Key Risk Analysis of Fall from Height Accidents in Engineering Construction Based on SEM

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***Abstract*—There are five major injurious accidents in China's construction industry, namely, falling from height, collapse, object strike, electric shock, and mechanical injury, among which falling from height is the the most common with great harm. On the basis of previous relevant literature and safety technical regulations, this paper firstly identified the risk factors for each of the five most common height fallings. Besides, according to the accident cause theory, 18 factors leading to height falling accidents were determined and screened out from four aspects of personnel, external objects, management and environment. Moreover, questionnaires were distributed to 350 front-line workers with 298 valid questionnaires collected. After reliability and validity tests of SPSS, confirmatory factor analysis (CFA) was conducted using structural equation model (SEM) to compare the influence of risk factors. The results showed that workers' unsafe behaviors are the most likely to lead to height falling accidents, followed by the influence of external objects, management factors and environmental effects. Besides, effective protective equipment, weather changes during construction, safety education and training are worth special attention. This paper aims to enrich the literature research on the cause factors of height falling, and tends to provide some constructive suggestions for construction site safety management.**

***Index Terms*—structural equation modeling (SEM); falling from height; confirmatory factor analysis (CFA); risk management; SPSS**

I. INTRODUCTION

Fard. MM studied 125 construction safety accidents in the United States in 2015 and found that falling from height accidents were the most common [1]. In 2019, it was reported that falling from height accidents, as prevalent accidents, accounted for 53.69% of the country's total number of safety accidents [2]. Therefore, it is essential to conduct a scientific and detailed analysis of the causes of falling from height accidents, identify the most critical causes and prevent them effectively.

Safety experts at NIOSH (National Institute for Occupational Safety and Health) have designed and developed a falling protection procedure for operators which can guarantee the safety of high-altitude operations [3]. Deng Hang used the accident diagram method to analyze ten risk factors and proposed relevant preventive measures from the aspects of technology, management, and others [4]. Shi established a hazard evaluation index system with four major categories and 23 subcategories, and evaluated the risk factors of work at a height using the FAHP (Fuzzy Analytical Hierarchy Process) model [6]. Qiu utilized ISM (Interpretative Structural Modelling Method) and concluded that administrative supervision and illegal contracting were the deep causes of accidents [7]. Xia combined BIM (Building Information Modeling Building Model Informatization), cloud computing, and RFID (Radio Frequency Identification) to construct a falling from height safety warning system for construction workers [9]. These studies have used different models to find out the influencing factors from various aspects and obtained their conclusions, but most of them merely stayed on the application of models. So full and detailed conclusions have not yet been drawn. Besides, most of them analyzed the causes directly from four aspects of human, object, management, and environment, and no scholars have studied the causal factors of each part from the point of falling site.

Given the current status of research on falling from height accidents, the author intended to determine the risk factors of each falling site and related cases from five common falling sites through literature reading and typical accident analysis, and then determine the critical causal factors from four significant aspects of risk causation theory, namely, human, object, management, and environment. After the validity and reliability tests of the data, the Structural Equation Model (SEM) was used to identify the key risks and analyze the correlation among the risk factors. Finally, relevant preventive measures were put forward in order to provide reference for the risk management of falling accident from height in construction in the future.

II. RISK FACTOR IDENTIFICATION

Referring to the relevant literature [9, 11-12], the six significant sites, as shown in Figure 1, are often subject to falling from height accidents. They are mainly concentrated in the parts such as adjacent cavities, vertical transportation facilities, scaffolds, and mechanical equipment. It is intended to start from the elements where accidents often occur and determine the specific causes of falling in different parts to provide some basis for the subsequent work.

According to the relevant literature, scholars usually analyzed the causal factors of safety accidents from the aspects of human, object, environment, and management. And the falling from height accidents studied in this paper are often caused by these four aspects. To find out the factors leading to the falling from height accidents in a complete way, this paper analyzed the common falling parts and related accident cases from the falling from height accidents to get their causes, and the specific risk factors for each

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falling site are shown in Table 1.

After analyzing the risk factors of each falling site separately, it can be found that some elements overlap, so the same influencing factors were eliminated. The most critical ones can be sorted into four significant aspects: human, object, environment, and management, and the risk factors affecting the falling from height can be obtained as shown in Figure 2.

