A Holistic Approach to Managing Risk Factors Contributing to Falls in an Aerospace Environment

Dr. Joylene Hall Ware
Engineering Directorate
NASA/Kennedy Space Center
John F. Kennedy Space Center, FL 32899
Joylene.L.Ware@nasa.gov

Dr. Pamela McCauley Bush
Industrial Engineering and Management Systems
University of Central Florida
Orlando, FL 32816
mcbush@mail.ucf.edu

Abstract - *In aerospace environments, personnel falls are key safety concerns. Suitable models are required to understand the likelihood of falls and measure risk factors that contribute to them. This research aims to develop and validate a fuzzy Analytical Hierarchy Process model that considers both qualitative and quantitative elements in assessing the likelihood of falls and aiding in the design of NASA Ground Support Operations. Six subject matter experts made pair-wise judgments on risk factors that lead to falls. The broadly categorized risk factors are human/personal, task related, organizational, and environmental. The model usability involved fifteen subjects applying the model to three scenarios at NASA/Kennedy Space Center. The model was validated testing the conformity of the fuzzy model to a NASA accepted model. There was no significant distinction between the current NASA model and the fuzzy model. The statistical results indicate minimal variability with fuzzy modeling, thus confirming the model's validity.*

Keywords: falls, fall hazards, system safety, NASA Ground Support Operations, fuzzy set theory, fuzzy model, aggregative risk value, risk factors, likelihood rating, aerospace environment, NASA risk scorecard, Analytical Hierarchy Process, Kendall Coefficient of Concordance.

1 Introduction

The National Aeronautics and Space Administration (NASA) Kennedy Space Center (KSC) is an operational facility responsible for carrying out both space shuttle and expendable vehicle launches, processing ground support operations, and developing hardware for delivery to the International Space Station. KSC environments such as facility maintenance, Space Shuttle operations, payloads, cranes, construction, and roofing are areas of concern for fall hazards. Under the umbrella of system safety, falls are events where an individual comes to rest unintentionally to a lower level and not by result of an intrinsic event such as a stroke. To address the issue safety related to falls NASA contracted with Gravitec Systems Inc., a fall-protection engineering firm, which assessed over 400 elevated work areas with regards to fall hazards. Gravitec developed a hazard ranking system based on the assumption that multiple risk factors such as human factors, environmental factors, and working conditions have a uniform influence on falls.

An Ishikawa "Fishbone" Diagram (Fig. 1) was used as the conceptual model to represent the factors that lead to falls in NASA Ground Support Operations. The fishbone diagram identifies, sorts, and displays possible causes of a problem or quality characteristic. The cause and effect diagram displays 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.

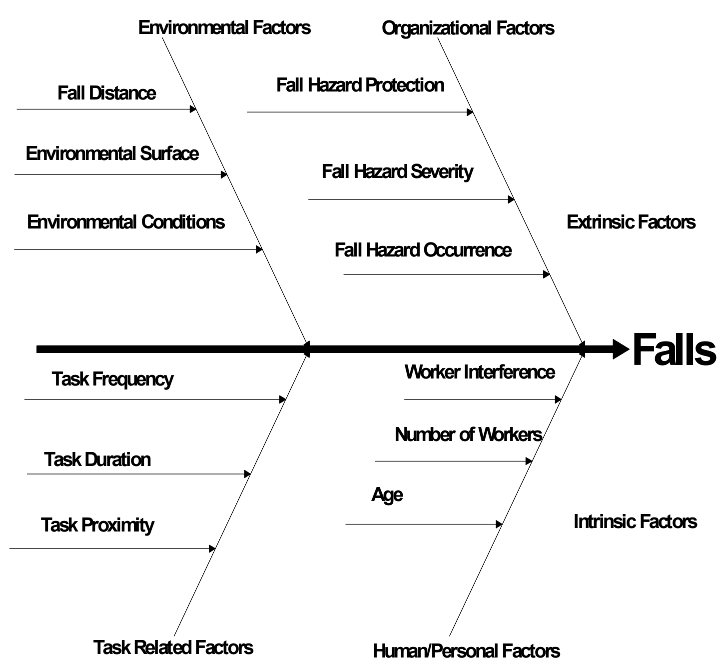

Figure 1. Conceptual Model.

2 Methodology

There were twelve phases in the methodology: knowledge acquisition, data collection, subject matter experts' interviews, Analytical Hierarchy Process (AHP), weight validation, fuzzification of variables, membership function development, fuzzy qualification using fuzzy set theory, fuzzy quantification using fuzzy set theory, model development, model usability, and model validation.

