A human factor analysis to mitigate fall risk factors in an Aerospace Environment

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Introduction

- UCF: Ph.D in Industrial Engineering, (Human Factors/Ergonomics)
- FSU: M.S. in Industrial Engineering (Engineering Management)
- FAMU: B.S. in Chemical Engineering (Cum Laude)
- Engineer at NASA/Kennedy Space Center
- Adjunct Professor at Florida Institute of Technology and Valencia Community College

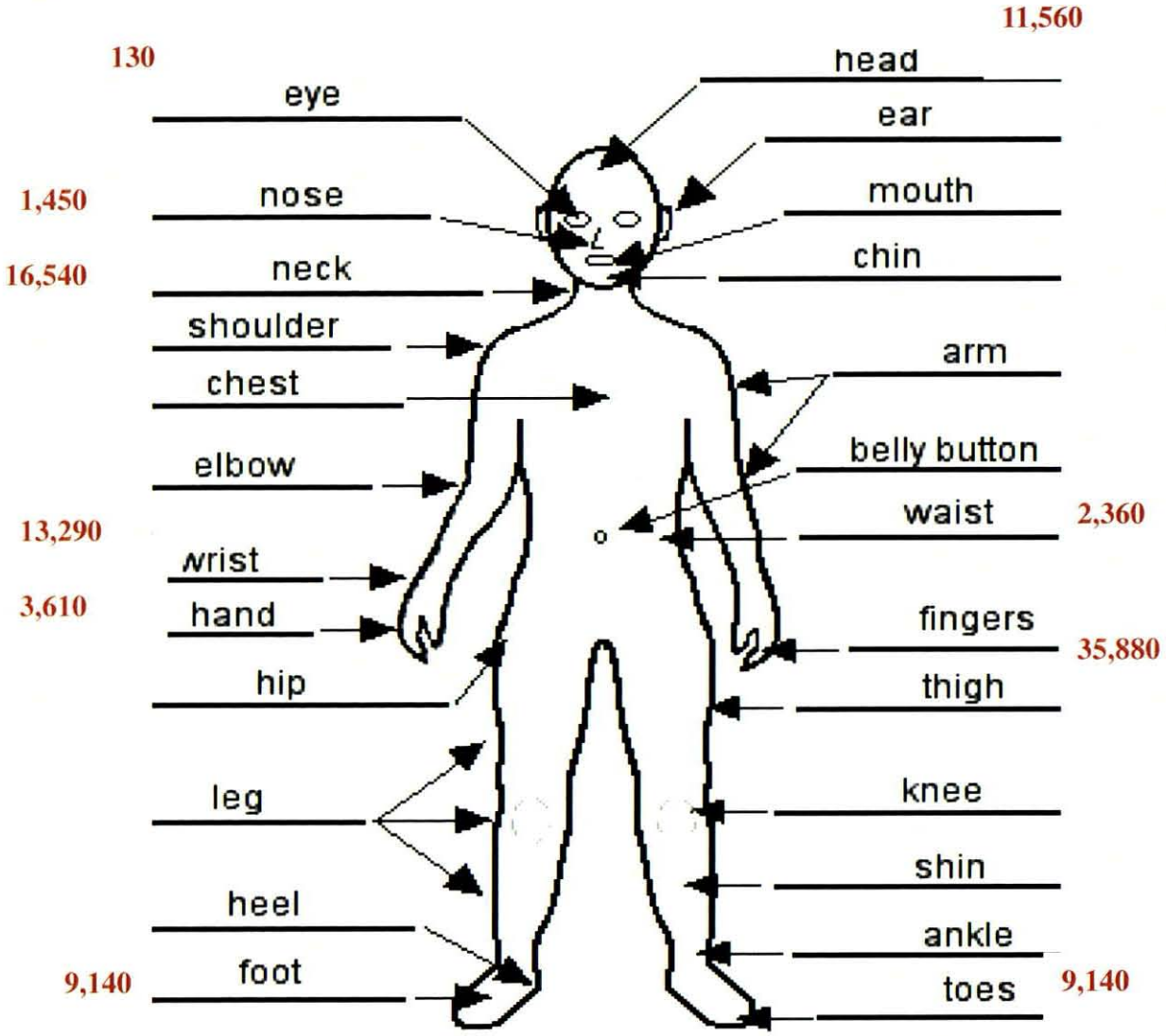
Presentation Outline

- Introduction
- Problem Statement
- Research Hypotheses
- Literature Review
- Research Methodology
- Research Results
- Discussion
- Conclusion
- Questions/Answers

What is a Fall?

Fall is "an event which results in 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 under the umbrella of System Safety.

Human Body and Falls



Total Falls:

365,510 on the Human Body

(BLS, 2007)

Note: Falls impact the entire human body. According to BLS 2007, there were approximately 300k falls that affected the human body.

Falls in an Aerospace Environment

- High risk exists in multiple tasks
- Work is performed at excessive heights
- Potential for high consequence outcomes
- Unique characteristics of environment and equipment

Problem Statement

- There are NASA/KSC environments where employees are required to perform tasks from heights that are high risk for falls.

