Environmental Condition or Environmental Surface	Environmental Condition or Environmental Surface More Important	Intensity

5. Which Organizational Risk Factor (Factor A or B) is more important that contribute to falls? What is the intensity of the importance? (i.e. 1=equal importance, 2=moderate importance, 3=moderate importance, 5=strong importance, 7=very strong importance, 9=extreme importance)

	More Important	Intensity
Fall Hazard Severity or Fall Hazard Protection	Which Organizational Risk Factor (Factor A or B) is more important that contribute to falls? What is the intensity of the importance? (i.e. 1=equal importance, 2=moderate importance, 3=moderate importance, 5=strong importance, 7=very strong importance, 9=extreme importance) Fall Hazard Severity or Fall Hazard Protection More Important	Intensity
Fall Hazard Severity or Fall Hazard Occurrence	Fall Hazard Severity or Fall Hazard Occurrence More Important	Intensity
Fall Hazard Protection or Fall Hazard Occurrence	Fall Hazard Protection or Fall Hazard Occurrence More Important	Intensity

APPENDIX F: NASA SAFETY INDEX

.1 Frequency Index (F)

This index quantifies how frequently worker(s) would be exposed to the particular fall hazard:

Frequency Index (F):		
Term	F	Description
Never	0.1	Never been accessed.
Occasionally	0.9	Worker(s) at the location once every 2 to 10 years
Annually	1.0	Worker(s) at the location or task is done once or twice per year.
Monthly	1.1	Worker(s) at the location 3-12 /yr. Monthly maintenance, "as needed" work
Weekly	1.2	Worker(s) at the location 13-52 /yr. Weekly maintenance, "as needed" work
Daily	1.3	Worker(s) at the location on a daily basis or once / shift.
Shift	1.4	Worker(s) at the location more than once per shift or several times per day.

.2 Occurrence Index (O)

This index quantifies how often the particular hazard is found at the facility being studied:

Occurrence Index (O):		
Term	O	Description
Unique	1.0	Hazard occurs at only one location.
Rare	1.1	Hazard occurs at two locations.
Common	1.2	Hazard occurs at 3 – 10 locations.
Very Common	1.3	Hazard occurs at more than 11 - 50 locations.
Recurring	1.4	Hazard occurs at more than 50 locations.

.3 Proximity Index (X)

This index reflects how close workers normally get to the hazard, as follows:

Proximity Index (X):		
Term	X	Description
Near	1.0	Worker(s) from 6 to 10 feet (1.8 to 3.0 m) an improperly guarded fall hazard
Close	1.1	Worker(s) from 3 to 6 feet (0.9 to 1.8 m) of an improperly guarded fall hazard
Very Close	1.2	Worker(s) from 1 to 3 feet (0.3 to 0.9 m) of an improperly guarded fall hazard
Immediate	1.3	Worker(s) Directly exposed to an unguarded fall hazard or working from a ladder

7 Environment Index (E)

This index measures whether work is being performed in an inside or outside work environment:

Environment Index (E):		
Term	E	Description
Ideal	0.9	Indoor, climate controlled, clean, dry. Worker(s) have adequate environmental PPE
Good	1.0	Some housekeeping, slipping or tripping hazards. Adequate environmental PPE
Variable	1.1	Uncontrolled variables or weather, may compromise worker comfort & stability
Extreme	1.2	Continuously slippery, steep, difficult or uncomfortable

Protection Index (T)

The protection index reduces the Risk Rating number according to the quality of existing fall protection.

Protection Index (T):		
Term	T	Description
Excellent	0.1	Adequate guardrails or fall restraint. No fall Possible, no visible concerns.
Good	0.3	Adequate fall arrest. Acceptable equipment, MAF, clearance, rescue plan, etc.
Poor	0.75	Protection needs improvement. Not life threatening. Swing fall, compatibility, etc.
None	1.0	No fall protection or system is life threatening.

Hazards that have fall protection systems that prevent falls (guardrails / barricades, fall restraint) will be reduced significantly as the system has abated the hazard. Hazards that use fall arrest systems are not reduced by the same amount as fall arrest systems have an inherent level of risk associated with them, even if the system is perfect. Hazards whose system needs improvement are slightly reduced, providing that the issue is not life-threatening. Hazards that have no fall protection or whose fall protection is inadequate or non-existent are not reduced.