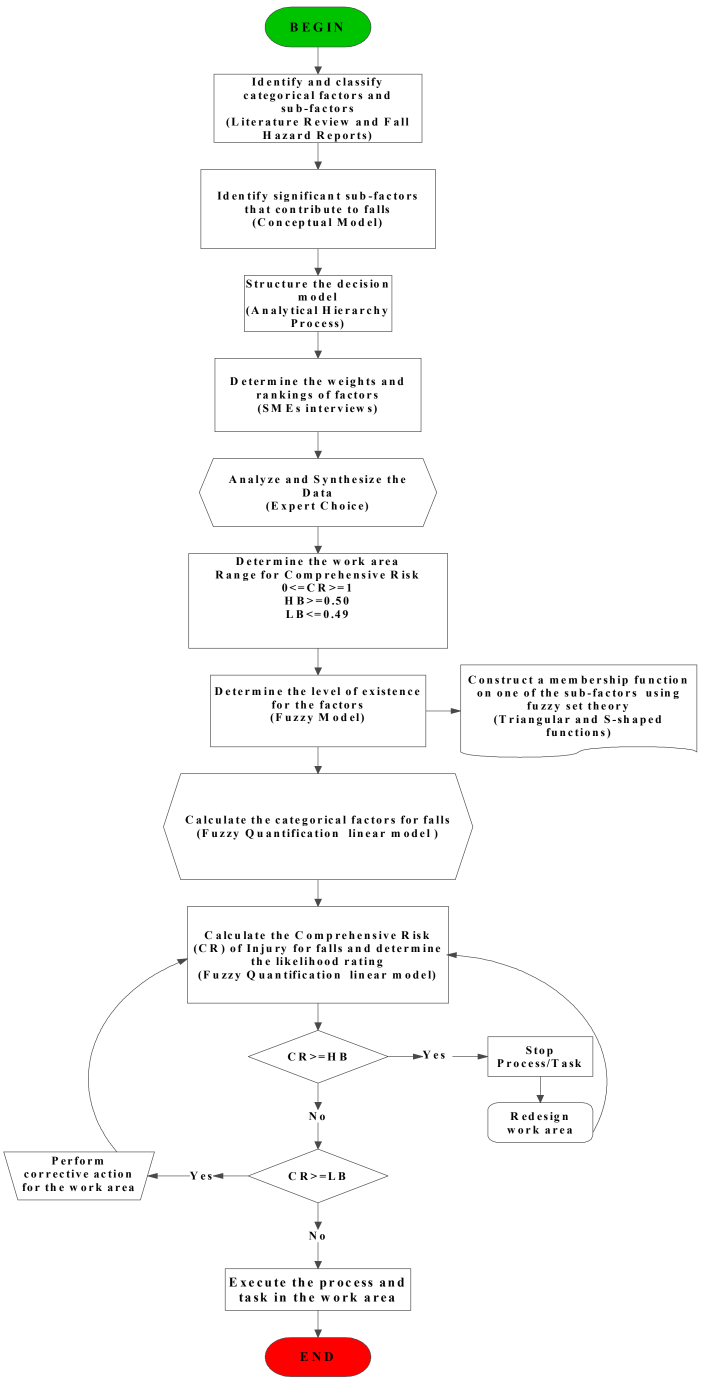

Figure 2. Schematic Diagram.

The research hypotheses are: (1) the development of a conceptual model that characterizes risk factors can be useful in reducing the likelihood of falls in NASA Ground Support Operations; and (2) a fuzzy Analytical Hierarchy Process model can be developed and validated to predict the likelihood of falls in NASA Ground Support Operations. Multiple risk factors that contribute to falls in NASA Ground Support Operations are task related, human/personal, environmental, and organizational. The previous Schematic Diagram as shown in Figure 2 represents the proposed model based on the fuzzy Analytical Hierarchy Process models [1, 2].

3 Results

3.1 Subject Matter Experts' Interviews

The Analytical Hierarchy Process (AHP) is a thorough mathematical process for prioritization and decision making. The process involves reducing difficult decisions to a series of pair-wise comparisons, and then synthesizing the results, decision-makers arrive at the best decision with a clear rationale for that decision. Six subject matter experts (SMEs) were asked to participate in a voting system involving a survey where they judge risk factors using the fundamental AHP pair wise comparison scale. The results were analyzed and synthesized using Expert Choice Software, which produced the relative weights for the risk factors (Fig. 3). 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 0.01, which indicates the model results were acceptable.