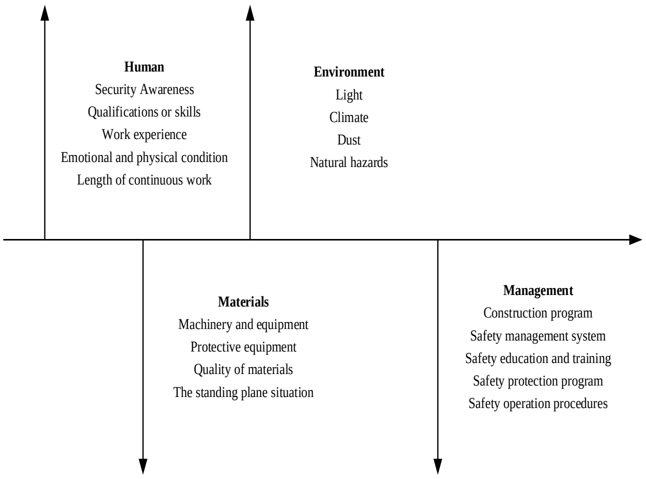

Fig. 2. Risk factors for fall from height

III. QUESTIONNAIRE AND ANALYSIS RISK FACTOR IDENTIFICATION

The analysis was carried out using a five-point Likert scale, with higher scores indicating more significant influence. The main content included: 1) Information about the respondents includes age, education, nature of the workplace, work experience in construction work etc; 2) The respondents' scores on the risk level of each safety risk are in Figure 2; 3) Information about the respondents’ workplace and other feedback.

The main target population of this study was construction site workers, and it finally contacted 350 respondents. The questionnaire survey took three months from October 15, 2020 to January 15, 2021. A total of 350 paper and electronic questionnaires were distributed, and 298 questionnaires were returned, with a return rate of 85%, of which 30 questionnaires with apparently inattentive responses were excluded (the answers to each question were chosen precisely or almost the same), yielding 268 valid questionnaires. The characteristics of the participants are shown in Table 2 below.

The questionnaire reliability test was performed using SPSS 26.0 software, and the Cronbach alpha coefficient was 0.874, greater than 0.7, indicating that the test was reliable. It is common to use the CR coefficient with the AVE coefficient and Bartlett's sphere test to determine whether the data can be suitable for factor analysis. Meanwhile, the CR coefficient and AVE coefficient are required to be directly calculated by SPSS software, which should be calculated by standard conformity instead of SPSS software. The component reliability CR value needs to be higher than 0.8, and the AVE value needs to be higher than 0.5. The analysis results in Table 3 show that all indicators are highly correlated with the questionnaire data and are suitable for factor analysis, manifesting that the questionnaire meets the validity criteria.

IV. STRUCTURAL EQUATION MODELING AND ANALYSIS

As a statistical method, structural equation modeling assists to analyze the relationship between variables based on the covariance matrix of the variables [13] and serves as an important tool for multivariate data analysis. SEM is essentially a validation type of comprehensive validation analysis, for example, in many indicator systems framed by psychology, education, and sociology, the individual indicators cannot be measured intuitively and precisely. These qualitative indicators are called latent variables, such as personnel intelligence, work motivation, and social environment influence. Observable indicators are used to measure these variables, which can estimate predictive models of latent variables, complex independent variables, or dependent variables through the relationships between the factors. Traditional linear regression analysis allows for measurement error in the dependent variable, provided that the independent variable is error-free. Structural equation models can be sorted into measurement models and structural models. Measurement models refer to the relationship between indicators and latent variables [14], and structural models refer to the relationship between latent variables after normalization correction.

The independent and dependent variables can be measured by the observed variables, and their correlation structure can be represented by the measurement matrix. The independent and dependent variables can be represented by Equation 1 and Equation 2.

$$X = \Gamma_X \gamma + \varepsilon \tag{1}$$

$$Y = \Gamma_Y \delta + \zeta \tag{2}$$

In the structural model, the relationship between the independent and dependent variables is shown in Equation 3.

$$\eta = \alpha\gamma + \beta\delta + \theta \tag{3}$$

In SEM construction diagrams, the latent variables are usually represented by ellipses, which are unpredictable. The measured variable can be measured directly, and they are usually represented by rectangles [15].

The SEM modeling was used, and the above key risk factors were further validated and refined. Combined with the existing studies [16-18], eight relevant indicators were selected to test the fitness degree of the model. By reviewing relevant literature, it can be known that scholars at home and abroad have established a set of acceptable ranges [16-19]. This paper sets the acceptable ranges of each index according to the standards of existing literatures. Values in Table 4 are the fitness indexes and acceptable ranges.

