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EXPLORING A COMPETENCY INDICATOR SYSTEM FOR THE SAFE OPERATION OF MAJOR TECHNICAL EQUIPMENT

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Abstract. *In view of the complexity, integration, intelligence, man-machine coordination and key determinants regarding the safe operation of major technical equipment, these factors will bring enormous challenges to personnel capacity requirements. To solve this problem, we take a safety personnel competency model as the starting point and safe production as the goal. At the same time, on the basis of multidisciplinary principles of human factors for engineering and psychology and the collection of 84 competency projects, we collect data and combine exploratory factor analysis and confirmatory factor analysis to study the key dimensions and measurement indicators of an operator's competency in realizing equipment safety. We also construct a structural equation model to verify its scientificity. The results show that the competency model includes six dimensions and can be condensed into 26 measurement indicators. The conclusions can be used for safety prediction and risk assessment of equipment personnel and are conducive to enhancing the safe development of equipment.*
Keywords: Major technical equipment, Safe operation, Capability model, Factor analysis

1. **Introduction.** Safety is particularly important for the operation of major technical equipment. The Central Party Committee and the State Council explicitly instructed that safety is first and that prevention is the main way of accomplishing this goal. Due to the production intelligence, operation automation, precision of major technical equipment and suddenness of safety accidents, many equipment types are accompanied by physical and chemical reactions in the production process, which are prone to major safety accidents such as explosions, gas leakage, and fires. Therefore, major technical equipment is one of the most important areas for national safety management. At the same time, considering that the maintenance operation is characterized by complexity, accuracy, high load and knowledge, we know that the safe, competent behavior of operators is the key to ensuring the safe operation of major technical equipment. Therefore, to achieve the safe operation of major technical equipment, operators and maintenance personnel must work together not only to ensure that maintenance personnel approach the maintenance work carefully but also to ensure that operators focus on the safe operation of major technical equipment.

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To define the safety production capacity of the staff, this paper is based on the competency model proposed by Mcclelland [1], considering that the competency model will provide decision-making basis for selecting suitable staff for different industries [2], to put forward an operational safety capability model for staff to ensure the safe operation of major technical equipment. In view of the important role of a competency model in the safe operation of major production equipment, it is necessary to construct the corresponding operational competency behavior theory model and an operational definition for the safe operation of major production equipment. We can reveal the role path and structural mechanism of the model by constructing its key dimensions and core indicators. Thus, the safety competency model proposed in this paper can be used to evaluate and predict the safety behaviors of major technical equipment operators. At the same time, the model can provide us with the criteria for personnel selection and with new perspectives and new ideas to solve the problems regarding the safe operation of major equipment. The model is also conducive to enriching and developing accident causation theory.

In this paper, we use major production equipment operators as our research objects. Based on brainstorming and expert group discussion methods, we develop items for the psychological and behavioral competence of the operators and maintenance personnel in the safe operation of major production equipment. Then, based on the questionnaire survey, we delete the indicators through the Delphi method and use exploratory factor analysis to traverse the factors and indicators. We condense the indicators into 30 operable indicators in practice. Next, we build a structural equation model to verify its scientificity. Finally, a hierarchical competency model with reliability, validity, scientificity and effectiveness for the safe operation of major equipment is built. This method enriches and develops safety management theory and capabilities. In theory, the dimensions and measures for the new competency model are presented. In practice, the model provides the theoretical basis, decision-making basis and logical starting point for the development, evaluation and allocation of human resources of major equipment. At the same time, it provides new perspectives and ideas for solving the difficult operation and safety problems of major technical equipment. The model also expands on new approaches for the selection of major technical equipment personnel, which is conducive to promoting and deepening the safe development of major equipment.