- To address the issue NASA contracted with Gravitec Systems Inc., a fall-protection engineering firm to developed a hazard ranking system to assess fall hazards.
  - The hazard ranking system was established based on the assumption that multiple factors such human factors, environmental factors, and working conditions have a uniform influence on falls. (*The ranking system has not been validated*)

Research Purpose

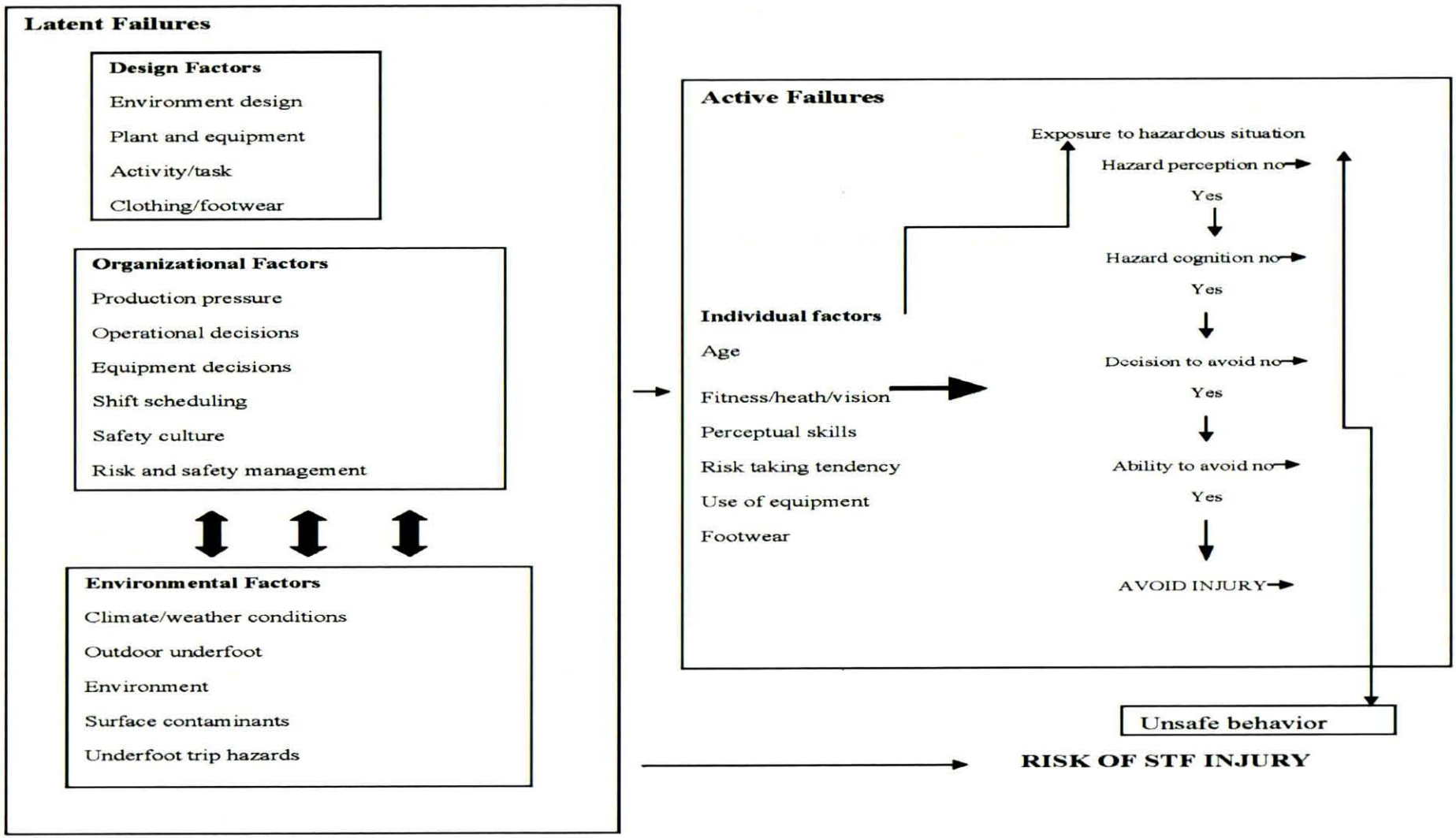
- Research, develop, and validate a fuzzy AHP quantifiable model that can be applied in aerospace environments
- Validate the present of fall hazards at NASA/KSC
- Validate the Gravitec model

Research Hypotheses (Null and Alternative)

- **H_0:** The development of a conceptual model that characterizes risk factors can be useful in reducing the likelihood of falls in NASA Ground Support Operations
- **H_1:** The development of a conceptual model that characterizes risk factors cannot be useful in reducing the likelihood of falls in NASA Ground Support Operations

- **H_0:** A fuzzy analytical hierarchy process model can be developed and validated to predict the likelihood of falls in NASA Ground Support Operations.
- **H_1 :** A fuzzy analytical hierarchy process model can not be developed and validated to predict the likelihood of falls in NASA Ground Support Operations.

Theoretical Foundation



Note: The information processing and ergonomic model is the theoretical basis for the research, categorization of risk factors, and the model development. In this theoretical model, there is a risk of slip, trips, and falls. Falls are a greater risk in an aerospace environment.

