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Identifying key risk factors in air traffic control by exploratory and confirmatory factor analysis

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SUMMARY

This study employs exploratory and confirmatory factor analysis to identify key risk factors in air traffic control (ATC) influencing aviation safety and to explore the correlational relationships among constructs from the perspectives of air traffic controllers. A total of 57 potential risk factors are first proposed based on the framework of SHEL, namely software, hardware, environment, and liveware, by referring to a review of the related literature and observing local issues in Taiwan. Interviews are then conducted with some 232 Taiwan air traffic controllers and supervisors. Exploratory factor analysis is first performed to determine the item-factor assignment and develop an initially proposed framework. Next, confirmatory factor analysis is performed to test the construct validity. The correlational relationships among constructs are further investigated. The results reveal that 26 of the 57 potential risk factors studied can be characterized as key risk factors. These factors are associated with five constructs – constitutional framework, human error, system interface, external communications, and controller capabilities and physical conditions. Based on the identified key factors and the tested correlational relationships among constructs, appropriate countermeasures are proposed for mitigating ATC risks. Copyright © 2010 John Wiley & Sons, Ltd.

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KEY WORDS: air traffic control; aviation safety; exploratory factor analysis; confirmatory factor analysis

1. INTRODUCTION

Air traffic control (ATC) provides essential information and instructions to pilots and allows them to maintain safe separation distances between aircrafts. Undoubtedly, ATC profoundly influences aviation safety. Without appropriate ATC assistance, aviation safety and operational efficiency would not be assured. From related investigation reports of aviation incidents, various ATC risks can be identified and classified into different dimensions, including human, institution, management, and so on. The identified risks and their combined effects have significantly impacted aviation safety and operational performance. Consequently, it is important to scrutinize the key risk factors of ATC and obtain in-depth insights into their mutual interrelations so as to propose appropriate countermeasures for alleviating the potential threats to aviation safety. Although ATC risks may not be the major contributory factors to aviation accidents in Taiwan, most aviation accidents are closely related to ATC risks. Furthermore, owing to the high workload and pressure, the average resignation rate of newly recruited air traffic controllers has soared to approximately 30% during the first year on the job in Taiwan recently; despite their salaries are up to 1.5 times greater than that of employees with comparable seniority working for other government departments. Certainly, such a high resignation

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rate negatively impacts organizational performance and thus endangers aviation safety. Also because of the shortage of staff in Taiwan, many controllers are frequently requested to work rotating shifts at different offshore ATC towers, adding more workload to them. Moreover, ATC agencies in Taiwan are affiliated to the Air Navigation and Weather Services (ANWS), which is then affiliated to the Civil Aeronautics Administration (CAA). CAA is then affiliated to the Ministry of Transportation and Communications (MOTC). Such a hierarchical organization makes the ATC agencies fourth-level affiliations of MOTC, meaning jobs in these agencies have rather low seniority. Many hard-working and high performing controllers thus have minimal opportunities for promotion. These problems may adversely affect ATC performance and even aviation safety, which need to be carefully and thoroughly examined.

Various studies have been undertaken on ATC risk analysis, focused on such aspects as human factor, system risk factor, organizational factor, and environmental factor. Human risk has been identified as the dominant aspect of risk in ATC, which comprises over 70% of aviation accidents [1]. Typical human risks include careless operation, negligence, poor judgment, low awareness and poor professional abilities in facing emergencies, failure to pay attention, failure to recognize conflict in communication, failure to obey standard operating procedures, errors in monitoring, timeliness, and coordination, communication errors in clearance composition, phraseology and delivery technique, reading/listening errors, and so on [2–6]. Additionally, dangerous situations in aviation frequently result from coordination or communication failures between air traffic controllers and other flight staff [7–10].

Some studies note that the interactions between human factor and other aspects of ATC also impact aviation safety, including liveware–hardware interaction (such as, man and machine) and liveware–liveware interaction (such as, controller and pilot). Naturally, the psychologic and physiologic conditions of air traffic controllers (such as, negligence of duty, failure to obey standard operating procedures, and inappropriate management) have also adversely impacted aviation safety [3,6,11].

Other studies indicate that improper organization management and deteriorating organization culture may lead to conflict or polarization between different organizational units or members and stress or negative impressions of controllers to their organization. Thus, overall operational performance and job satisfaction may be deteriorating, leading to careless mistakes made by controllers. Consequently, aviation safety and operating efficiency would directly suffer such adverse effects [3,7,12].

The system of ATC is also crucial for aviation safety. Man and machine play complementary roles in controlling air traffic. Many ATC systems worldwide have been gradually upgraded to some extent of automation in order to avoid any possible human errors and to mitigate the workload of controllers. Unfortunately, some types of automation have contrarily increased the degree of monitoring efforts required by human operators, resulting in even more human errors (Goettl, 1991; [13,14]). Additionally, the ATC system has also affected humans in various ways, including roles and functions, job satisfaction, health, and morale [8]. Therefore, the risks in ATC system should be considered not merely for its function and capability, but also for the causality between it and the other aspects of ATC, particularly the man–machine relationship. Some recent findings demonstrate that most human errors are resulted from improper design of ATC system, which even adversely affects controller psychologic condition, training failure, and shortages of qualified staff [2,15,16].

Operating environment is another major aspect of risk in ATC. Operational distractions also contribute to errors. Expected changes in the ATC environment are likely to affect the nature of controller tasks and possibly staffing level [17].

To summarize, ATC risk factors originate from a wide range of sources. Thus, to explore risks by focusing on any one aspect is inappropriate. To derive a comprehensive understanding, it requires a systematic and quantitative analysis, which is rarely found in field of ATC risks. Hence, this study attempts to identify the key risk factors of ATC and analyze their interrelations from the perspectives of controllers. The results can help in proposing more practical countermeasures for risk mitigation to enhance aviation safety and operational efficiency. In doing this, we first propose potential ATC-related risks based upon the SHEL framework, first proposed by Edwards [18]. Then exploratory factor analysis is employed to analyze the inter-relationship between items and to extract constructs for establishing a new framework, then tested by confirmatory factor analysis. Finally, correlational relationships between constructs are investigated.