2. **Literature Review.**

2.1. **Safety-related behavioral research review.**

The definition of safety is the logical starting point for the study of safe and competent behavior, a lack of which usually results in 75-90% of accidents. Safety generally means that there are no accidents or losses, no adverse events and no consequences, and low levels of acceptable risks [3]. In 2003, Hofmann et al. proposed the concept of safe citizenship actions, which refers to self-issued action to ensure the safety of other members of the team and the safety of the entire project. Representative dimensions in the area of safe citizenship include the following examples. Hofmann et al. [4] argued that safe citizenship consists mainly of six subdimensions: assisting, managing, making changes, making claims, citizenship, and reporting, which have a positive effect on improving the level of safety through empirical research. Safety compliance is a typical example of safety behavior and the single most important activity for individuals in maintaining workplace safety [5]. This term mainly refers to compliance with the safety laws, procedures, their associated regulations and other requirements, adherence to safety standards and work procedures, compliance with safety regulations, and working in a safe manner. Safety compliance is a better predictor of the reduction in accident rates and even death [6], which has a positive effect on safety performance and can reduce production accidents and personal injury [5]. Accordingly, we can obtain two conclusions: the first is that safe citizen behavior is one of the key dimensions to ensure the safe operation of major technical equipment, and the second is that safety compliance behavior is one of the key dimensions for ensuring the safe operation of major technical equipment.

2.2. **Competency research.** The competency model takes the prediction of high performance as the starting point. The model brings together a set of psychological and behavioral features with high efficiency goals. The elements in the collection are usually unique and individual characteristics that can discriminate between outstanding performers and common performers, such as knowledge, skills, abilities, qualities, motivations and values used in the job [7]. However, accidents are not randomly distributed to everyone. Some people have a higher probability of accidents than others. People who have more accidents tend to be more prone to accidents than people who have fewer incidents, which is caused by different psychological characteristics. On this basis, a human error model is developed, which mainly studies human perception and stimulation due to dangerous events, understanding, recognition and response to events. The core point of view of the human error model is that people are the main factor leading to accidents. In many cases, the operation system structure, or parts of major technical equipment, are damaged due to insufficient machine or technical knowledge of the operators or maintenance personnel [8]. Thus, knowledge of the correct equipment operation, maintenance and repair is one of the key dimensions to ensure the safe operation of major technical equipment.

Human body performance mainly refers to the limits of human physical ability, including human perception, feeling, reaction speed, physical strength, and biological rhythms. All of these have a great impact on safe operation [9]. Crowl [10] believed that the factors leading to unsafe behavior are memory loss, distractions and fatigue. Equipment operation accidents are usually related to unsafe human behavior [11]. These accidents are closely related to factors of the human body, the most important of which is the fatigue factor. Fatigue refers to the phenomenon in which a decrease in working ability is caused by a series of physical and psychological changes due to continuous energy consumption during the operation. In conclusion, body performance is one of the key dimensions to ensure the safe operation of major technical equipment.

Risk management includes aspects such as risk perception, analysis, evaluation and processing. Risk means that an uncertain activity can have serious consequences and a direct impact on safety. Risk perception, identification and analysis, assessment, and even treatment have a crucial impact on the occurrence of unsafe behavior [12]. Risk perception is the personal subjective judgment of risk [13]. Because risk perception is subjective, when people perceive risk, they may take different approaches to determine the risk, which involves rational behaviors such as risk analysis, judgment and understanding [14]. Thus, risk management capability is one of the key dimensions to ensure the safe operation of major technical equipment.

Human-machine complementarity is the combination of the equipment and the workers' skills in the production process. Equipment and people are interdependent and ideally can complement each other. In the process of production, and operation of major technical equipment, the same device must produce personalized products that meet different customers' needs. The operator must ensure that the production equipment can be switched between different uses according to market demand. Therefore, within the background of digitization, the operation and maintenance personnel must carry out safety, debugging, trial operation and maintenance of the digital control systems according to the production demands to ensure the safe operation of major technical equipment. Based on this aspect, a sixth hypothesis is proposed: the digitization capability is one of the key dimensions to guarantee the safe operation of major technical equipment.