Severity Index (S)

The Severity Index is a relative measure of the severity, cost or consequences of an accident.

The following table lists the 5 classifications of Severity used in this rating system and assigns a relationship between the height of fall and the Severity Index. While there is always a risk of a fatality or serious injury in any fall, regardless of height, the index defines the likely severity based on one easily measured factor, height. Where other factors such as unguarded machinery or hazardous materials in the landing area need to be accounted for, the assessor would select the appropriate index based on the description rather than the height.

Severity Index (S):		
Term	**S**	**Description**
Minor	1	0 to 6 ft: May cause minor injury requiring first aid or medical attention
Moderate	2	>6 to 10 ft: Likely to cause moderate injury requiring first aid or medical attention
Severe	3	>10 to 16 ft: Likely to cause severe injury or result in temporary disability
Critical	4	>16 to 30 ft: Likely to cause critical injury, permanent or temporary disability, or death
Extreme	5	>30 ft: extremely likely to cause permanent disability, or death

!.4 Duration Index (D)

This index quantifies how long workers spend at the location each time they are exposed to the hazard. The determination of man-hours must consider both the number of workers and the time spent at the hazard:

Duration Index (D):		
Term	D	Description
Brief	1.0	Worker(s) at the location for less than 6 man-minutes (0.1 man-hour) per occurrence
Short	1.1	Worker(s) at the location from 0.1 to 1.0 man-hours per occurrence, on average
Medium	1.2	Worker(s) at the location from 1 to 8 man-hours per occurrence, on average
Long	1.3	Worker(s) at the location from 8 to 40 man-hours per occurrence, on average
Extensive	1.4	Worker(s) at the location continuously or more than 40 hours per project

!.5 Interference Index (I)

This index examines the effect multiple workers at the same location may have on each other and whether they may interfere with each other's movements or create trip or other hazards that are not seen by the other workers around them:

Interference Index (I):		
Term	I	Description
Independent	1.0	All workers are separated or there is only one worker
Dependent	1.1	Multiple workers on the same work platform
Multiple	1.2	Multiple workers in close proximity

!.6 Security Index (C)

This index measures the security of the platform or structure that the worker is using to support his / her weight.

Security Index (C):		
Term	C	Description
Excellent	0.9	Solid, flat, secure & stable, designed and engineered walking/working surface.
Fair	1.0	Not designed for walk & work or outdoor / worker can still navigate relatively easily
Poor	1.1	Difficult structure, I-beams, bracing, structural climbing, pipe racks, trusses etc.
Vertical	1.2	Vertical ladder, rebar, bosun chair, hoist, rope access, temp. staging, or similar

LIST OF REFERENCES

Agnew, J. and Saruda, A. J. 1993, Age and fatal work-related falls, *Human Factors*, Vol. 35, pgs. 731 -736.

Ahn, N., Jae, M., Yu, J. (2004). A Quantitative Assessment of Organizational Factors Affecting Safety Using System Dynamics Model, *Journal of the Korean Nuclear Society*, Vol. 36, pgs. 64-72.

Andres, R. O. and Chaffin, D. B. (1985). Ergonomic analysis of slip-resistance measurement devices, *Ergonomics*, Vol. 28, pgs. 1065 - 1079.

Andres, R. O., O'Connor, D. and Eng, T. (1992). A practical synthesis of biomechanical results to prevent slips and falls in the workplace, in S. Kumar (ed.), *Advances in Industrial Ergonomics and Safety IV* (London: Taylor and Francis), pgs. 1001 - 1006.

Bentley, T. A. and Haslam, R. A.(1998), Slip, trip and fall accidents occuring during the delivery of mail, *Ergonomics*, Vol. 41, pgs. 1859 -1872.

Bentley, T. (2009). The role of latent and active failures in workplace slipts, trips, and falls: An information processing approach, *Applied Ergonomics*, Vol. 40, pgs.175-180.