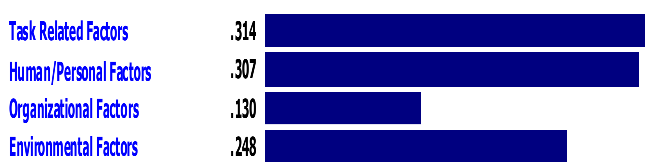

Figure 3. Categorical Risk Factors.

3.2 Weight Validation

The weights were validated by having two different teams of SMEs create priority vectors separately and confirm the weights are similar (see Table 1). Priority vectors are the average of the weights for each risk factor that lead to the falls. The validation is confirming that task related factors are a high priority at NASA due to the high risk environment, schedule driven tasks, and the demanding task performance for safety.

Table 1. Weight Validation.

Risk Factor	Priority Vector	Relative Weight	Rank
Task Related	0.304	0.314	1
Human/ Personal	0.302	0.307	2
Environmental	0.21	0.248	3
Organizational	0.17	0.13	4

3.3 Fuzzy Set Theory

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 [3]. 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, inclusive, which provides the lower and upper approximations of a concept [4]. Zimmermann identifies the necessity to use mathematical language to map several membership functions and develop FST models [5].

3.3.1 Fuzzy AHP Model

The following fuzzy model is representative of the McCauley-Bell and the Baiduru fuzzy model [2], which uses the Fuzzy Quantification Linear Models [6].

Fuzzy Quantification Linear Models

Task Related Risk:

$$X_1 = F(TR) = a_1w_1 + a_2w_2 + a_3w_3 \quad (1)$$

Human/Personal Risk:

$$X_2 = F(HP) = b_1z_1 + b_2z_2 + b_3z_3 \quad (2)$$

Organizational Risk:

$$X_3 = F(O) = c_1u_1 + c_2u_2 + c_3u_3 \quad (3)$$

Environmental Risk:

$$X_4 = F(E) = d_1v_1 + d_2v_2 + d_3v_3 \quad (4)$$

where risk sub-factors relative weights are

a = task related
b = human/personal
c = organizational risk
d = environmental risk

and risk sub-factors levels of existence are

w = task related
z = human/personal
u = organizational
v = environmental

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

$$Y = e_1X_1 + e_2X_2 + e_3X_3 + e_4X_4 \quad (5)$$

where Y = comprehensive risk for the given condition and

e_1 = weighting factor for the task related factors
e_2 = weighting factor for the human/personal factors
e_3 = weighting factor for the organizational 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 risk (Table 2), which is equal to the product of relative weight respective to the categorical risk factors.

Table 2: Aggregate Risk Value.

Aggregate Risk Value (Y)	Risk Association	Likelihood Rating
0.00 - 0.20	Very Low risk	1
0.21 - 0.40	Low risk	2
0.41 - 0.60	Moderate risk	3
0.61 - 0.80	High risk	4
0.81 - 1.00	Very high risk	5

3.3.2 Membership Function

Membership functions are developed to characterize risk factors or show the universe of discourse in fuzzy modeling. In general, the triangular membership function can be specified from the formula below:

$$\mu_{triang} = \begin{cases} 0 & x < L \\ 1 - \dfrac{|C - x|}{(R - L)/2} & L < x < R \\ 0 & x > R \end{cases} \quad (6)$$

The symbol μ represents the degree of membership of the scalar quantity x which takes values along the universe of discourse of the membership function. In this research, scalar quantity is the risk factor that contributes to falls.

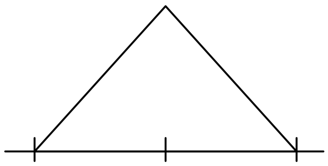

Figure 4. Triangular Membership Function.

L and *R* are the left and right bounds, respectively, and *C* is the center of the symmetric triangle as shown in Figure 4. Table 3 lists the linguistic variables and their meaning in terms of fuzzy number ranges.

Table 3. Linguistic Variables and Meaning.

Linguistic Variables	Meaning of Fuzzy Numbers
Low	0-0.33
Medium	0.34-0.66
High	0.67-1.0

Age is a Human/Personal risk factor. A triangular membership function was used to characterize the risk factor Age. The range for the Age membership function as determined by the subject matter experts was: $21 \leq x \leq 70$. Table 4 lists numerical results for the Age Membership Function shown in Fig. 5. It is inferred from the results that the high instances for falls occur in the age range of 40-45. The results are based on the NASA population. The NASA/Kennedy Space Center workforce includes a vast number of employees in the age range of 40-45.