3. Research Methods and Data Analysis.

3.1. Initial questionnaire formation and research description. In this study, we selected operation and maintenance personnel as the research objects in the safe operation of major technical equipment. Through a theoretical literature review, job description analysis, web recruitment conditions analysis, brainstorming and other ways, we adopted the idea of "union" and obtained 86 initial items of competency behavior. Accordingly, the deputy factory director, first-line job manager, first-line workers, and experts and scholars in charge of safety management were invited as experts. Through the Delphi method and after four rounds of repetition, the items with semantic repetition or nonpractical or ambiguous meanings were deleted. Through this process, 84 indicators converged to 26. Finally, we compiled a questionnaire.

3.2. Research sample statistical characteristics analysis. Formal questionnaires are conducted in enterprises that produce major technical equipment in the country. The companies mainly investigated are the Anshan Iron and Steel Group's hot rolling mill and chemical industry division, Bengang Coking Plant, Shenfei Group and other enterprises. Paper versions of the questionnaires were distributed through production team meetings, Huajin Group senior leadership training courses, and party member learning sessions. Each unit issued 160 questionnaires, and a total of 800 questionnaires were issued; 618 completed questionnaires were returned, with a questionnaire recovery rate of 77%. To ensure the diversity of the sample, sample statistics were analyzed as follows: age, gender, highest academic qualification, major, professional title, work experience, position and department distribution.

3.3. Initial questionnaire exploratory factor analysis. Because this study is at the initial stage of development, there are no clear dimensions or key measurement indicators to be used as a basis. Therefore, an exploratory factor analysis method is used to divide the dimensions and key indexes of a competency behavior model for the safe operation of major technical equipment. Using the method, 320 points were randomly selected for exploratory factor analysis; 13 questionnaires were missing data and were not used. Cronbach's alpha reliability coefficient for the questionnaire is 0.961, indicating that the questionnaire's reliability is very good. In terms of questionnaire validity, the qualitative analysis of expert opinions showed that the questionnaire has good content validity. The construct validity of the scale was confirmed by factor analysis. KMO and Bartlett's test results proved that the scale was suitable for factor analysis, as shown in Table 1.

TABLE 1. KMO and Bartlett's test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy		.931
Bartlett's Test of Sphericity	Approx. Chi-Square	7.713E3
	df	325
	Sig.	.000

In terms of commonality, the principal component analysis was used. The variances of the common factors are as follows: body and mind, 0.698; reaction speed, 0.815; fatigue resistance, 0.757; practical ability, 0.743; different knowledge fusion, 0.691; role adaptation, 0.808; good communication, 0.785; altruism, 0.812; risk awareness, 0.811; risk prediction, 0.844; risk identification, 0.863; risk assessment, 0.799; risk management, 0.754; control system installation, 0.849; control system debugging, 0.907; control system operation and maintenance, 0.85; control system principle, 0.77; mechanical equipment operation inspection knowledge, 0.885; electrical equipment operation inspection knowledge, 0.91; control system operation inspection knowledge, 0.90; equipment fault diagnosis knowledge, 0.83;

obedience to discipline, 0.733; proactive investigation of potential risks, 0.691; compliance with working procedure flow, 0.70; and strict implementation of order, 0.777. The common-factor variance of all the subjects is above 0.65, which shows that the common factor explains most of the variation of the observed variables and that the selected index is better relative to the common factor, making it suitable for factor analysis.

Based on the Kaiser criterion, we use principal component analysis to extract six factors whose eigenvalues are greater than one. The cumulative variance contribution rate of the six factors is calculated, and the results are over 80%. In this study, the 6 factors are selected and extracted by principal component analysis. The orthogonal rotation method is used to obtain the factor loading after rotation, as shown in Table 2. Based on the previous analysis, we obtain the competency model to ensure the safe operation of major technical equipment.