Bobick, T.G. (2004). Falls through roof and floor openings and surfaces, including skylights, *Journal of Construction Engineering and Management-ASCE*, Vol. 130, pgs. 895-907.

Bonisson, P. P. (1980). *A fuzzy sets based linguistic approach: theory and applications* Proceedings of the 1980 Winter Simulation Conference

Boucher, T.O., and MacStravic, E.L. (1991). Multiattribute Evaluation Within a Present Value Framework and Its Relation to the Analytic Hierarchy Process. *The Eng. Economist*, Vol.3, pgs. 1-32.

Buck, P. C. and Coleman, V. P., (1985). Slipping, tripping and falling accidents at work: a national picture, *Ergonomics*, Vol. 28, pgs. 949 - 958.

Bureau of Labor Statistics, 2007, *Workplace Injuries and Illnesses in 2005-2007 Case and Demographic Characteristics for Workplace Injuries and Illnesses Involving Days Away From Work*, Supplemental Tables, US Department of Labor, BLS, Washington, DC.

Chang, C., et al. (2005). Accident patterns and prevention measures for fatal occupational falls in the construction industry, *Applied Ergonomics*, Vol. 36, pgs. 391-400.

Chang, W.R. and Matz, S. (2001). The Slip Resistance of Common Footwear Materials Measured With Two Slipmeters, *Applied Ergonomics*, Vol. 32, pgs.549-558.

Chiou , S., Bhattacharya, A. and Succop, P. A. (1996). Effect of worker' s shoe wear on objective and subjective assessment of slipperiness, *American Industrial Hygiene Association Journal*, Vol. 57, pgs. 825 - 831.

Clark, M., Jackson, P. and Cohen, H. H. (1996). What you don' t see can hurt you: understanding the role of depth perception in slip, trip, and fall incidents, *Ergonomics in Design*, Vol. 4, pgs. 16 - 21.

Cohen, H. H. and Compton, D. A. J. (1982). Fall accident patterns, *Professional Safety*, Vol. 27, pgs. 16 - 22.

Cohen, H. H. and Compton, D. M. J. (1982). Fall accident patterns: characterization of most frequent work surface-related injuries. *Professional Safety*, Vol. 27, pgs. 16 -35.

Culver, C. and Connolly, C. (1994). Prevent fatal falls in construction, *Safety and Health*, Vol. 150, pgs. 72 - 75.

Dagdeviren, M. and Yuksel, I., (2008). Developing a fuzzy analytical hierarchy process (AHP) model for behavior-based safety management, *Information Sciences*, Vol. 178, pgs. 1717-1733.

Davis, P. R. (1983). Human factors contributing to slips, trips and falls, *Ergonomics*, Vol. 26**,** pgs. 51-59.

Fothergill, J., O'Driscoll, D., and Hashemi, K., (1995). The role of environmental factors in causing injury through falls in public places, *Ergonomics*, Vol. 38, pgs. 220 - 223.

Gauchard, G. and Strandberg, L. (1983). On accident analysis and slip-resistance measurement, *Ergonomics*, 26, 11 - 32.

Gravseth et al., (2006). Risk factors for accidental injuries in the construction industry, *Tidsskr Nor Laegeforen*, Vol. 126, pgs. 453-456.

Gronqvist, R., (1995). "Mechanisms of Friction and Assessment of Slip Resistance of New and Used Footwear Soles On Contaminated Floors," *Ergonomics*, Vol. 38, pgs. 224-241.

Grönqvist, R., Hirvonen, M., Rajamäki, E., and Matz S., (2003).The Validity and Reliability of a Portable Slipmeter for Determining Floor Slipperiness During Simulated Heel Strike, *Accident Analysis and Prevention*, Vol. 35, pgs. 211-225.

Grönqvist, R., Matz, S., and Hirvonen, M., (2003).Assessment of Shoe-Floor Slipperiness with Respect to Contact-Time-Related Variation in Friction During Heel Strike, *Occupational Ergonomics*, Vol. 3, pgs. 197-208.

Gronqvist, R. and Roine, J. (1993). Serious occupational accidents caused by slipping, in R.Nielson and R. Jorgensen (eds), *Advances in Industrial Ergonomics and Safety V*(London: Taylor & Francis), pgs. 515 - 519.