Comparative Analysis

Multiple Factors that contribute to falls

General Work Environment

- Experience (OF)
- Job and Safety Program (OF)
- Type of Task/Activity (TF)
- Sex/Gender (HF)
- Load weight (TF)
- Environmental Conditions (EF)
- Task Frequency (TF)
- 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)

Aerospace Environment (NASA Ground Support Operations)

- Worker Interference (HF)
- Number of Workers (HF)
- Age (HF)
- Fall Distance (EF)
- Environmental Conditions (EF)
- Environmental Surface (EF)
- Task Duration (TF)
- Task Frequency (TF)
- Fall Hazard Severity (OF)
- Fall Hazard Protection (OF)
- Fall Hazard Occurrence (OF)
- Task Proximity (TF)

Legend

OF-Organizational Factor

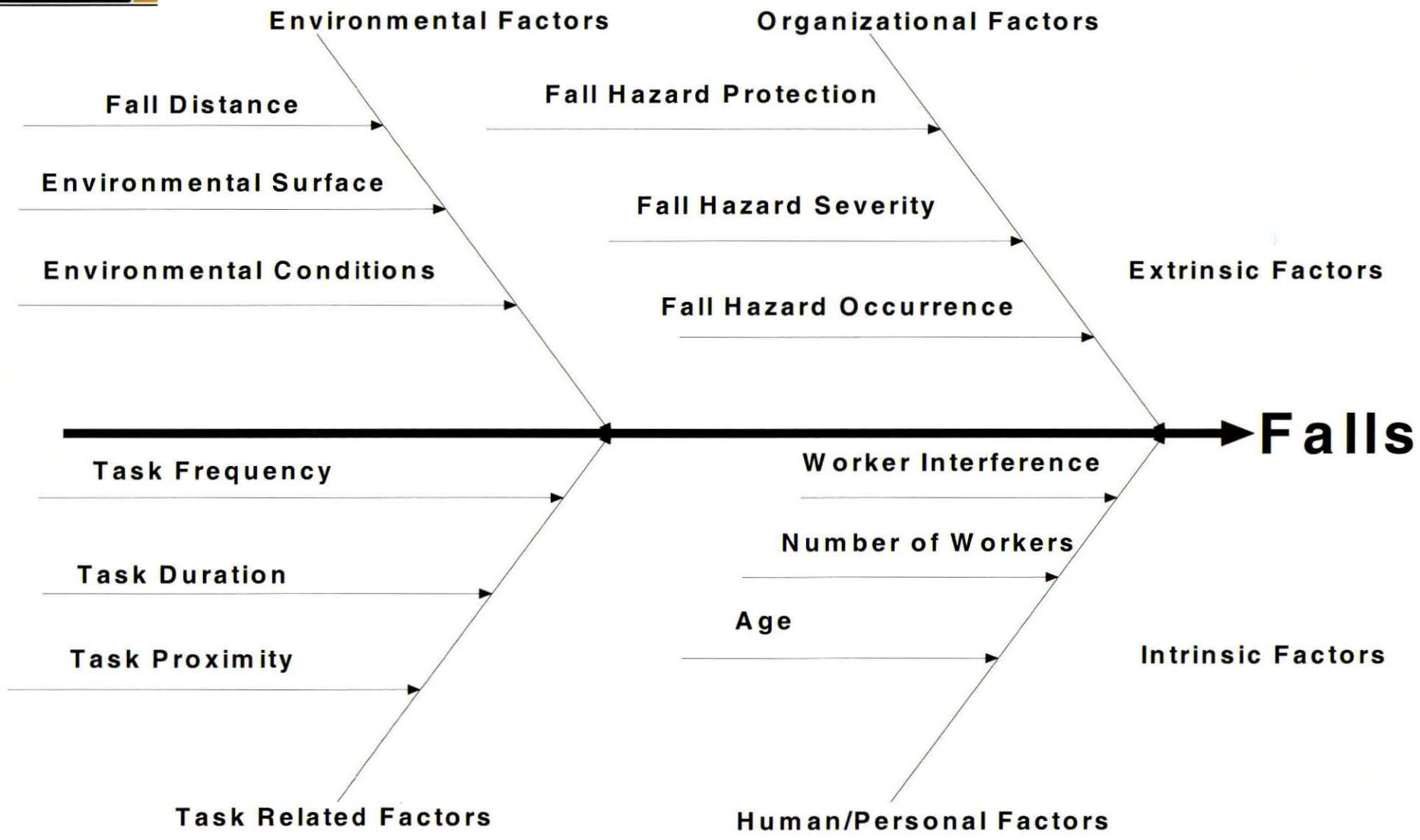
EF-Environmental Factor

TF-Task Related Factor

HF-Human/Personal Factor

Benchmark: The risk factors were observed multiple times (3 reoccurrences) in the literature and there was a common thread in the Bureau of Labor Statistics (BLS) Data, Liberty Mutual Data, Mishap Data, IRIS, Empirical Studies, Safety Mishap Data, and NASA/Gravitec Fall Hazard Analysis Report. The risk factors will be assessed and used in the fuzzy AHP model. The list is not conclusive.

Final Conceptual Model



Research Gaps and Objectives

Research Gaps

Knowledge and understanding of contributing risk factors that influence falls in NASA ground support operations (Hongwei Hsiao, 2008; Petre Simeonova, 2001)

Aggregate impact of risk factors that influence falls and Interactive Nature of Risk Factors (Gauchard, G., 2001)

Model that Quantifies risk factors that influence falls in NASA ground support operations (Dagdeviren, M., 2008)

Research Objectives

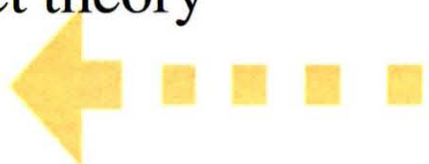
Identify and classify risk factors that influence falls in an aerospace environment

Develop a conceptual model that includes multiple risk factors that contribute to falls (i.e. human/personal, task related, environmental, organizational)

Develop and validate a fuzzy analytical hierarchy process model to predict the likelihood of falls in an aerospace environment (NASA ground support operations) and aid in the design of work areas.