Table 4. Age Linguistic Variables.

Age (years)	Degree of Membership	Variables
21	0	low
33.25	0.5	medium
40	*0.77*	*high*
45.5	*1*	*high*
57.75	0.5	medium
70	0	low

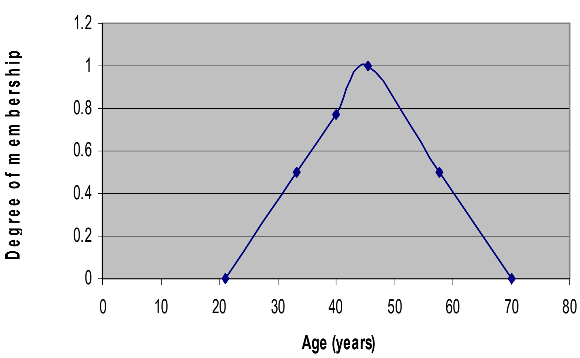

Figure 5. Age Membership Function.

3.4 Model Usability and Statistical Analysis

The model usability involved a repeated measures analysis experimental design of fifteen subjects applying the fuzzy AHP model to three scenarios associated with falls in facilities or areas used in NASA Ground Support Operations. The three facilities or areas were the Shuttle Landing Facility (SLF), Launch Complex Payloads (LCP), and Vehicle Assembly Building (VAB). The predicted and accepted values for three scenarios are in Table 6. Then, a NASA safety manager compared the predicted value to the accepted value. The results from this model application confirmed that the predicted value and accepted value for the likelihood rating were similar. Equation 7 was used to calculate the percentage error for the three scenarios.

$$\%error = \frac{(predicted - accepted)}{accepted} \tag{7}$$

Table 5. Percentage Error.

Scenario	Percentage Error
SLF	0%
LCP	33%
VAB	0%

The statistical analysis included tests for agreement of data and variability [7]. The test for data agreement was the Kendall Coefficient of Concordance (KC). The KC for assessment agreement between and within the subjects was significantly 1.00. Therefore, the appraisers are applying essentially the same standard when evaluating the scenarios. 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). Therefore, there is minimal variability with fuzzy modeling. Table 6 shows the Statistical Analysis results.

The statistical results show that the overall KC 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 (0.05) for all subjects, the null hypothesis is accepted. Agreement within the subject is due to a chance that the p-value provides the likelihood of obtaining a sample. However, the results for the subject indicate a slight disagreement for one of the three scenarios. The rationale for this outlier is that the subject probably did not understand the scenario. As a result, there is a relative agreement among the subjects in the likelihood of falls.

3.5 Model Validation

Model validation in Table 6 was the guarantee of agreement with the NASA standard. The model validation process was partitioned into three components: reliability, objectivity, and consistency. The model was validated by comparing the fuzzy AHP model to the NASA accepted model. The results indicate there was minimal variability with fuzzy AHP modeling. As a result, the fuzzy AHP model is confirmed valid.

Table 6. Model Validation.

Scenario	Risk Value (Y)	Predicted Rating	Accepted Rating
SLF	0.404	2	2
LCP	0.351	2	3
VAB	0.451	3	3

4 Discussion

The synthesis is displayed in Figure 6, which 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. The overall inconsistency ratio was 0.07, which is less than 0.1 and acceptable. Therefore, task related factors are the leading risk factors that contribute to falls. The results show that task related risk factors are the highest cause for falls and the organizational risks are the lowest cause for falls in NASA Ground Support Operations.

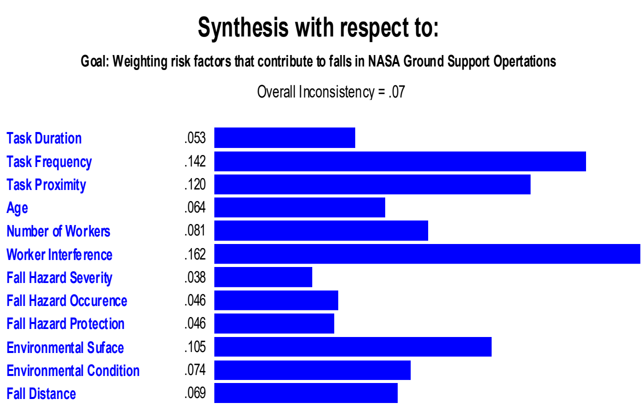

Figure 6. AHP Synthesis.