Gronqvist, R., Roine, J., Jarvinen, E. and Korhonen, E. (1989). An apparatus and a method for determining the slip resistance of shoes and floors by simulation of human foot motions, *Ergonomics*, Vol. 32, pgs. 979 -995.

Hallowell, D., Analytical Hierarchy Process (AHP)-Getting Oriented, iSix Sigma LLC. http://software.issixsigma.com/library/content/co50105a.asp

Hanson, J.P., Redfern, M.S., and Mazumdar, M., M. (1999). Predicting slips and falls considering required and available friction, *Ergonomics*, Vol. 42**,** pgs. 1619-1633.

Hignet, S. and Masud, T. (2006). A review of environmental hazards associated with in patient falls, *Ergonomics*, Vol. 49, pgs. 605-616.

Hsia, T. et al. (2008). Measuring the readability performance (RP) of aircraft maintenance technical orders by fuzzy MCDM method and RP index, *Quality and Quantity*, Vol. 42, pgs. 795-807.

Hsiao, H. and Simeonov, P. (2001). Preventing falls from roofs: a critical review, *Ergonomics*, Vol. v4444**,** pgs. 537 -561.

Huang, X. et al, (2003). Analysis of construction worker fall accidents, *Journal of Construction Engineering and Management-ASCE,* Vol. 129, pgs. 262-271.

Bhattacharya and J. D. McGlothlin (eds), *Occupational Ergonomics Ð Theory and Applications* (New York: Marcel Dekker), pgs. 545 - 568.

Janicak, C. A. (1998). Fall-related deaths in the construction industry, *Journal of Safety Research*, Vol. 29, pgs. 35 -42.

Kemmlert, K. and Lundholm, L.(1998). Slips, trips and falls in different work groups with reference to age, *Safety Science*, Vol. 28, pgs. 59-75.

Kerzman et al. (2004). Characteristics of falls in hospitalized patients, Journal of Advanced Nursing, Vol. 47, pgs. 223-229.

Kisner, S. and Fosbroke, D. E. (1994). Injury hazards in the construction industry, *Journal of Occupational Medicine*, Vol. 36, pgs. 137- 143.

Klir, G. J., St. Clair, U. H. and Yuan, B. (1997). Fuzzy Set Theory: Foundations and Applications Prentice Hall Upper Saddle River, NJ

Klir, G. J. and Yaun B. (1995) Fuzzy Sets and Fuzzy Logic: Theory and Applications Prentice Hall

Leamon, T.B. and Murphy, P.L., (1995). "Occupational Slips and Falls: More Than a Trivial Problem," *Ergonomics*, Vol.38, No. 3, pp. 487-498.

Leclercq, S. (1999)., Prevention of same level falls: a more global appreciation of this type of accident, *Journal of Safety Research*, Vol. 30**,** pgs.103 -112.

Leclerq, S. (1999). The prevention of slipping accidents: a review and discussion of work related to the methodology of measuring slip resistance, *Safety Science*, Vol. 31, pgs. 95 - 125.

Leclercq, S., Tisserand, M. and Saulnier,H. (1995). Tribological concepts involved in slipping accident analysis, *Ergonomics*, Vol. 38, pgs.197 - 208.

Leclercq, S., Tisserand, M. and Saulnier, H., (1995). Assessment of slipping resistance of footwear and floor surfaces. In¯uence of manufacture and utilization of the products, *Ergonomics*, Vol. 38, pgs**.** 209 - 219.

Leveson, N. et al, "Effectively Addressing NASA's Organizational and Safety Culture: Insights from Systems Safety and Engineering Systems," Engineering Systems Division Symposium, March 29-31, 2004, MIT, Cambridge, MA.

Lipscomb, H. et al (2006). Injuries form slips and trips in construction, *Applied Ergonomics,* Vol. 37, pgs. 267-274.

Lord, S., Menz, H., and Tiedemann, A., (2003). A physiological Profile Approach to Fall Risk Assessment and Prevention, Physical Therapy, Vol. 83, pgs. 27-252

Lundstrom, T, et al., (2002). Organizational and environmental factors that affect worker health and safety and patient outcomes, *American Journal of Infection Control*, Vol. 30, pgs. 93-106.