The rest of this paper is organized as follows. Section 2 briefly introduces exploratory factor analysis, confirmatory factor analysis and questionnaire design. Section 3 then outlines the structure of the proposed framework and describes the results. Next, Section 4 tests the correlational relationships among constructs and discusses the implications of the results. Finally, concluding remarks and suggestions for future research are addressed.

2. METHODOLOGIES

Based on the perceptions of ATC-related staff, this study first employs exploratory factor analysis to propose an initial framework for ATC risk factor based on the SHEL framework. Following that confirmatory factor analysis is employed to test the validity of the proposed framework and identify the ATC key risk factors. Brief introductions to exploratory factor analysis and confirmatory factory analysis are given below. Additionally, a questionnaire is designed for surveying perceptions of ATC-related staff for each risk factor. The questionnaire and study population are also described below.

2.1. *Exploratory factor analysis*

Factor analysis examines the covariance structure of a set of variables and provides an explanation of the relationships among those variables in terms of a smaller number of unobserved latent variables called constructs. Factor analysis can be divided into two main types: exploratory and confirmatory. Exploratory factor analysis explores data to determine the number or nature of factors that account for the covariation between variables when the researcher does not possess sufficient a priori evidence to establish a hypothesis regarding the number of factors underlying the data. Exploratory factor analysis thus is generally considered a theory-generating procedure rather than a theory-testing procedure [19]. In contrast, confirmatory factor analysis is a theory-testing model. Consequently, this study first employs exploratory factor analysis to establish a new framework of ATC-related risks, then uses confirmatory factor analysis to test and fine-tune the proposed framework.

Essentially, exploratory factor analysis can assist researchers in assessing the nature of relationships among variables and establishing the construct validity of test scores. From a practical perspective, exploratory factor analysis offers a useful approach for proposing hypotheses for further research under experience and knowledge of researchers.

2.2. *Confirmatory factor analysis and structural equation modeling*

Since many latent risk factors of ATC cannot be measured directly, some surrogate indicators must be measured using appropriate techniques to represent the latent factors in the analysis of causal relations. The structural equation modeling (SEM) approach is one of the most appropriate techniques for identifying latent variables and analyzing the correlational relationship among them, since it combines the advantages of confirmatory factor analysis and path analysis (multiple regression), which can test the linear causal relationship among variables and assess the hypothetical model with both manifest and latent variables. SEM has been widely applied in various transportation fields, including travel behavior and demand (e.g., [20–29]), mode choice (e.g., [30–33]), service quality (e.g., [34–36]), and transport safety (e.g., [37,38]) during recent decades. The SEM approach possesses several technologic advantages over other statistical methods. For example, (1) SEM can test the significance of indicators and constructs simultaneously across models; (2) SEM enables the estimation of measurement errors in multiple regression equations and permits all relationships among residuals; and (3) SEM also allows simultaneous estimation of all direct and indirect effects.

In SEM, the latent factors are those variables that cannot be observed directly but can be estimated using representative indicators (measured variables). Confirmatory factor analysis is used to test the relationship between latent factors and measured variables. SEM comprises two main parts, structural model and measurement model. This study only adopts the measurement model technique, namely confirmatory factor analysis. Confirmatory factor analysis estimates the relationship between measured variances and latent variances, and allows a prior specification of the relationships between the constructs and their indicators and the hypothetic relationships to be tested against the data.

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Furthermore, confirmatory factory analysis is useful when multiple indicators must be used for construct measurement, and can estimate structural relations between variables [39–41].

As mentioned above, confirmatory factor analysis is a theory-testing method rather than a theory-generating method like exploratory factor analysis. Confirmatory factor analysis begins with a hypothesis and then tests the validity of that hypothesis. This model, or hypothesis, specifies which variables are correlated with which constructs and which constructs are inter-correlated. The hypothesis is based on a strong theoretical and/or empirical foundation [19].

Some commonly used goodness-of-fit indices, depicting how well a SEM (or CFA) model explains the "true" relationship among variables, are briefly elucidated below.

2.2.1. *Ratio of Chi-square to degrees of freedom*

The difference between the observed sample covariance matrix and the estimated covariance matrix is essential in assessing the goodness-of-fit of a SEM model. A Chi-square (χ^2) test provides a statistical test of this difference for a specified model. This test can be represented by the following equation:

$$\chi^2 = (N - 1)\,(\text{observed sample covariance matrix} - \text{estimated covariance matrix}) \qquad (1)$$

where, N denotes overall sample size.

In the case of the Chi-square statistic, a good fit is indicated by smaller values. Notably, the Chi-square value is highly sensitive to sample size. Consequently, another index of $\chi^2 = /df$ can also be used to assess the model, where df denotes the degrees of freedom.

2.2.2. *Goodness-of-fit index (GFI) and adjusted goodness-of-fit index (AGFI)*

The goodness-of-fit index (GFI) is a measure of the relative amount of variances and covariances jointly accounted for by the model [42]. GFI ranges from 0 to 1, with higher values indicating better fit. This index can be conceived as roughly analogous to R^2 in multiple regression. An adjusted goodness-of-fit index (AGFI) further considers differing degrees of model complexity. AGFI adjusts GFI using a ratio of the degrees of freedom used in the model to total degrees of freedom. AGFI values are typically lower than GFI values proportionally to model complexity.

2.2.3. *Normed fit index (NFI)*

The NFI is the ratio of the difference in the χ^2 values for the fitted model and a null model divided by the χ^2 value for the null model, a common baseline model which assumes that no correlations exist among the observed variables. The values of NFI range from 0 to 1 and a model with perfect fit would produce an NFI of 1.

2.2.4. *Comparative fix index (CFI)*

The CFI is an improved version of NFI, which is normed so that values range between 0 and 1, with higher values indicating better fit. CFI is one of the most widely used indices. CFI values of less than 0.90 are generally not associated with good model fit.