Table 2. Rotation factor analysis result

Factors	Risk management capability	Equipment inspection knowledge	Security citizenship behavior	Digital capabilities	Body performance	Safety compliance
Physical and mental health	.291	.176	.198	.162	**.695**	.183
Reaction speed	.177	.153	.232	.212	**.785**	.215
Fatigue resistance	.309	.093	.313	.194	**.697**	.175
Hands-on ability	.159	.178	.259	.188	**.754**	.119
Multidomain fusion	.225	.343	**.671**	.075	.244	.085
Character adaptation	.236	.184	**.736**	.265	.278	.171
Good at communicating	.237	.210	**.724**	.291	.213	.176
Build trust	.279	.133	**.772**	.164	.236	.206
Altruistic behavior	.330	.080	**.727**	.233	.234	.244
Risk awareness	**.799**	.102	.255	.146	.186	.203
Risk forecast	**.814**	.147	.227	.147	.239	.173
Risk identification	**.835**	.085	.210	.179	.197	.208
Risk assessment	**.799**	.097	.226	.228	.168	.142
Risk management	**.782**	.228	.171	.112	.139	.173
Digital systems installation	.192	.254	.225	**.775**	.251	.180
Digital systems debug	.165	.263	.231	**.824**	.214	.181
Digital systems operation and maintenance	.192	.274	.169	**.801**	.180	.190
Digital systems support	.243	.270	.208	**.749**	.142	.127
Mechanical inspection knowledge	.133	**.846**	.190	.212	.191	.186
Electrical inspection knowledge	.121	**.870**	.186	.262	.110	.172
Digital systems inspection	.112	**.854**	.194	.287	.073	.189
Troubleshooting knowledge	.219	**.790**	.121	.214	.219	.239
Observe discipline	.337	.125	.267	.194	.103	**.696**
Check the hidden dangers	.239	.307	.112	.101	.154	**.702**
Follow the procedure	.107	.236	.257	.136	.228	**.705**
Execute the command	.192	.142	.093	.197	.164	**.804**

3.4. **Safe operation of major equipment and a competency structure equation model.** To verify the scientific veracity of the theoretical model constructed in Figure 1, a structural equation model [15] was constructed. Among the observed variables (endogenous variables), 26 are shown in Figure 1. All variables observed were scored using a Likert scale. Nonobservational variables (exogenous variables) include six factor variables and error terms. On this basis, the structural equation model constructed was solved by AMOS software, which obtained the path coefficients of the endogenous and exogenous variables of the measurement model (as shown in Table 2). At the same time, in