Research Phases

1. Knowledge Acquisition
2. Data Collection
3. Subject Matter Experts' (SMEs) interviews
4. Analytical Hierarchy Process (AHP)
5. Weight Validation
6. Fuzzification of variables
7. Membership Functions Development
8. Fuzzy Qualification using Fuzzy set theory
9. Fuzzy Quantification using Fuzzy set theory
10. Model Development
11. Model Usability
12. Model Validation



Research Variables

- Dependent Variable: Fall (effect)
- Independent Variable: Factors that contribute to falls (cause) are the following:
  - task related
  - human/personal
  - organizational
  - environmental

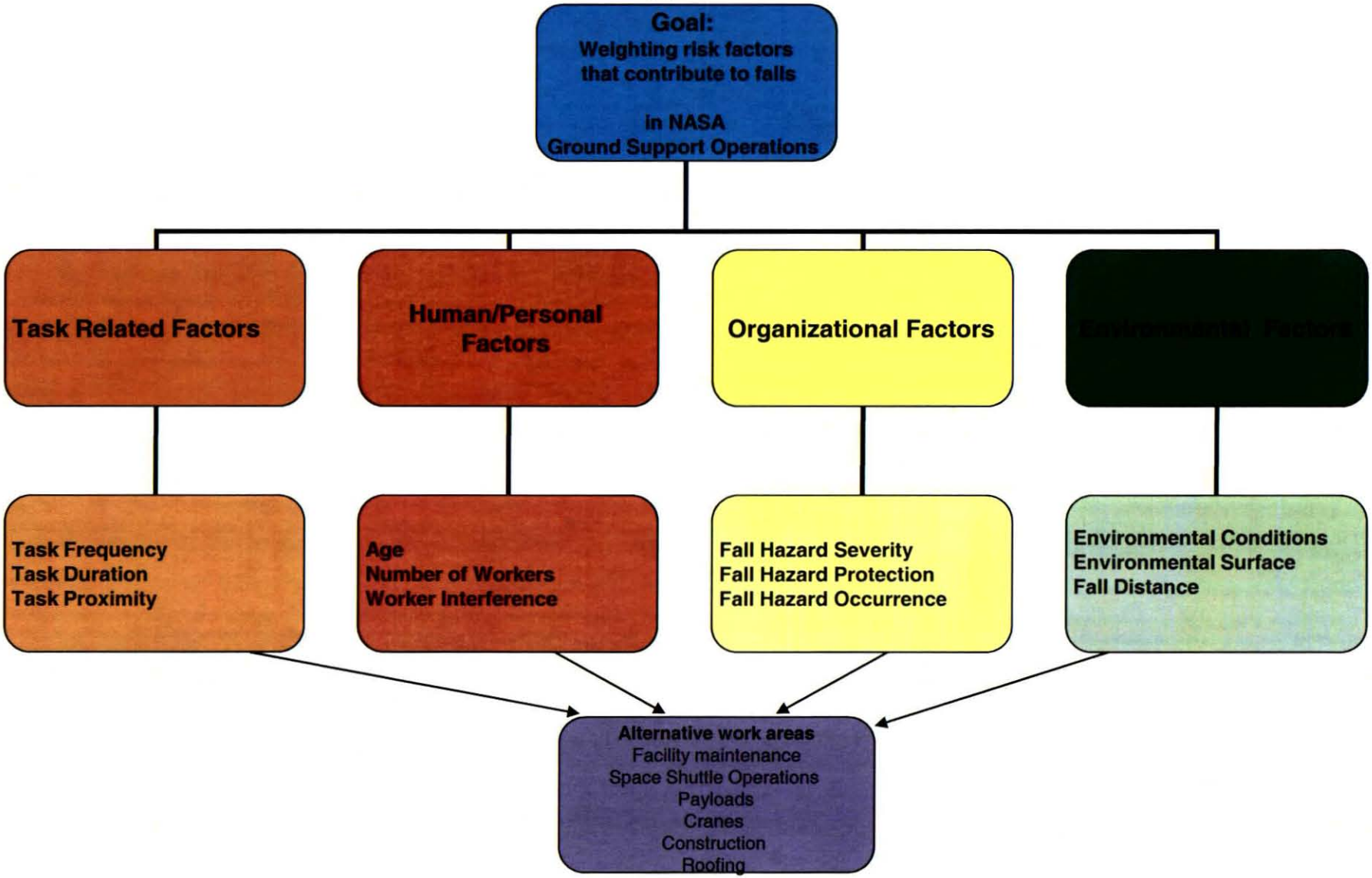
Research Questions

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

Analytical Hierarchy Process (AHP) Model

Affinity Diagram

Saaty, 1990



Subject Matter Experts (SMEs)

Team 1	Team 2
1 Fall Protection Expert	1 Fall Protection Expert
1 Human Factors Expert	1 Human Factors Expert
1 Safety Expert	1 Safety Expert

Results and Discussion

Risk Factors Relative Weights
Expert Choice Results

Task Factors

Task Frequency	.451
Task Proximity	.381
Task Duration	.168

Inconsistency = 0.11
with 0 missing judgments.