The four aspects of people-object-environment-management were modeled respectively, and the first-order modeling of the first three factors have a good fitting effect, while the fitness of the management factor is not satisfactory, and the specific fitting results are as follows:

Among the first-order modeling of the factors influencing high altitude falling, the management factor χ^2/df>3, RMSEA>0, 1, failed to pass the indicator validation, and the model needs to be revised. According to the MI value (Modification Indices) to amend the model, the most significant MI value is R18. After deletion, the fit index of the model performs well, and the modified model is shown in Figure 3 below.

As shown above, the first-order model aptitude indicators are good. All of them reached a significant level of 0.05, indicating that the latent variables are highly correlated and may be affected by another common factor of higher order. The second-order model will be used for further analysis.

From the above, it can be seen that the sample data fit well in the first-order modeling, and the latent variables were highly correlated with each other. The existence of higher-order common potential factors should be considered. According to the questionnaire results and related factor

After the validation factor analysis and correction, the path coefficients of each indicator as shown in the above are obtained, and the average weighting method will be used to calculate the weights of each indicator to quantify the risk [20]. The steps are as follows:

Assume that the second-order path coefficients between the second-order latent variables and the four first-order latent variables are X_i(i =1, 2, …, 5).

The first-order path coefficients between each observed variable ($R_1 \sim R_{17}$) and the corresponding four first-order latent variables are assumed to be $X_{i,\ j}$ (j=1, 2, …, 13).

The contribution value (weight 1) of the four first-order latent variables to the second-order latent variables is assumed to be Q_i.

The contribution values (weight 2) of each observed variable (R1 to R17) to their corresponding first-order latent variables are considered to be $Q_{i,\ j}$.

The calculation formulas are as follows:

$$Q_i = \frac{X_i}{\sum_1^4 X_i} \tag{4}$$

$$Q_{i,\ j} = \frac{X_{i,\ j}}{\sum_{j=1}^{k} X_{i,\ j}} \text{(k= Observed variable serial number)} \tag{5}$$

$$Q_j = Q_i \times Q_{i,\ j} \tag{6}$$

In summary, the specific risk factor weights can be obtained as shown in Table 6.

V. CONCLUSION

This paper identifies the specific causes of high altitude falling in different heights or positions by reading relevant literature on falling from height and making statistical analysis of the accident report cases. The questionnaire on falls from height designed in this paper passed the reliability and validity tests and proved that the data obtained from this questionnaire can be used to analyze the key factors of falls from height. Using SEM, this study reveals the role of human, external, environmental, and management influences on the occurrence of falling from height and provides a qualitative and quantitative analysis of the causal factors of falling from height. The detailed findings are as follows:

1) The rank of risk factors leading to high fall accidents during construction is human factors > external factors > management factors > environmental factors. Safety managers on construction sites need to pay extra attention to these aspects, especially for human factors.

analysis results, the higher-order risk factors are named as key factors of high altitude falling. The second-order model is drawn, and the second-order model and fitting results are shown in Figure 4. The fitting results are as follows: χ^2/df = 2.642 < 3, GFI=0.888 > 0.8 , AGFI=0.851 > 0.8 , RMSEA=0.078 < 0.08, a good fitting effect; CFI=0.917 > 0.9 , IFI=0.918 > 0.9 , TLI=0.902 > 0.9, a good fitting effect. The t-value of each index was greater than 2.8, indicating that all of them reach the significant level of 0.01. Therefore, the second-order SEM is generally better.

2) Among the human factors, the risk factors most likely to lead to high fall accidents are workers' safety awareness, workers' quality or skills, workers' work experience, workers' emotional and physiological conditions, and workers' continuous working hours. Safety awareness will directly affect workers' judgment of the actual situation. Once workers do not pay enough attention to the safety problem, there will be misjudgment, which is more apt to cause accidents. Good physical and psychological conditions can effectively reduce the probability of accidents.

3) Among the external factors, the risk factors most likely to lead to high fall accidents are the lack of protective equipment, the condition of standing surfaces, and the quality of building materials and mechanical equipment. The absence of protective gear is considered the most influential of all risk factors. The manager should prepare protective equipment and check its effectiveness. Mechanical equipment and construction materials may fall in the lifting process, which may strike construction personnel, so it is necessary to check the quality of construction materials and equipment and ask the lifting driver to operate reasonably.