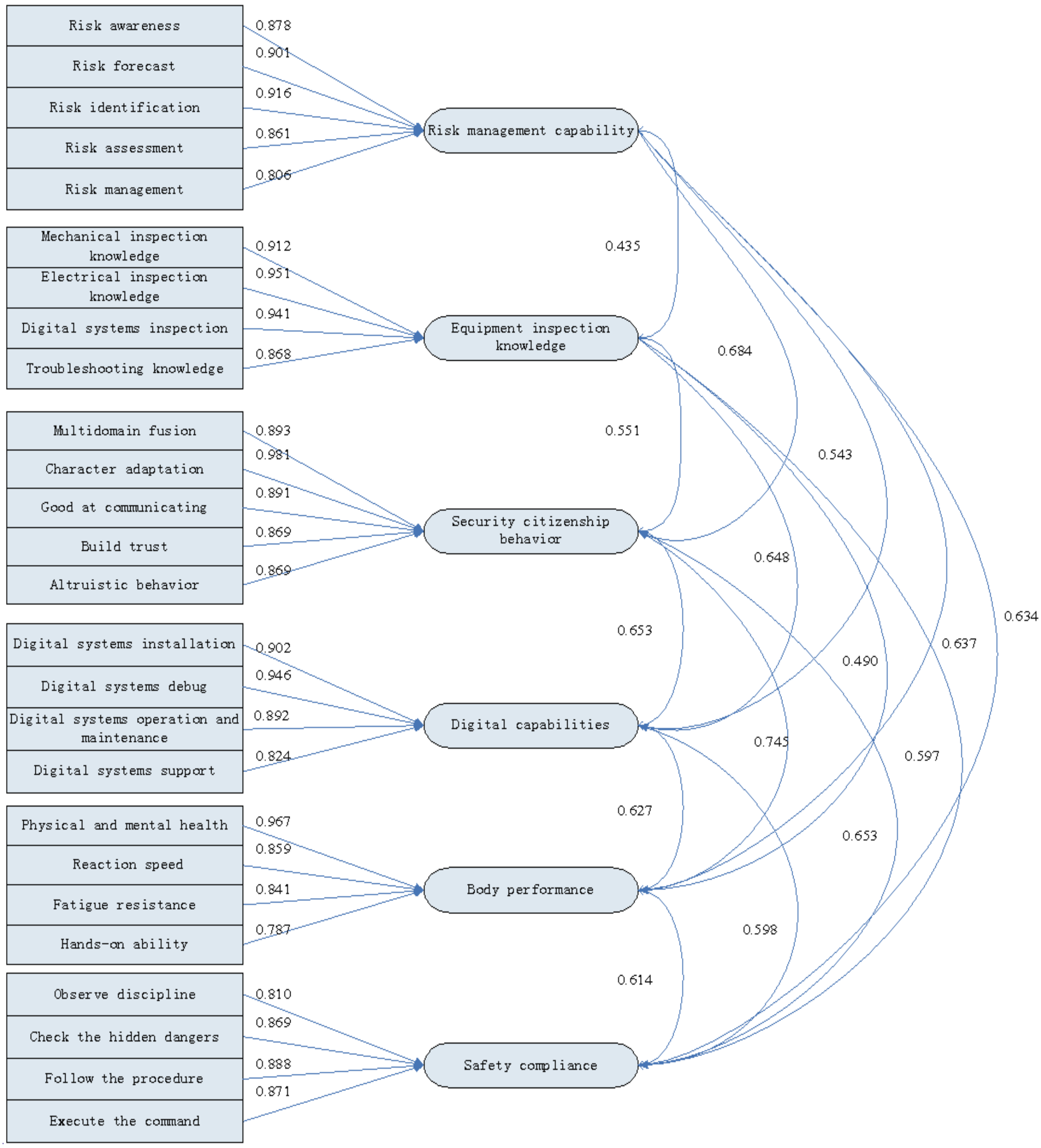

Figure 1. Correlation coefficients between factors

order to obtain a structural model of competency behavior to ensure the safe operation of major technical equipment, the correlation coefficient between the latent variables was obtained by solving the structural equation model. The path coefficients of endogenous and exogenous variables were obtained, as shown in Table 3.

In terms of the fit of the theoretical model and the actual statistical data, the CMIN/DF (Chi square value/degree of freedom) value was 2.996. The CFI (comparison fit index) value was 0.926, the IFI (incremental fit index) value was 0.927, the GFI (goodness of fit index) value was 0.909 and the RMSEA (root mean square error of approximation) value was 0.080. All of these data points meet the condition(s) of a good model fit. Therefore, the theoretical model has been verified, and it can be considered that the model has a good fit. From this, the correlation coefficients between various factors in the competency model can be derived, as shown in Figure 1.

Table 3. Correlation coefficients of latent variables in structural equation models

			Correlation coefficient
Safety compliance	⟷	Safe citizenship behavior	.653
Safety compliance	⟷	Risk management capabilities	.634
Safety compliance	⟷	Digital capabilities	.598
Safety compliance	⟷	Inspection knowledge	.597
Body quality	⟷	Safety compliance	.614
Safe citizenship behavior	⟷	Risk management capabilities	.684
Safe citizenship behavior	⟷	Digital capabilities	.653
Safe citizenship behavior	⟷	Inspection knowledge	.551
Body quality	⟷	Safe citizenship behavior	.745
Risk management capabilities	⟷	Digital capabilities	.543
Risk management capabilities	⟷	Inspection knowledge	.435
Body quality	⟷	Risk management capabilities	.637
Inspection knowledge	⟷	Digital capabilities	.648
Body quality	⟷	Digital capabilities	.627
Body quality	⟷	Inspection knowledge	.490

3.5. **Data analysis and discussion.** The parameters of all structural equation models were checked. The key dimensions and the measured indicators were compared with the calibration standard, which proved that the structural equation model is scientific. The path analysis results show that the measurement indexes can measure and represent the information, as the normalized path coefficients are all greater than 0.7. The correlation coefficient of the latent variables of the structural equation shows that there is correlation between each dimension and that the structural model of each latent variable is proved. The final results show that the competency model consists of six dimensions, which can be classified into 26 measurement indicators. This conclusion can be used for equipment personnel's safety prediction and risk assessment, which will help enhance the development of equipment safety. Therefore, it proves the feasibility and effectiveness of the competency model based on the six conclusions mentioned above. At the same time, it proves that the six conclusions drawn from the previous literature are correct and practical.