Human/Personal Factors

Worker Interference	.528
Number of Workers	.263
Age	.209

Inconsistency = 0.01
with 0 missing judgments.

Environmental Factors

Environmental Suface	.422
Environmental Condition	.298
Fall Distance	.279

Inconsistency = 0.11
with 0 missing judgments.

Organizational Factors

Fall Hazard Occurence	.356
Fall Hazard Protection	.354
Fall Hazard Severity	.289

Inconsistency = 0.00
with 0 missing judgments.

Categorical Factors

Task Related Factors	.314
Human/Personal Factors	.307
Organizational Factors	.130
Environmental Factors	.248

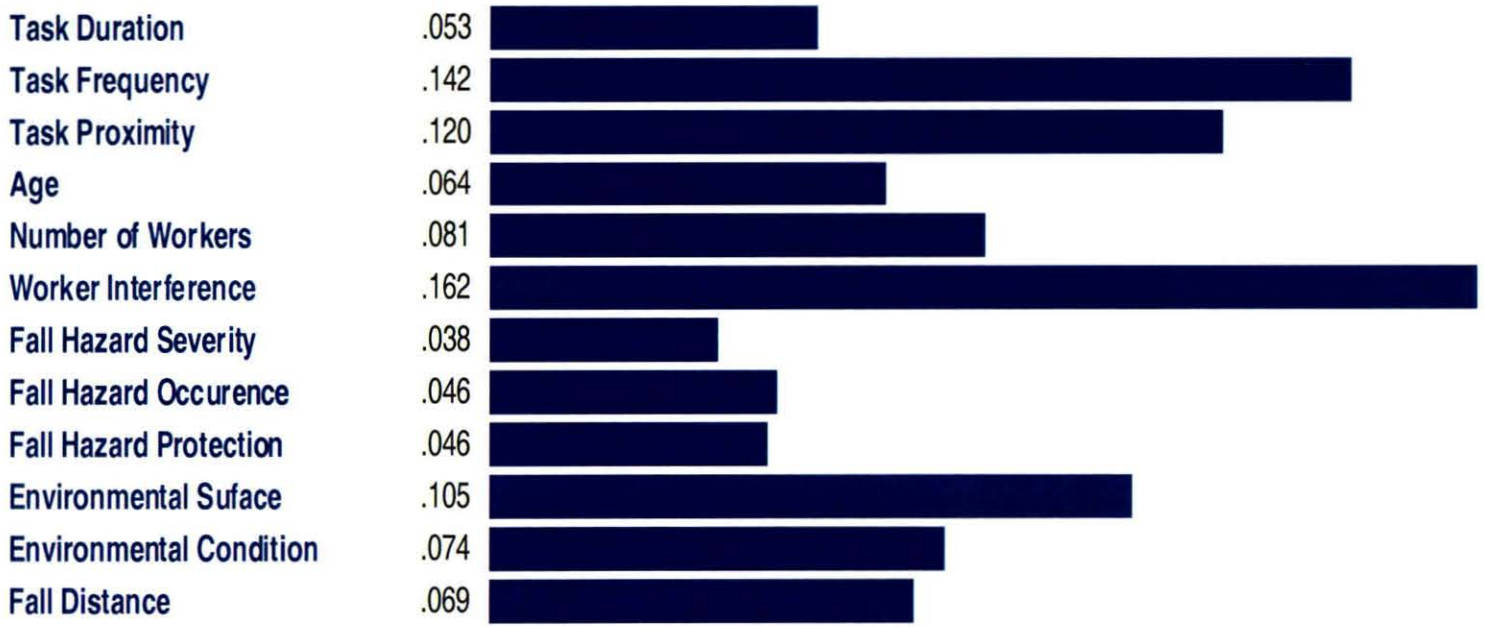
Inconsistency = 0.01
with 0 missing judgments.

Synthesis

Synthesis with respect to:

Goal: Weighting risk factors that contribute to falls in NASA Ground Support Opertations

Overall Inconsistency = .07



Note: The Synthesis with respect to the goal lists the global weights for the risk factors. Worker Interference (0.162), Task frequency (0.142), and task proximity (0.120) are the highest contributing risk factors to falls. Therefore, task related factors are the leading risk factors that contribute to falls.

Weight Validation

The values in the pairwise comparison matrix are the geometric averages between the SMES judgments of risk factors. The sum is the total value for each column or the categorical risk factor.

Weight Validation Pairwise Comparison Matrix from Expert Choice Software				
	Task Related	**Human**	**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 values in the following table 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. There results are similar. Therefore, the weights are confirmed valid.