The empirical approach and the quantitative analysis are showing a correlation between the fuzzy model and NASA Safety Risk Scorecard which is a tool to assess risks at NASA. The NASA risk scorecard includes a 5 x 5 matrix shown in Figure 7. 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 was 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. In addition, there is a consequence associated with each risk. The fuzzy model will be applied at NASA for future assessment of falls. As an example, consider a worker 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.

Therefore, the final assessment using the following NASA Scorecard is a 4 x 5 risk. The likelihood is 4 and the consequence is 5. Thus, fall hazard risk is high (Red) and catastrophic.

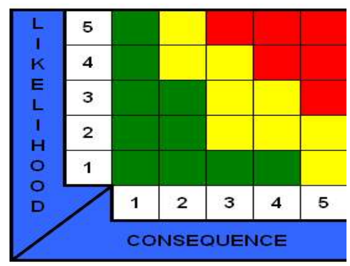

Figure 7. NASA Safety Risk Scorecard.

5 Summary and Conclusions

In conclusion, the results indicate there is minimal variability with fuzzy modeling. The research focused on multiple risk factors that contribute to falls in an aerospace environment. The research emphasized the importance of system safety with respect to falls and concentrated on interdependence of falls. Ultimately, the result of the research was a systematic analysis for fall prevention that will lead to fall protection guidelines. 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.

This fuzzy model is an innovative method for evaluating a problem and specifically risk factor measurement associated with fall hazards [8]. This is a step towards fall mitigation and prevention and can be applied to any work environment concerning falls. The limitations in the study include lack of consideration of the interaction of risk factors in the model that contribute to falls or the global weights of risk factors. In this research, only local weights for the risk factors were considered in the model. However, the global weights of the model were analyzed.

The global weights indicate how the risk factors compare against each other in the whole model. It is confirmed that falls are preventable by multidimensional assessment and targeted intervention. 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. Future research on preventing falls in an industrial environment 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.

Acknowledgment

I would like to thank NASA/Kennedy Space Center for funding the research. I am grateful to my NASA management and coworkers: Mike Benik, Denise Thaller, Kim Manguikian, Tyrell Hawkins, Dr. Gena Henderson, and Dr. David Tipton. I appreciate Karen Milford and the Kennedy Space Learning Institute for their patience and assistance. I would like to thank the late John Maryland who encouraged me to apply to the PhD Program at UCF and Ed Markowski who encouraged me to apply for the NASA/KSC Graduate Fellowship. I owe a special note of gratitude to the Research Assistants: Chaz Wendling, Christopher Lee, Tareq Ahram, Dr. Karwowski, and Hal Mendelsohn for beneficial assistance with the dissertation from which this paper is derived. I would like to honor my advisor and doctoral committee members: Dr. Pamela Bush, Dr. Kent Williams, Dr. James Brown, and Dr. Lesia Crumpton-Young, for their expertise, valuable discussions, thorough knowledge, and accessibility. Last but certainly not least, I am grateful to Dr. Edward Tunstel for assistance with configuration management. The research is dedicated to them.

References

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

[2] P. McCauley-Bell and A. Badiru, "Fuzzy modeling and analytic hierarchy 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, pp. 132-138, May 1996.

[3] P.P. Bonissone, "A fuzzy sets based linguistic approach: Theory and applications," Proc. 12th Winter Simulation Conference, Orlando, FL, pp. 99-111, Jan. 1980.

[4] Y.Y. Yao and S. Wong, "A decision theoretic framework for approximating concepts," *International Journal of Man-machine Studies*, Vol. 37, No. 6, pp. 793-809, 1992.

[5] H.J. Zimmermann, *Fuzzy Set Theory and its applications*, 2nd ed., Kluwer Academic Publishers, Boston, MA, 1991.

[6] T. Terano, K. Asia and M. Sugeno, *Fuzzy Systems Theory and Its Applications,* Academic Publishers, Boston, MA, 1992.

[7] S. Siegel and N. Castellan, *Nonparametric Statistics for the Behavioral Sciences,* 2nd ed., McGraw-Hill, Columbus, OH, 1988.

[8] J. H. Ware, *A systematic analysis to identify, mitigate, evaluate, and measure risk factors contributing to falls in NASA Ground Support Operations*, Ph.D. dissertation, University of Central Florida, Industrial Engineering and Management Systems, Aug. 2008.