4. **Research Conclusions.** Taking account of the importance of the safe operation of major technical equipment, this study has carried out analytical work based on the characteristic features of operator competency. By combining exploratory factor analysis with confirmatory factor analysis, we have constructed a key scale and measurement index of staff competency to ensure the safe operation of major technical equipment. At the same time, the theory of safety management for major technical equipment is extended, and we provide a decision-making basis and theoretical support for safety human resource management of major technical equipment. Based on this paper, it is necessary to realize the importance of intelligent, automated and integrated production operation regarding the use of major technical equipment. This study not only enhances the importance of operation and maintenance to ensure safe use but also poses new challenges to competency training for maintenance and operation staff. This competency training ensures both the correct equipment operation by the staff and the professionalism of the maintenance staff. Therefore, the follow-up study will be a more in-depth investigation of human-based safety issues in major technical equipment production.

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REFERENCES

[1] D. C. Mcclelland, Testing for competence than for intelligence, *American Psychologist*, vol.28, 1973.
[2] X. Zhou, B. Jing and L. Ou, Empirical study on competency model of innovative talents, *Chinese Journal of Management*, vol.9, no.7, 2012.
[3] F. A. Manuele, Acceptable risk, in *On the Practice of Safety*, 3rd Edition, John Wiley & Sons, Inc., 2005.
[4] S. Hofmann, C. de Rham, G. Dvali et al., Cascading gravity: Extending the Dvali-Gabadadze-Porrati model to higher dimension, *Physical Review Letters*, vol.100, no.25, 2008.
[5] N. J. Bell, C. J. Schoenrock and K. K. O'Neal, Self-monitoring and the propensity for risk, *European Journal of Personality*, vol.14, no.2, pp.107-119, 2010.
[6] L. M. Goldenhar, L. J. Williams and N. G. Swanson, Modelling relationships between job stressors and injury and near-miss outcomes for construction labourers, *Work & Stress*, vol.17, no.3, pp.218-240, 2003.
[7] J. Sandberg, Understanding human competence at work: An interpretative approach, *Academy of Management Journal*, vol.43, no.1, pp.9-25, 2000.
[8] Z. Fan, Analysis of the causes of drilling electrical equipment damage and maintenance methods, *Chemical Industry Management*, vol.26, 2016.
[9] W. Karwowski, A review of human factors challenges of complex adaptive systems discovering and understanding chaos in human performance, *Human Factors: The Journal of the Human Factors and Ergonomics Society*, vol.54, no.6, pp.983-995, 2012.
[10] D. A. Crowl, *Human Factors Methods for Improving Performance in the Process Industries*, John Wiley & Sons, 2007.
[11] A. Cavalleri and F. Gobba, Identification of occupations with greater risk of accidents and micro-accidents, *Giornale Italiano Di Medicina Del Lavoro*, vol.11, nos.1-2, p.39, 1989.
[12] E. U. Weber, A. R. Blais and N. E. Betz, A domain-specific risk-attitude scale: Measuring risk perceptions and risk behaviors, *Journal of Behavioral Decision Making*, vol.15, no.4, pp.263-290, 2002.
[13] T. Aven and O. Renn, The role of quantitative risk assessments for characterizing risk and uncertainty and delineating appropriate risk management options, with special emphasis on terrorism risk, *Risk Analysis*, vol.29, no.4, pp.587-600, 2010.
[14] V. Denes-Raj and S. Epstein, Conflict between intuitive and rational processing: When people behave against their better judgment, *J. Pers. Soc. Psychol.*, vol.66, no.5, pp.819-829, 1994.
[15] S. Lin and Y. Jiang, Structural equation model theory and its application in management research, *Science and Technology Management*, vol.2, pp.38-41, 2006.