2.2.5. *Root mean square error of approximation (RMSEA)*

RMSEA attempts to correct for the tendency of the χ^2 test to reject models with large samples or a large number of observed variables. RMSEA represents how well a model fits a population, not just a sample used for estimation. Lower RMSEA values indicate better fit.

2.2.6. *Standardized root mean square residual (SRMR)*

A covariance term that cannot be explained by the model creates a residual. The root mean square residual (RMSR) is the square root of the mean of the squared residuals. In addition, the SRMR is a standardized value of RMSR and thus is more useful for making cross-model comparisons.

2.3. *Questionnaire design*

This study conducts a questionnaire survey of ATC-related staff to collect their opinions regarding the extent to which ATC risk factors influence aviation safety. In doing this, all potential risk factors must be systematically proposed. To facilitate risk factor recognition, this study refers to the research of Isaac and Ruitenberg [3], which used the SHEL framework, first proposed by Edwards [18], to classify ATC risks into four aspects: software, hardware, liveware, and environment. The software aspect includes risks related to ATC organization, regulations, and operating procedures of ATC as well as organizational management. The hardware aspect describes the facilities and equipment of ATC system and its interaction with controllers. Furthermore, the liveware aspect comprises human errors. Moreover, the environmental aspect describes external communications and external managerial factors. From review of the related literature, historical aviation incidents and interviews with ATC experts, this study proposes 57 potential risk factors under these four aspects. Where the software aspect is measured by 19 variables (V_1–V_{19}); the hardware aspect by 12 variables (V_{20}–V_{31}), the liveware aspect by 17 variables (V_{32}–V_{48}), and the environment aspect by nine variables (V_{49}–V_{57}), as depicted in Figure 1. For clarity, please refer to Appendix A, which details the operational definitions of manifest variables (risk factors).

Most questionnaire survey studies adopt a Likert five-point scale to capture respondent perceptions; however, this collection method might loose some insights of human recognition and fail to notify the different perceptions of various respondents even with same scale answered. To resolve this deficiency, this study employs fuzzy set theory for questionnaire design. Alongside a five-point Likert scale, five linguistic degrees (very high, high, medium, low, and very low) are used, with each degree being assumed to be an isosceles triangular membership function. All respondents are asked to indicate numerically an interval value ranging from 0 to 100 for each linguistic degree before answering risk items. The lower and upper bounds of the intervals, respectively, represent the left and right anchors of the fuzzy set, while their average indicates the cortex of the fuzzy set. This approach attempts to consider the possibility of different respondents having different perceptions of a single linguistic degree. The questionnaire thus comprises three parts: the first part surveys individual respondent perceptions of five fuzzy linguistic degrees: very low, low, medium, high, and very high by using a 100-point scale. The second part surveys the influence of each risk factor on aviation safety from the

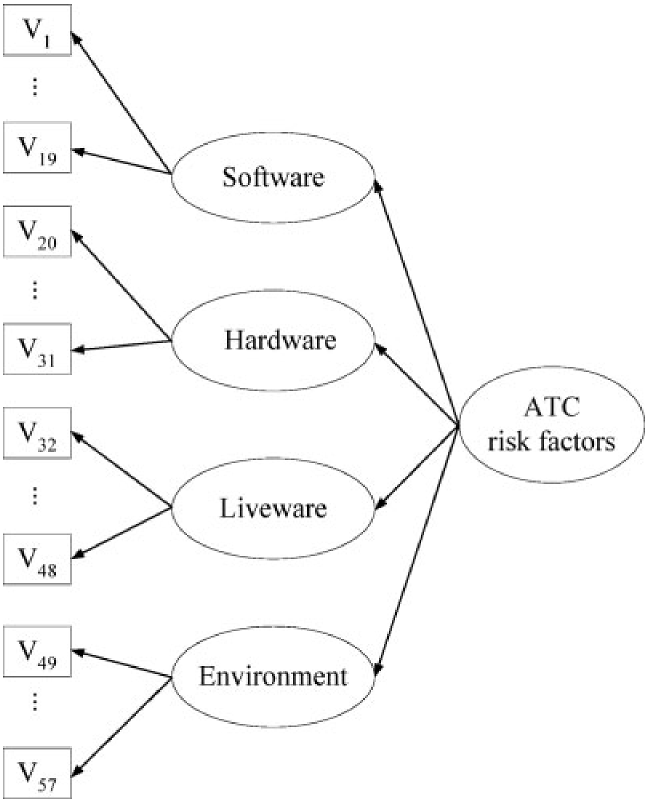

Figure 1. The initial framework of ATC risk factors.

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respondent perspectives using the fuzzy items, each of which possesses five linguistic degrees. The third part gathers respondent demographic information, including gender, education, age, work experience, affiliation, and title. Appendix B presents the questionnaire in details.

Additionally, to ensure the words and phrases used in the questionnaire complying with ATC phraseology, the questionnaire was carefully reviewed by a panel of experts, comprising two aviation professors and one trainer. Subsequently, the questionnaire was pilot tested *via* a series of on-site interviews ($n = 35$). Based on the pilot test data, a Cronbach's coefficient alpha (α) was calculated to identify items with low reliability. After that, three items with α values below 0.70 were further revised to avoid obscure words or phrases causing internal inconsistencies.

2.4. *Study population*

The study population comprises all the staff working for ATC authorities in Taiwan. The population is divided into two groups. Group 1 comprises the on-line air traffic controllers responsible for en-route, approach, and aerodrome control, respectively. Group 2 comprises supervisors, instructors, and senior administrative staff. Table 1 lists the numbers of various types of staff alongside the breakdown of the questionnaire respondents. Notably, the study population comprised 260 individuals, of which 178 (68.46%) were on-line controllers and 82 (31.54%) were their supervisors or other senior staff. This study attempted to distribute the questionnaire to all of the ATC-related staff. Except for 28 staff who refused to answer the questionnaire, a total of 232 questionnaires were successfully distributed. One hundred and ninety-eight of them were returned, of which 166 (71.55%) were valid, meaning the questionnaires were fully completed with no items left blank. Except for the en-route controllers, those who usually are the busiest ATC-related staffs, the rates of number of valid questionnaires to entire population for all other categories of staff exceed over 65%.