4) Among the environmental factors, the weight of risk factors leading to accidents is successively climate change, light, dust, and natural disasters. Contrary to expectations that environmental factors would play a significant role in accidents, the impact of environmental factors is not particularly significant, perhaps because construction companies in China today do not require workers to work in extreme weather. When the weather is terrible, construction workers are required to rest.

5) Among the management factors, lack of safety education and training are the most likely factors to cause accidents, which can be the same as the analysis result of human factors. Safety education and training can improve the safety awareness of construction workers, which will affect the judgment of construction workers. Safety management systems and safety protection schemes cannot be ignored, and timely emergency treatment can effectively alleviate the damage of accidents; The construction scheme is less of a consideration probably because the development of China's construction industry has been relatively perfect, and the construction technology has been fairly complete.

6) This paper has tried to enrich the literature on the cause analysis of high fall accidents and provide a particular reference for preventing high fall accidents. Construction safety management personnel can start with the conclusions obtained in this paper, strengthen the management of related risk factors, and reduce the probability of falling accidents.

7) The analysis results obtained from this paper can provide a theoretical and practical basis for the safety management of construction units and the improvement of workers' behavior. The model developed in this paper can not only provide a reference and basis for the establishment of a safety risk grading and control system in the construction industry but can also be used as a framework for the investigation and analysis of high fall accidents and provide standards for basic accident analysis reports.

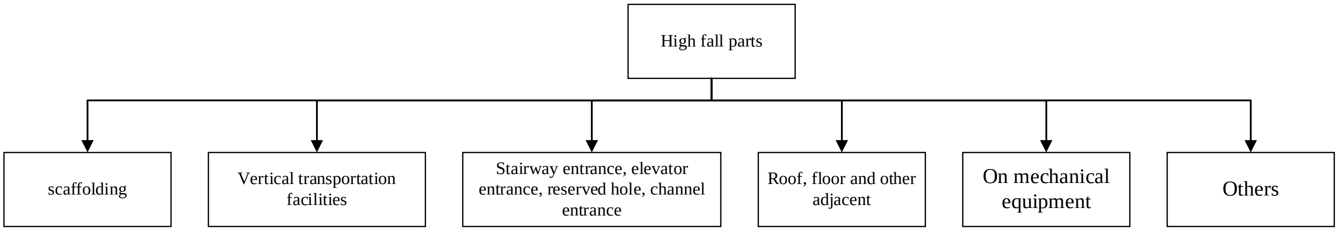

Fig. 1. Common parts of a fall from height accident

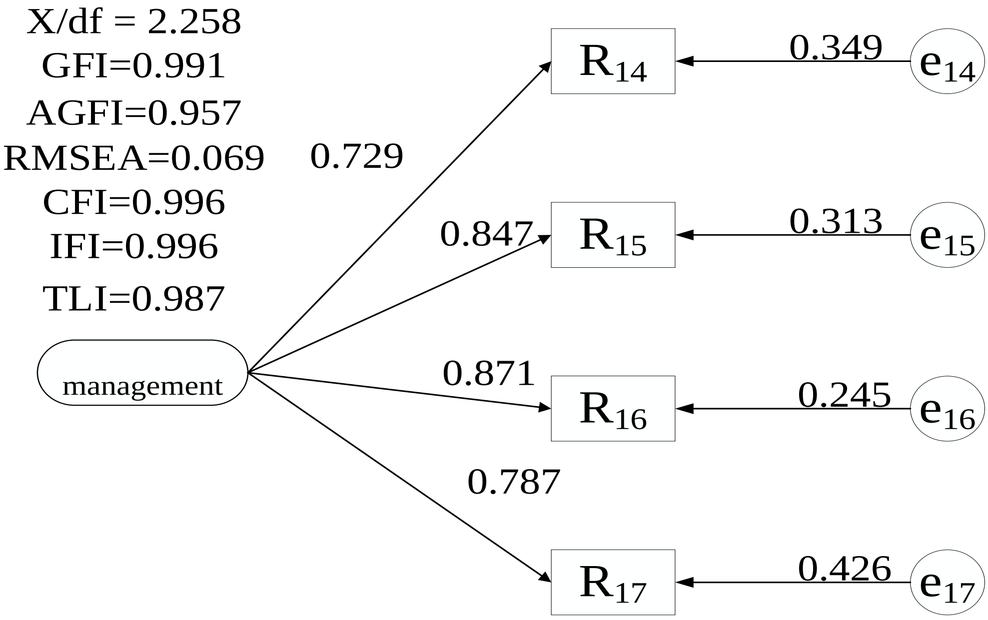

Fig. 3. Model for measuring the risk of falling from height due to management factors (after correction)