Manning, D.P. (1983). Deaths and injuries caused by slipping, tripping and falling, *Ergonomics*, Vol. 26**,** pgs**.** 3 - 9.

Manning, D. P., Ayers, I., Jones,C., Bruce, E, M. and Cohen,K. (1988). The incidence of underfoot accidents during 1985 in a working population of 10,000 Merseyside people, *Journal of Occupational Accidents*, Vol. 10, pgs.121 -130.

Marletta, W. 1991, Trip, slip and fall prevention, in D. J. Hansen (ed.), *The Work Environment, vol.1: Occupational Health Fundamentals* (Chelsea, MN: Lewis).

Masud et al. (2001). Epidemiology of falls, *Age and Ageing*, Vol. 30-S4, pgs. 3-7.

Maynard, Wayne S. Tribology: Preventing Slips and Falls in the workplace, Occupational Health and Safety: Sep 2002: 71, 9, AB/Inform Global pg. 134

McCauley-Bell, P. and Badiru, A. (1996). *Fuzzy Modeling and Analytic Hierarch Processing—Means to Quantify Risk Levels Associated with Occupational Injuries—Part I: The Development of a Fuzzy Linguistic Risk Levels.* IEEE Transactions on Fuzzy Systems, Vol 4, No 2

McCauley-Bell, P. and Badiru, A. (1996). *Fuzzy Modeling and Analytic Hierarch Processing—Means to Quantify Risk Levels Associated with Occupational Injuries—Part II: The Development of a Fuzzy Rule-Based Model for the Prediction of Injury.* IEEE Transactions on Fuzzy Systems, Vol 4, No 2

McCauley-Bell, P., Wang, H., and Crumpton, L. (1997). A Fuzzy Linear Regression Model to Measure the Impact of Risk Factors on Cumulative Trauma Disorder in Occupational Tasks. IEEE Transaction Systems, Mang, Cyberbetics, pgs. 1-14.

Merrick et al, (2005). Understanding organizational safety using value-focused thinking, *Risk Analysis,* Vol. 25, pgs. 1029-1041

Murphy, P.L. and Courtney, T.K., (2000). Low Back Pain Disability: Relative Costs by Antecedent and Industry Group, *American Journal of Industrial Medicine*, Vol. 37, pgs. 558-571.

Nagata, H. (1991). Occupational accidents while walking on stairways, *Safety Science*, Vol.14**,** Pgs. 199- 211.

Navon, R. and Kolton, O. ((2007). Algorithms for automated monitoring and control of fall hazards, *Journal of Computing in Civil Engineering*, Vol. 21, pgs. 21-28.

Nicholson, A. S. and David, G. C. (1985). Slipping, tripping and falling accidents to delivery drivers, *Ergonomics*, Vol. 28**,** pgs. 977 - 991.

Neitzel R., et al. (2008). Exposure to fall hazards and safety climate in the aircraft maintenance industry, Journal of Safety Research, Vol. 39, pgs. 391-402.

Parsons, T.J. and Pizatella, T. J. (1985). Safety analysis of high risk activities within the roofing industry, Technical Report, NTIS PB-85163236, National Technical Information Service, Spring® eld, VA.

Pate, C.E., (2002). Finding and fixing systems weaknesses: Probabilistic methods and applications of engineering risk analysis, *Risk Analysis,* Vol. 22, pgs. 319-334.

Patla, A. E. (1997). Understanding the role of vision in the control of human locomotion, *Gait & Posture*, Vol. 5, pgs. 54 - 69.

Patla, A. E. 1997, Slips, trips and falls: implications for rehabilitation and ergonomics, in S. Kumar (ed.), *Perspectives in Rehabilitation Ergonomic s* (London: Taylor & Francis), 196 - 209.

Perell et al. (2001). Fall Risk Assessment Measures: An Analytic Review, *Journal of Gerontology: Medical Sciences,* Vol. 56A, pgs. M761-M766.