3. RESULTS

3.1. *Respondent demography*

Table 2 summarizes the demographic statistics of all respondents. Notably, the majority of respondents are male, aged 31–40 years old, holding a B.S. degree and with average work experience of 13.79 years. The respondents in Group 2 are more likely to be male, and have older age and longer work experience than those in Group 1. Notably, the difference in average work experience between Groups 1 and 2 is 11.9 years, implying a serious bottleneck in promotion channels for on-line ATC staff. This bottleneck may also explain the high resignation rate among Group 1.

Table 1. Study population and questionnaire surveyed.

Groups	Authorities/Titles	Number of ATC-related staff in Taiwan	Number of distributed questionnaires	Number of valid questionnaires
Group 1: On-line controllers	En-route Control	54	42	15
	Approach Control	88	81	58
	Aerodrome Control	36	33	24
Group 2: Supervisors	Chief, Vice Chief, Coordinators, and Chief Controllers	45	42	39
	Air Traffic Control Division	13	10	10
	Analysis section of Flight Standards Division	6	6	4
	Aviation Training Institute	6	6	6
	Air Traffic Services Management Office under Air Navigation and Weather Services	12	12	10
Total	—	260	232	166

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Table 2. Breakdown of respondents' demography.

Demography	Category	Group 1	Group 2	Total
Gender	Male	47 (48.45%)	48 (69.57%)	95 (57.23%)
	Female	50 (51.55%)	21 (30.43%)	71 (42.77%)
Age	20–30	8 (8.25%)	1 (1.45%)	9 (5.42%)
	31–40	77 (79.38%)	11 (15.94%)	88 (53.01%)
	41–50	11 (11.34%)	33 (47.83%)	44 (26.51%)
	51–60	1 (1.03%)	21 (30.43%)	22 (13.25%)
	Over 60	0 (0%)	3 (4.35%)	3 (1.81%)
Education	Senior high school	0 (0%)	2 (2.9%)	2 (1.20%)
	B.S. degree	92 (94.85%)	61 (88.41%)	153 (92.17%)
	Master or above	5 (5.15%)	6 (8.7%)	11 (6.63%)
Average work experiences (years)		8.84	20.74	13.79

3.2. Item analysis

This study uses item analysis and exploratory factor analysis to examine the improper items and extract principal components before developing the measurement model.

Item suitability and reliability is verified using the indicators of skewness, item-total correlation, factor loading, and reliability, as shown in Table 3. Where, skewness is used to indicate the distribution of an item. A positive skewness indicates the distribution is concentrated on the left, which is said to be right-skewed; while a negative skewness indicates the distribution is concentrated on the right, which is said to be left-skewed. Following Nunnally's [43] suggestion, items with absolute values of skewness approaching or exceeding 1, indicating a highly skewed distribution, are considered to be discarded. Item-total correlation measures the correlation coefficients between each of the items and the total score of all other items. A low item-total correaltion means the item is little correlated with the overall scale. Items with item-total correlations less than 0.3 are considered to be excluded [43]. Factor loading of an item is calculated based on single factor model, which can also be used to assess the dimensionality of the item. Items with factor loadings less than 0.3 are also considered to be discarded [43]. Cronbach's coefficient alpha is also calculated as an index of the internal consistency of the scale.

In terms of skewness, a total of eight items (V_6, V_9, V_{19}, V_{22}, V_{42}, V_{43}, V_{44}, and V_{52}) with absolute skewness approaching or exceeding 1 exhibits extreme skew distribution in respondent perceptions. In terms of item-total correlation coefficient and factor loading, a total of four items (V_9, V_{39}, V_{49}, and V_{52}) with values below 0.3 on either of these two indicators indicate the high heterogeneity of respondent perceptions. Anyhow, all items have high reliability, and the overall questionnaire reliability reaches 0.979. Accordingly, two items (V_9 and V_{52}) are deleted because of their high skewness and heterogeneity, leaving a total of 55 items for further analysis.

To further investigate whether the perspectives of controllers and supervisors are statistically different from each other, a *t*-test on the mean perspectives between these two groups is performed. Result shows that only two items (V_9, V_{52}) reach significance level of 0.05. This result also supports the above decision of excluding them from further analysis. The discrepancy in perspectives between these two groups seems obvious. Because these two items both survey the perceptions regarding the influences of obedience and compliance of subordinates to their supervisors. Usually, supervisors tend to acknowledge the influences, while controllers do not.

3.3. Exploratory factor analysis

Before performing the exploratory factor analysis, the Bartlett's test of sphericity and Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy are used to assess the suitability of the questionnaire. The results reveal that $\mathrm{KMO} = 0.939$ and Bartlet's test is significant at $\alpha = 0.01$ with a Chi-square of 8862.478, indicating the suitability of conducting exploratory factor analysis, according to Kaiser [44].

Exploratory factor analysis is conducted by using SAS software and the results are presented in Table 4. Notably, a total of six constructs are extracted with accumulative explanatory variance reaching 73.971%, while a total of 48 items are retained with factor loadings higher than 0.5. Each construct is named based on its constituent items with high coefficients. The first construct comprises

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Table 3. Results of item analysis.