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

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

Level of Existence

Level of Existence	
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

Fuzzy Quantification Linear Models Categorical Risk Factors for falls

Task Related Risk Factors

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

Human/Personal Risk Factors

$$X_2 = F(H/P) = b_1 z_1 + b_2 z_2 + b_3 z_3 \ldots . b_n z_n$$

Organizational Risk Factors

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

Environmental Risk Factors

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

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

Fuzzy Quantification Linear Models Comprehensive Risk for falls

$$Y = e_1 X_1 + e_2 X_2 + e_3 X_3 + e_4 X_4$$

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

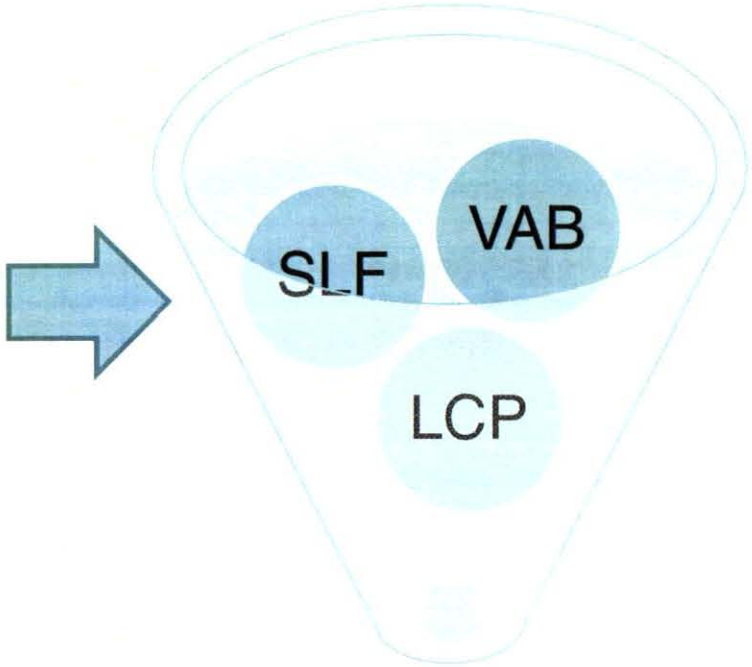
The weighting factors (e_1, e_2, e_3, e_4) represent the relative significance of the given risk factor category's contribution to the likelihood of injury.

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

Model Usability

- **Design of Experiment**
  - Repeated measures analysis
    - 15 Subjects
    - Between and within subjects
  - Agreement of Data
  - Variability of Data

- **NASA Ground Support Operations Scenarios**
  - SLF-Shuttle Landing Facility
  - LCP-Launch Complex Payloads
  - VAB-Vehicle Assembly Building



NASA Scenarios

Aggregate Risk Value and Likelihood Rating

Aggregate Risk Value (Y)	Risk Associated with Numeric Value	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

NASA Fall Hazard Accepted Scale

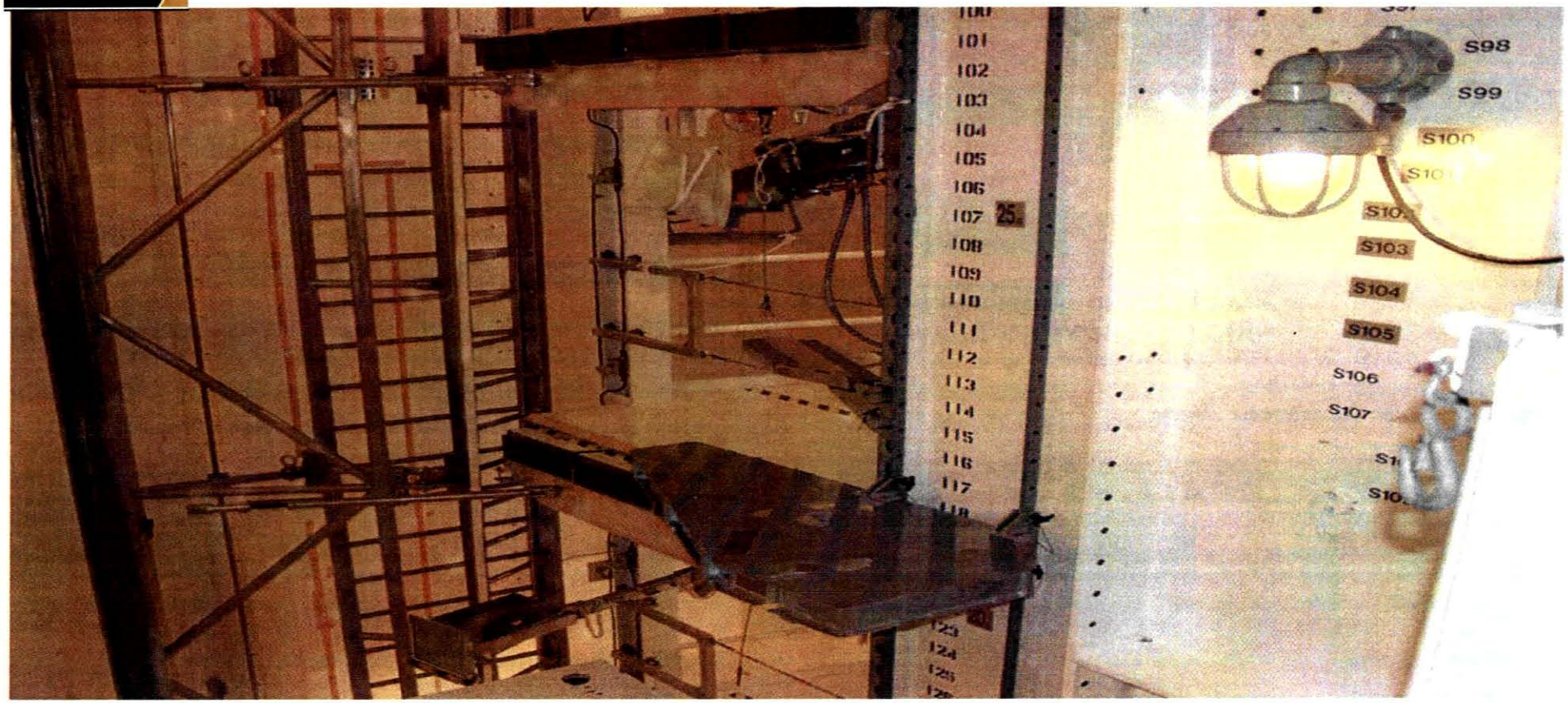
Numerical Risk Value	Risk Associated with the Value	Likelihood Rating
0-5	Low Risk Hazards	1
6-10	Medium Risk Hazards	2
10-15	High Risk Hazards	3
15-20	Dangerous Risk Hazards	4
20-25	Extreme Hazards	5

Shuttle Landing Facility (SLF)

Mate / De-mate Device Camera

Case Study: A worker 32 years old required to conduct routine maintenance on the camera pictured in the red circle outside the Shuttle Landing Facility. 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.