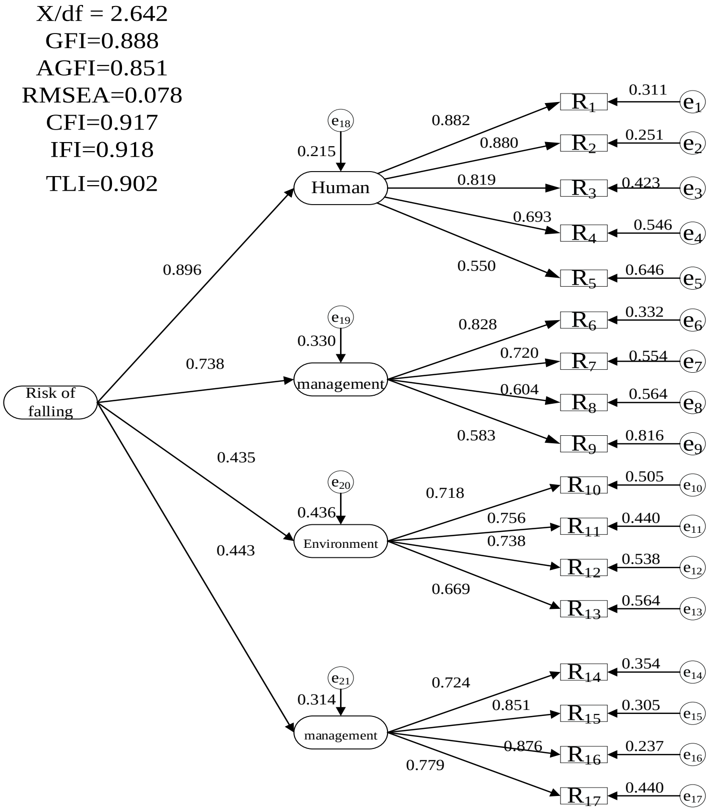

Fig. 4. Second-order model of fall risk from height

TABLE I
Risk factors for each fall location for fall from height accidents

Falling parts	Influence factors	Source
Scaffolding	a_1 Safety awareness; a_2 Protective measures; a_3 Quality or skills; a_4 Emotional-physiological situation; a_5 Continuous working hours; a_6 Scaffolding tying knot situation; a_7 Scaffolding surface; a_8 Insufficient light; a_9 Climatic abnormalities; a_{10} Safety management system; a_{11} Safety education and training; a_{12} Construction program a_{13} Safety protection program	Literature [2-11]
Vertical transportation facilities	b_1 Continuous working hours; b_2 Protective measures; b_3 Emotional-physiological condition; b_4 Equipment service life; b_5 Cargo accumulation; b_6 Continuous working hours of equipment; b_7 Safety education and training; b_8 Transportation program; b_9 Safety protection program; b_{10} Work experience	
Stairway entrance, Elevator entrance, Reserved hole, Channel entrance	c_1 Safety awareness; c_2 Protective measures; c_3 Quality or skills; c_4 Emotional-physiological situation; c_5 Continuous working hours; c_6 Insufficient light; c_7 Working experience; c_8 Ground conditions; c_9 Safety education and training; c_{10} Construction plan; c_{11} Safety protection plan; c_{12} Material accumulation	
The edge of roof or floor	d_1 Safety awareness; d_2 Protective measures; d_3 Quality or skills; d_4 Emotional-physiological situation; d_5 Continuous working hours; d_6 Insufficient light; d_7 Work experience; d_8 Ground condition; d_9 Material accumulation; d_{10} Safety education and training; d_{11} Construction plan; d_{12} Safety protection plan; d_{13} Safety management system; d_{14} Material accumulation; d_{15} Ground condition	
On mechanical equipment	e_1 Safety awareness; e_2 Protective measures; e_3 Quality or skills; e_4 Emotional-physiological situation; e_5 Continuous working hours; e_6 Machinery condition; e_7 Construction program; e_8 Safety protection program; e_9 Safety management system; e_{10} Safety education and training	