Item	Skewness	Correlation coefficient	Factor loading	Reliability
V_1	−0.849	0.708	0.514	0.979
V_2	−0.523	0.599	0.385	0.979
V_3	−0.396	0.599	0.379	0.979
V_4	−0.681	0.761	0.599	0.979
V_5	−0.559	0.754	0.586	0.979
V_6	−1.055	0.613	0.408	0.979
V_7	−0.764	0.557	0.344	0.979
V_8	−0.804	0.749	0.573	0.979
V_9	−1.054	0.425	0.193	0.979
V_{10}	−0.769	0.743	0.562	0.979
V_{11}	−0.742	0.639	0.433	0.979
V_{12}	−0.648	0.710	0.532	0.979
V_{13}	−0.600	0.632	0.413	0.979
V_{14}	−0.855	0.705	0.504	0.979
V_{15}	−0.806	0.745	0.570	0.979
V_{16}	−0.783	0.684	0.493	0.979
V_{17}	−0.719	0.713	0.539	0.979
V_{18}	−0.808	0.782	0.644	0.979
V_{19}	−1.042	0.753	0.586	0.979
V_{20}	−0.877	0.653	0.461	0.979
V_{21}	−0.596	0.701	0.531	0.979
V_{22}	−1.189	0.631	0.434	0.979
V_{23}	−0.729	0.721	0.550	0.979
V_{24}	−0.617	0.593	0.383	0.979
V_{25}	−0.755	0.688	0.509	0.979
V_{26}	−0.880	0.683	0.507	0.979
V_{27}	−0.823	0.738	0.581	0.979
V_{28}	−0.700	0.631	0.425	0.979
V_{29}	−0.846	0.543	0.324	0.979
V_{30}	−0.571	0.641	0.428	0.979
V_{31}	−0.814	0.623	0.420	0.979
V_{32}	−0.892	0.589	0.378	0.979
V_{33}	−0.756	0.699	0.518	0.979
V_{34}	−0.594	0.638	0.436	0.979
V_{35}	−0.689	0.614	0.411	0.979
V_{36}	−0.566	0.614	0.409	0.979
V_{37}	−0.662	0.605	0.390	0.979
V_{38}	−0.814	0.626	0.407	0.979
V_{39}	−0.799	0.392	0.172	0.979
V_{40}	−0.88	0.753	0.561	0.979
V_{41}	−0.808	0.772	0.586	0.979
V_{42}	−1.123	0.79	0.615	0.979
V_{43}	−1.131	0.744	0.549	0.979
V_{44}	−1.017	0.786	0.608	0.979
V_{45}	−0.633	0.767	0.58	0.979
V_{46}	−0.899	0.79	0.616	0.979
V_{47}	−0.807	0.785	0.607	0.979
V_{48}	−0.887	0.800	0.635	0.979
V_{49}	−0.716	0.397	0.169	0.979
V_{50}	−0.677	0.768	0.601	0.979
V_{51}	−0.608	0.769	0.596	0.979
V_{52}	−0.954	0.359	0.136	0.980
V_{53}	−0.746	0.676	0.462	0.979
V_{54}	−0.324	0.668	0.474	0.979
V_{55}	−0.456	0.727	0.547	0.979
V_{56}	−0.643	0.695	0.507	0.979
V_{57}	−0.364	0.580	0.359	0.979

Note: Overall reliability of the questionnaire reaches 0.979.

Table 4. Results of exploratory factor analysis.

Construct	Number of items contained	Eigenvalue	Explained variance (%)	Accumulative explained variance (%)	Cronbach's α	Name
1	16	24.225	50.469	50.469	0.963	Constitutional framework
2	9	3.815	7.948	58.418	0.984	Human error
3	11	3.106	6.470	64.888	0.942	System interface
4	4	1.773	3.694	68.582	0.852	Internal communications
5	4	1.430	2.978	71.560	0.876	External communications
6	4	1.157	2.411	73.971	0.849	Controllers capabilities and physical conditions

Note: Cronbach's α of these six common factors reaches 0.9514.

16 items, named the "constitutional framework" of ATC, with explained variance of 50.469% and Cronbach's α of 0.963. The second construct comprises nine items, named the "human error" of ATC, with explained variance of 7.948% and Cronbach's α of 0.984. The third construct comprises 11 items, named the "system interface" of ATC, and has explained variance of 6.470% and Cronbach's α of 0.942. The fourth construct consists of four items, named the "internal communications" of ATC, and has explained variance of 3.694% and Cronbach's α of 0.852. The fifth construct comprises four items, named the "external communications" of ATC, and has explained variance of 2.987% and Cronbach's α of 0.876. The final construct comprises four items, named the "controllers capabilities and physical conditions," and has explained variance of 2.411% and Cronbach's α of 0.849. Notice that all Cronbach's α of these constructs exceed 0.7, demonstrating their high reliability, according to Cronbach [45].

3.4. Model estimation and verification

The model is further tested using the data from the questionnaire survey, *via* confirmatory factor analysis with maximum likelihood estimator. A commonly used SEM software, LISREL version 8.54, is adopted. An initial framework of the second-order confirmatory factor analysis model with six first-order latent factors, measured using 48 manifest items is depicted in Figure 2. The results are listed in Table 5. In Figure 2, ξ represents a way of referring to the covariance or correlation matrix between a set of constructs. ζ_i represents a way of capturing the covariation between construct errors. η_i represents the i-th latent construct. λ_j represents the relationship between the latent constructs and the j-th measured item (i.e., factor loading). ε_j represents the error term associated with the j-th measured item.

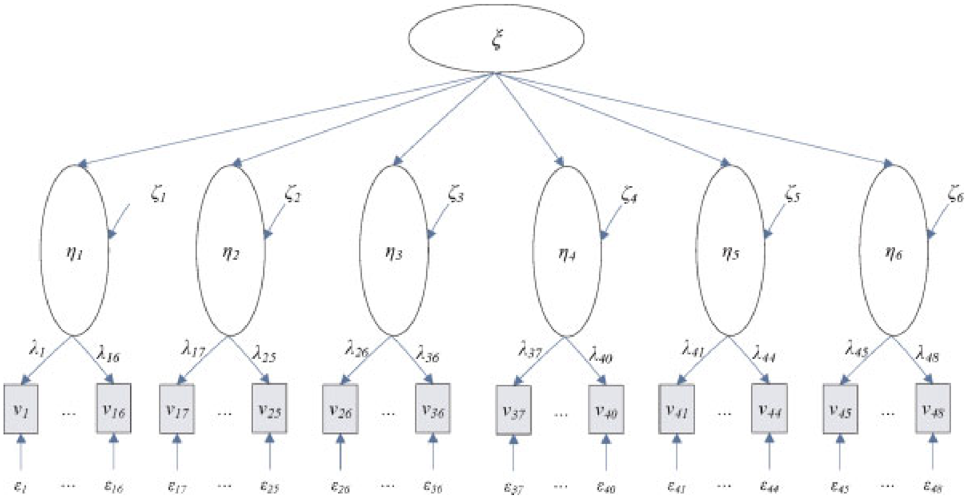

Figure 2. Initial framework of second-order confirmatory factor analysis.