Perkins, P. J. 1978, Measurement of slip between the shoe and ground during walking, in C.Anderson and J. Senne (eds), *Walkway Surfaces: Measurement of Slip Resistance, ASTM STP 649* (Philadelphia: American Society for Testing and Materials), 71 -87. Occupational Safety & Health Administration (2007-2009). Inspections within Industry. Department of Labor. http://www.osha.gov/pls/imis/industry.html.

Quintana, R.(1999). A task-delineated safety approach for slip, trip, and fall hazards, *Safety Science*, Vol. 33, pgs. 31-45.

Ramsey, J. (1973). Identification of contributory factors in occupational injury, *Journal of Safety Research*, Vol. 5, pgs. 260- 267.

Ruser, J. W. (1995). *A Relative Risk Analysis of Workplace Fatalities, Fatal Workplace Injuries In 1993: A Collection of Data and Analysis*, Report 891, US Department of Labor, BLS, Washington, DC, 18 - 22.

Saaty, T.L (1990). How to make a decision: The analytic hierarchy process. European Journal of Operational Research. Vol. 48, no. 1, pp. 9-26.

Salazar et al, (2005). Occupational Risk Among Orchard Workers: A Descriptive Study, Family & Community Health, Vol. 28, pgs. 239-252.

Sawacha, E, et al. (1999). Factors affecting safety performance on construction sites, *International Journal of Project Management,* Vol. 17, pgs.309-315.

Schwartz, J. (1962). The pernicious influence of mathematics in science. In Nagel, Supper and Tarski Logic Methodology and Philosophy of Science. Standard.

Siegel, S. and Castellan, N. (1988). Nonparametric Statistics for the Behavioral Sciences, 2nd edition, McGraw-Hill.

Skinner, H. B., Barrack, R. L. and Cook, S. D. (1984) Age-related decline in proprioception, *Clinical and Orthopaedic Related Research*, 184, pgs. 208 - 211.

Strandberg, L. (1983)./ On accident analysis and slip-resistance measurement, *Ergonomics*, Vol. 26, pgs. 11- 32.

Strandberg, L. and Lanshammer, H. (1981). The dynamics of slipping accidents. *Journal of Occupational Accidents*, Vol 3, pgs. 153 - 162.

Swensen, E. E., Purswell,J. L., Schlegel,R. E. and Stanevich, R. L. (1992). Coefficient of friction and subjective assessment of slippery work surfaces, *Human Factors*, Vol. 34, pgs**.** 67 –77.

Terano, T., Asai, K., Sugeno, M. Fuzzy Systems Theory and Its Applications Academic Press, Inc. 1992

Terano, T., Asai, K., Sugeno, M. Fuzzy Systems Theory and Its Applications. Boston, MA: Harcourt-Brace, 1987.

Tideiksaar,R. (1996). Preventing falls: How to identify risk factors, reduce complications, *Geriatrics*, Vol. 51, pg. 43.

Tisserand, M. (1985). Progress in the prevention of falls caused by slipping, *Ergonomics*, Vol. 28**,** pgs**.** 1027 -1042.

Tinetti, M., (1988). A Multifactorial intervention to reduce the risk of falling among Elderly People living in the community, Risk factors for falls among elderly persons living in the community, Vol. 319, pgs. 1701-1707.

Verma, S.K., Lombardi, D.A., Chang, W.R., Courtney, T.K., and Brennan, M.J., (2007). Circumstances of Occupational Same-Level Falls and Risk of Hip Fracture in Women Over 45 Years of Age Who Fell at Work, *Proceedings of the International Ergonomics Association's Technical Committee on Slips, Trips and Falls, International Conference on Slips, Trips, and Falls 2007: From Research to Practice*, Hopkinton, MA, pgs. 25-30.

Yao, Y. Y. and Wong, S. K. M. (1992). A decision theoretic framework for approximating concepts. International Journal of Man-Machine Studies, Vol. 37, pgs. 793-809.

Zadeh, L. A. (1965). Fuzzy Sets. *Information and Control*, Vol. 8, pgs. 338-353

Zimmermann, H.-J. (1991). Fuzzy Set Theory and Its Applications 2 Ed.