Launch Complex Payloads (LCP)



LC 39 A & B - Payload Platforms

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

Vehicle Assembly Building (VAB)

Building Roof

Case Study: During construction, up to three workers (25 years of age) replace and repair roof material near the edge of the 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.

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

Scenario 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	**.45**	**.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

Note: The values were calculated using an Excel (Fuzzification) spreadsheet.

Model Usability Hypotheses (Null and Alternative)

- $\mathbf{H_{0:}}$ The p-value provide the likelihood of obtaining the sample, with its Kendall's coefficient, agreement within subject is due to chance.
- $\mathbf{H_{1:}}$ The p-value provide the likelihood of obtaining the sample, with its Kendall's coefficient, agreement within subject is not due to chance.

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 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. Because the p-values are greater than the alpha level for all subjects, accept the null hypothesis. Agreement within the subject is due to chance and the p-value provide the likelihood of obtaining the sample. As a result, there is a relative agreement among the subjects in the likelihood of falls.

Variability

Multiple descriptive statistics for a 95% confidence interval and t-test are the following:

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

Therefore, there is minimal variability with the fuzzy AHP modeling.

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

Percentage Error

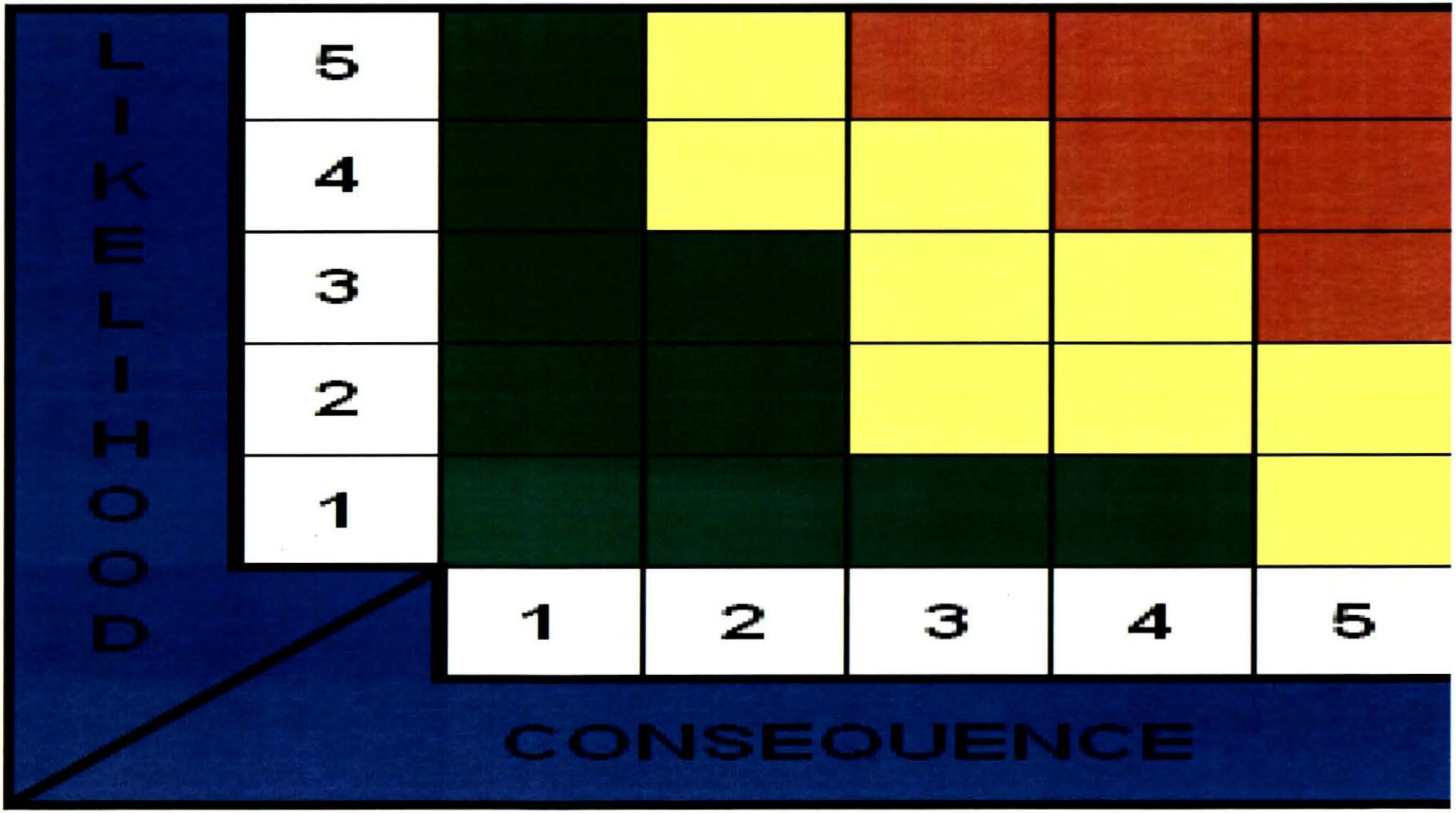
$$\%error = \frac{(predicted - accepted)}{accepted}$$