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Table 5. The values of goodness-of-fit indices of various measurement models.

Goodness-of-fit indices	Original model	First revised model	Second revised model	. . .	Final model
Modification	—	Delete V_{55}	Delete V_{35}		Delete V_{25}
χ^2	2732.99	2588.64	2468.25		502.11
χ^2/df	2.545	2.518	2.5109		1.708
GFI	0.59	0.6	0.61		0.81
AGFI	0.55	0.56	0.57		0.77
NFI	0.94	0.94	0.95		0.96
CFI	0.97	0.97	0.97		0.98
RMSEA	0.097	0.096	0.096		0.065
SRMR	0.07	0.07	0.068		0.047

Note: GFI, goodness of fit index; AGFI, adjusted goodness of fit index; NFI, normed fit index; CFI, comparative fix index; RMSEA, root mean square error of approximation; SRMR, standardized root mean square residual.

Note that Table 5 also shows how the proposed model has been revised according to several goodness-of-fit indices. Following 29 revisions and exclusions, the final measurement model displays good fit for all types of model fit: $\chi^2 = 502.11$ (p-value <0.0000) and $\chi^2/df = 1.708$ (less than 2). NFI and GFI all exceed 0.9, SRMR $= 0.047$, which is less than 0.05 [42], and RMSEA $= 0.065$, which is

Table 6. Overall confirmatory factor analysis of the final measurement model.

Variable	Completely standardized loading	*t*-Value	Construct and indicator reliability	Variance extracted
$C1$	0.86	9.6^{***}	0.91[a]	0.64
V_{10}	0.76	-	0.58	
V_{11}	0.76	10.16^{***}	0.58	
V_{12}	0.79	10.65^{***}	0.63	
V_{15}	0.83	11.27^{***}	0.69	
V_{16}	0.81	10.92^{***}	0.65	
V_{17}	0.84	11.47^{***}	0.71	
$C2$	0.70	9.28^{***}	0.98[a]	0.87
V_{40}	0.91	-	0.83	
V_{41}	0.92	20.14^{***}	0.84	
V_{44}	0.93	21.38^{***}	0.87	
V_{45}	0.90	19.12^{***}	0.81	
V_{46}	0.97	24.05^{***}	0.93	
V_{47}	0.95	22.42^{***}	0.90	
V_{48}	0.94	21.85^{***}	0.88	
$C3$	0.86	9.90^{***}	0.91[a]	0.59
V_{21}	0.78	-	0.61	
V_{24}	0.69	9.38^{***}	0.48	
V_{26}	0.86	12.20^{***}	0.73	
V_{27}	0.91	12.18^{***}	0.83	
V_{28}	0.77	10.67^{***}	0.59	
V_{29}	0.66	8.91^{***}	0.44	
V_{31}	0.69	9.32^{***}	0.47	
$C5$	0.83	9.40^{***}	0.86[a]	0.58
V_{54}	0.79	-	0.63	
V_{56}	0.88	11.96^{***}	0.78	
V_{57}	0.78	10.56^{***}	0.61	
$C6$	0.81	8.97^{***}	0.83[a]	0.62
V_{34}	0.78	-	0.61	
V_{36}	0.82	10.36^{***}	0.68	
V_{37}	0.75	9.52^{***}	0.56	

Note: -: the factor loading of the first measured variable as reference indicator of each factor is set as 1.0 [41], so the variance of each latent factor could be estimated.

[a] Composite reliability of each construct.

***A significant value of $\alpha = 0.001$.

close to 0.05 [46]. The values of GFI and AGFI are 0.81 and 0.77, respectively, and thus also lie within acceptable limits. Notably, the final measurement model comprises five constructs measured by 26 items. Additionally, the fourth construct is deleted because of the exclusion of all its constituent items.

After assessing the overall model, each of the constructs in the final measurement model is assessed separately by examining the completely standardized factor loading, significance of error variance, reliability, and variance extracted and the results are summarized in Table 6. The *t*-value associated with each of the completely standardized loading achieves the significance level of $\alpha = 0.001$ and the construct reliabilities of all five constructs (0.91, 0.98, 0.91, 0.86, and 0.83) exceed the recommended level of 0.7. The first and third constructs have the highest completely standardized loading of 0.86, suggesting that these two constructs exert the strongest impacts on aviation safety.