TABLE II
Characteristics of survey respondents

Age			Work Experience			Education		
Characteristic	Number	Proportion	Characteristic	Number	Proportion	Characteristic	Number	Proportion
20-25	95	32%	1-4 years	110	36.9%	High school students	53	17.8%
26-35	167	56%	5-8 years	111	37.2%	Specialized students	154	51.7%
36-45	21	7%	9-12 years	44	14.8%	Undergraduates	74	24.8%
46+	15	5%	13+ years	33	11.1%	Graduate Students	17	5.7%

TABLE III
Reliability and validity tests of the questionnaire

Latent variables	Observed variables	Standard load	Cronbach α	AVE （Mean extracted variance values）	CR （Combination reliability）
Human Factors	R_1 Security awareness	0.819	0.877	0.6363	0.8965
	R_2 Quality or skills	0.836			
	R_3 Work experience	0.819			
	R_4 Emotional and physical condition	0.764			
	R_5 Length of continuous work	0.659			
Material Factors	R_6 Protective equipment	0.663	0.786	0.5223	0.8128
	R_7 Standing surface condition	0.654			
	R_8 Material quality	0.796			
	R_9 Mechanical equipment	0.767			
Environmental	R_{10} Dust	0.724	0.811	0.6086	0.8611

factors					
	R_{11} Climate	0.830			
	R_{12} Light	0.807			
	R_{13} Natural disasters	0.755			
Management factors	R_{14} Construction plan	0.795	0.892	0.6831	0.915
	R_{15} Safety Management System	0.812			
	R_{16} Safety education and training	0.833			
	R_{17} Safety Protection Program	0.879			
	R_{18} Safety operation procedures	0.811			

TABLE IV
Selection of model adaptation indicators and acceptable range

Indicator	Acceptable range	Supporting literature
χ^2/df	≤3.00 Good fit	[16] [18]
GFI（Goodness-of-fit）	>0.80 Good fit	[16] [18]
AGFI（Adjusted Goodness-of-fit）	>0.80 Good fit	[16] [18]
IFI（Incremental Fit Index）	>0.90 Good fit	[16] [18]
TLI（Tucker-Lewis Index Tucker-Lewis）	>0.90 Good fit	[16] [18]
CFI（Comparative Fit Index）	>0.90 Good fit	[16] [18]
RMSEA（Root Mean Square Error Approximation）	<0.05 Good fit <0.08 Better fit <0.10 Fitting general	[17-19]
RMR（Standardized Root Mean Square Residual）	<0.05 Good fit <0.08 Better fit	[17-18]

TABLE V
First-order modeling results

Indicator	χ^2/df	GFI	AGFI	IFI	TLI	CFI	RMSEA	RMR
Human	0.183	0.999	0.996	1.006	1.011	1.000	0.000	0.007
Materials	2.230	0.992	0.959	0.992	0.975	0.992	0.068	0.024
Environment	1.207	0.995	0.977	0.999	0.996	0.999	0.028	0.016
Management	**8.593**	0.934	0.803	0.952	0.904	0.952	**0.169**	0.038

TABLE VI
Risk factor weights for fall from height safety accidents

Latent variables	Weight 1	Weight 1 ranking	Observed variables	Weight 2	Weight 2 ranking	Total weight	Total weight ranking
Human Factors	0.357	1	R_1	0.0823	1	0.0823	2
			R_2	0.0821	2	0.0822	3
			R_3	0.0764	3	0.0765	5
			R_4	0.0646	4	0.0647	7
			R_5	0.0513	5	0.0513	9
Material Factors	0.294	2	R_6	0.0889	1	0.0890	1
			R_7	0.0773	2	0.0774	4
			R_8	0.0649	3	0.0649	6
			R_9	0.0626	4	0.0627	8
Environmental factors	0.173	4	R_{10}	0.0432	3	0.0431	14
			R_{11}	0.0454	1	0.0454	12
			R_{12}	0.0444	2	0.0443	13
			R_{13}	0.0402	4	0.0402	16
Management factors	0.176	3	R_{14}	0.0395	4	0.0395	17
			R_{15}	0.0465	2	0.0464	11
			R_{16}	0.0478	1	0.0477	10
			R_{17}	0.0425	3	0.0424	15

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