For Shuttle Landing Facility (SLF)

$$0\ \%\ \ error \quad = \quad \frac{(2.0 - 2.0)}{2.0}$$

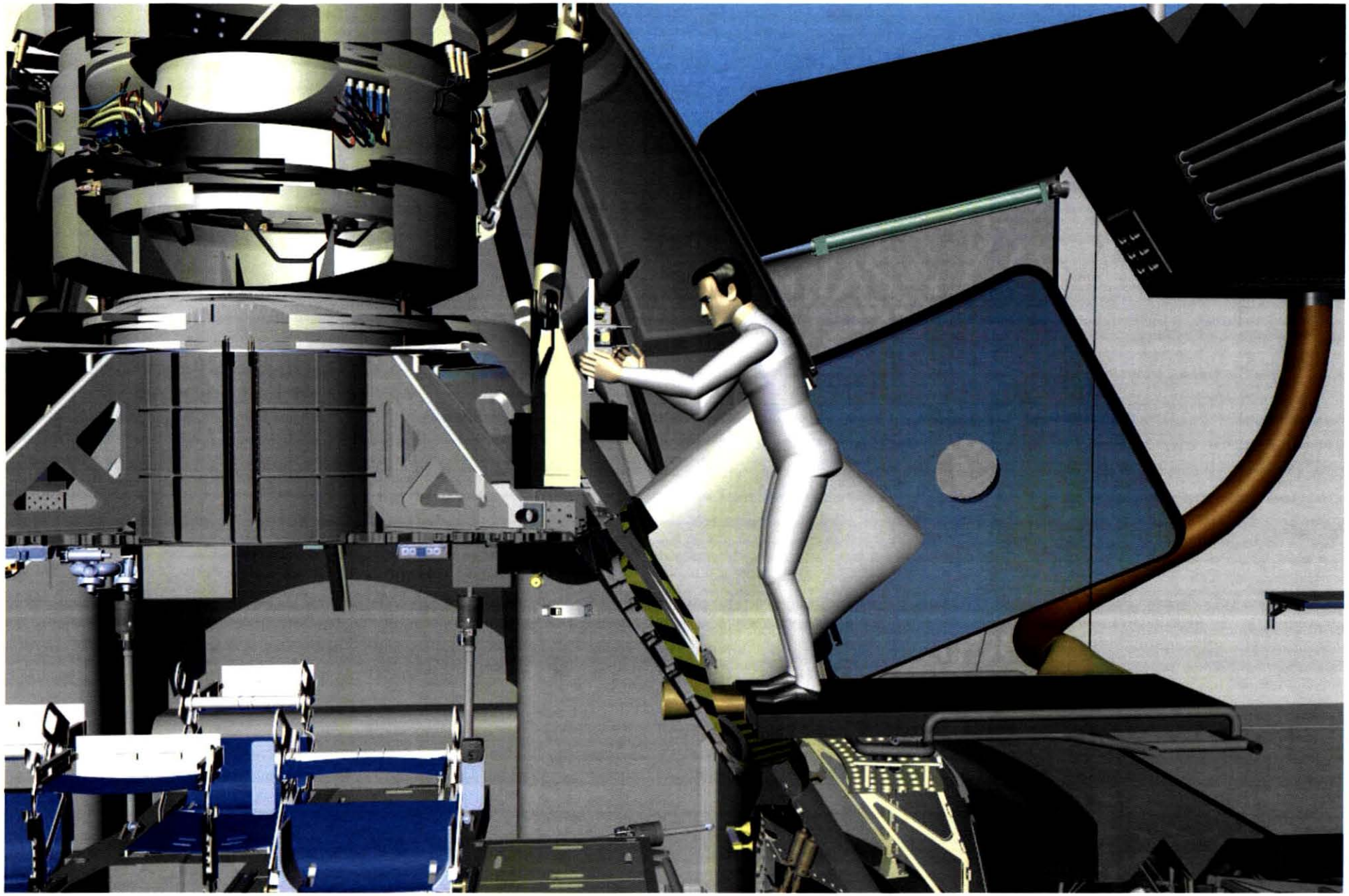
Scenario	Percentage Error
Shuttle Landing Facility (SLF)	**0%**
Launch Complex Payloads (LCP)	**33%**
Vehicle Assembly Building (VAB)	**0%**

Empirical Approach
NASA Risk Scorecard



NASA Safety Risk Scorecard Consequence

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 (Falls)	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



NOTE: Constellation ORION Project: High Bay Area with an excessive fall distance. There is no Personal Protection Equipment (PPE) or spotter present. For example, a NASA Safety Expert will evaluate this scenario as a 4 x 5 (Catastrophic Hazard-RED).

Conclusion

- Research Questions Addressed
- Research Hypotheses Addressed
- Research Contributions Addressed
- Research Limitations
- It is confirmed that falls are preventable by multidimensional assessment and targeted intervention

Questions and Answers