4. HYPOTHESIS TESTS AND DISCUSSIONS

4.1. Correlational relationship among constructs

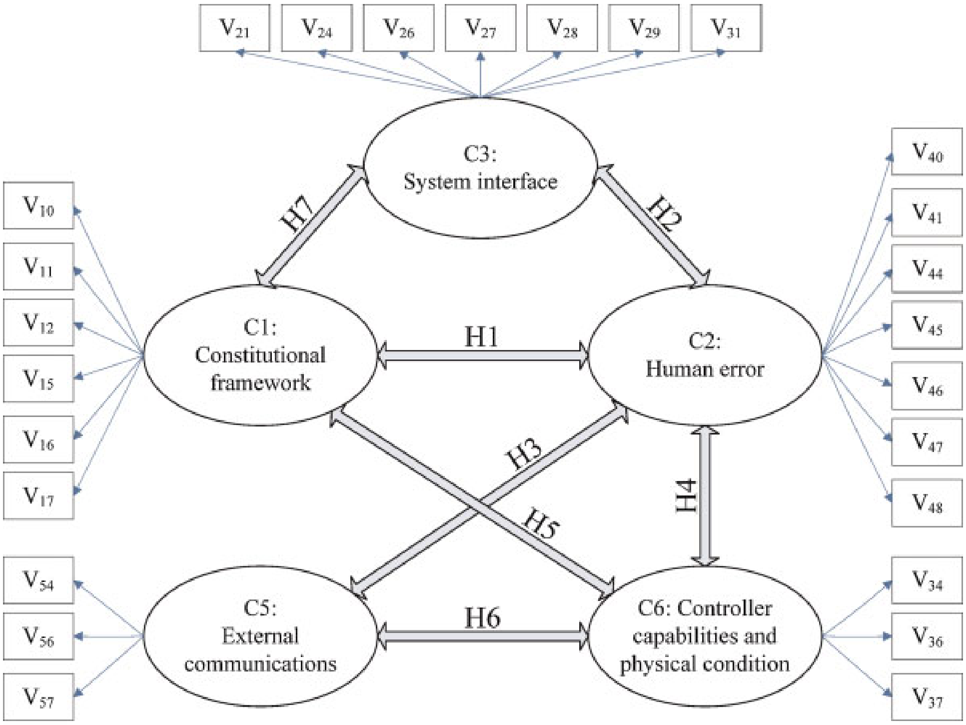
Since an aviation incident is generally caused by a series of errors, which may come from more than one aspect of ATC risk factors, the relationships among these constructs must also be tested. Seven hypotheses are proposed in this study. These hypotheses focus on whether relationships exist between the five constructs, as depicted in Figure 3.

H1: A positive relationship exists between C1 (constitutional framework) and C2 human error.

H2: A positive relationship exists between C2 (human error) and C3 (system interface).

H3: A positive relationship exists between C2 (human error) and C5 (external communications).

H4: A positive relationship exists between C2 (human error) and C6 (controller capabilities and physical condition).



χ^2/df=1.738, GFI=0.81, AGFI=0.77, NFI=0.96, CFI=0.98, RMSEA=0.067, SRMR=0.047.

Figure 3. The hypothetic framework of measurement model.

H5: A positive relationship exists between C1 (constitutional framework) and C6 (controller capabilities and physical condition).

H6: A positive relationship exists between C5 (external communications) and C6 (controller capabilities and physical condition).

H7: A positive relationship exists between C1 (constitutional framework) and C3 (system interface).

$\chi^2/df = 1.738$, GFI = 0.81, AGFI = 0.77, NFI = 0.96, CFI = 0.98, RMSEA = 0.067, SRMR = 0.047.

The test results for the above seven hypotheses are presented in Table 7. Notably, all the hypotheses are highly significant, indicating considerable interaction among these constructs. Particularly, the significant relationship of the second construct with other four constructs confirms that human error could result from risk factors in other aspects of ATC.

4.2. *Discussion*

The final measurement model estimated and tested in this study contains five constructs, measured by 26 indicators. The second and sixth constructs are closely related to the individual controller factors (liveware). Meanwhile, the third construct is related to system factors (hardware). The first construct comprises the organizational factors (software), while the fifth construct concerns external factors (environment). These findings confirm that the key risk factors for ATC in Taiwan can relate to software, hardware, liveware, and environment, as classified by Isaac and Ruitenberg [3]. Moreover, the first construct (constitutional framework) and third construct (system interface) have been found to exert the greatest influence on the risks associated with ATC. Investigation of the relationships between constructs has also revealed a significant relationship between human error and the other four risk aspects of ATC, and particularly to the third construct (system interface).

Further examining the first and third constructs, it reveals that the constitutional framework construct comprises six items: identification of controllers with their supervisors, appropriateness of recruitment and promotion channel, appropriateness of scheduling and attendance regulations, fairness of the system for investigating aviation incidents, implementation of a safety appraisal system, and appropriateness of the training and assessment system, implying that the organization of ATC should be carefully re-assessed, particularly in terms of management style, recruitment and promotion, scheduling and attendance, and training and assessment. This construct also reflects the profound concerns of controllers regarding the promotion channel. That is, to adequently enhance the job seniority of ATC-realted agencies, to provide more promotion opportunities, or to reduce the number of shifts requested at different offshore towers will mitigate this risk. Furthermore, this construct is significantly related to human error and contollers capabilities and physical conditions. Since the application of crew resource management to flight crews has enhanced airline safety performance. Thus it appears worthwhile to introduce this concept to ATC resource management.

Notably, the system interface construct comprises the sufficiency of information provided for ATC, the reliability of the ATC backup system, the user friendliness of the operation interface of the ATC system, the appropriateness of the orders and procedures of the ATC system, the appropriateness of the automatic warning alarm incorporated into the ATC system, the understanding and response of controllers to warning alarms, and the excessive reliance of controllers upon the ATC system. Although

Table 7. Results of hypothesis test.

Hypothesis	Correlation coefficient	*t*-Value
H1	0.61	5.82
H2	0.59	5.75
H3	0.60	5.76
H4	0.56	5.56
H5	0.70	5.77
H6	0.66	5.59
H7	0.74	6.08

the automation of the aviation operating system in Taiwan has remarkably reduced human errors resulting from manual operations, the reliability of the system, hardware–liveware interface, and excessive reliance of controllers upon the system continue to be perceived by ATC staff as key risks to aviation safety. The positive relationship between this construct and the human error construct further confirms the findings of previous studies that most human error results from improper designation of ATC system, in turn adversely affecting controller psychologic conditions.

5. CONCLUSIONS

This study attempts to identify the key ATC-related risk factors to aviation safety from the perspective of air traffic controllers. The results show that the key ATC-related risk factors in Taiwan can be represented by five constructs (measured by 26 items), with the two most important constructs being the constitutional framework and system interface. Human error is significantly related to other four constructs, and particularly to the system interface construct. To mitigate the risk factors identified, several suggestions can be concluded, such as to adequently enhance the job seniority of ATC-related agencies, to provide more promotion opportunities for controllers, to reduce the number of shifts requested at different offshore towers, to introduce ATC resource management system, and to carefully re-examining the designation of ATC system.

Three future research directions can be identified. First, this study only develops the framework of ATC risk factors by employing the measurement model exploratory and confirmatory factor analysis of SEM. Besides ATC, aviation safety is also influenced by numerous other sectors, including airlines and airport administration. A full SEM for overall aviation safety, including path analysis, deserves further consideration. Second, the study population considered in this study incorporates two groups (controllers and supervisors). Due to the sample size required by confirmatory factor analysis (at least of 150 samples suggested by [47]), this study did not conduct factor analysis (both exploratory and confirmatory) separately based on these two groups. However, the differences between the perceptions of these two groups in terms of ATC risk factors also deserve a closer study. Last but not least, this study surveys the fuzzy perceptions of respondents, which are defuzzfied before the model estimation. Future research can consider a fuzzy SEM model.

6. LIST OF ABBREVIATION

ATC	Air traffic control.
ANWS	Air Navigation and Weather Services.
CAA	Civil Aeronautics Administration.
MOTC	Ministry of Transportation and Communications.
EFA	exploratory factor analysis.
CFA	confirmatory factor analysis.
SEM	structural equation modeling.
GFI	goodness-of-fit index.
AGFI	adjusted goodness-of-fit index.
NFI	normed fit index.
CFI	comparative fix index.
RMSEA	root mean square error of approximation.
SRMR	standardized root mean square residual.
SHEL	an analytical framework first proposed by Edwards (1972) to classify ATC risks into four aspects: Software, Hardware, Environment and Liveware.
KMO	Kaiser-Meyer-Olkin measure.
V_i	variable i (*i.e.* risk factor i).
α	Cronbach's coefficient alpha.
ξ	a way of referring to the covariance or correlation matrix between a set of constructs.
ζ_i	a way of capturing the covariation between construct errors.

η_i	the i^{th} latent construct.
λ_j	the relationship between the latent constructs and the j^{th} measured item (*i.e.* factor loading).
ε_j	the error term associated with the j^{th} measured item.

APPENDIX A: OPERATIONAL DEFINITION OF MANIFEST VARIABLES

Items	Descriptions
Software aspect	
1. Communication within ATC	
V_1	Leadership of supervisor
V_2	Esprit de corps
V_3	Working atmosphere
V_4	Staffing shortage conditions
V_5	Communication between controllers and supervisors
V_6	Communication between controllers and coordinators
V_7	Communication among controllers
V_8	Responsiveness of supervisors to controller suggestions
V_9	Obedience of controllers to supervisor orders
V_{10}	Identification of controllers with supervisor management styles
2. Related regulations and procedures	
V_{11}	Appropriateness of recruitment and promotion channel
V_{12}	Appropriateness of the regulations governing scheduling and attendance
V_{13}	Rationality of remuneration structure
V_{14}	Fairness of rewards and penalties
V_{15}	Fairness of the system for investigating aviation incidents
V_{16}	Implementation of the safety appraisal system
V_{17}	Appropriateness of the training and assessment system
V_{18}	Appropriateness and adequacy of training resources
V_{19}	Applicability of related operation procedures and regulations
Hardware aspect	
1. System and equipment	
V_{20}	Air traffic control system equipment is sufficient to meet air traffic control demand
V_{21}	Information provided is sufficient for effective ATC
V_{22}	Display and accuracy of ATC system provided information
V_{23}	ATC system reliability and stability
V_{24}	Reliability of ATC backup system
V_{25}	Maintenance efficiency of ATC system
2. Conflict of man–machine interface	
V_{26}	User friendliness of the operating interface of the ATC system
V_{27}	Appropriateness of ATC system orders and procedures
V_{28}	Appropriateness of ATC system automatic warning alarm
V_{29}	Understanding and response of controllers to warning alarms
V_{30}	Conflicts between system function and human decision-making
V_{31}	Excessive reliance of controllers upon ATC system
Liveware aspect	
1. Ability, physiologic, and psychologic conditions of controllers	
V_{32}	Controller coordination ability
V_{33}	Controller contingency response and judgment ability
V_{34}	Controller English ability
V_{35}	Ability of controllers to operate the ATC and backup systems
V_{36}	Controller understanding of aircraft performance
V_{37}	Controller health condition
V_{38}	Controller emotional response
V_{39}	Strong controller consciousness
2. Individual operating errors	
V_{40}	Improper clearance
V_{41}	Failure to comply with the standard operation procedure
V_{42}	Errors of speech or failure to listen to hearback

(*Continues*)

APPENDIX (Continued)

Items	Descriptions
V_{43}	Insufficient separation
V_{44}	Negligence in confirming and paying attention to fight plan and aircraft condition
V_{45}	Improper operation of fight progress strips
V_{46}	Failure to complete aircraft take over procedures
V_{47}	Failure to promptly provide information impacting flight safety to pilots
V_{48}	Misreading of flight codes
Environment aspect	
1. Operating environment	
V_{49}	Working pressure
V_{50}	Working environment amenities and safety
V_{51}	Responsiveness of higher authorities to the suggestions of subordinate units
V_{52}	Compliance of ATC unit with the orders of higher authorities
V_{53}	Identification of ATC unit with the management attitude of higher authorities
2. Communication between ATC units, higher/subordinate authorities and non-ATC units	
V_{54}	Communication among ATC units
V_{55}	Communication between higher authorities and subordinate units
V_{56}	Communication between controllers and pilots of civil and air force aviation
V_{57}	Communication between controllers and airport flight operators

APPENDIX B: DESCRIPTION OF THE QUESTIONNAIRE

The questionnaire comprises three parts, as outlined below:

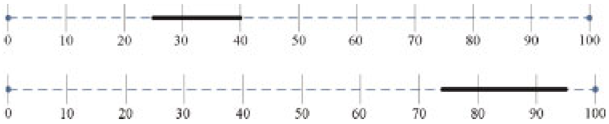
1. The first part comprised five questions surveying respondent perceptions using five linguistic degrees. The questions are listed below:

Question: Based on your perceptions of the five linguistic degrees: very low, low, medium, high, and very high, please indicate numerically what these degrees mean to you:

For example,

Very Low = (25) ~ (40) points

High = (73) ~ (95) points



Please indicate numerically the intervals and draw a solid line below:

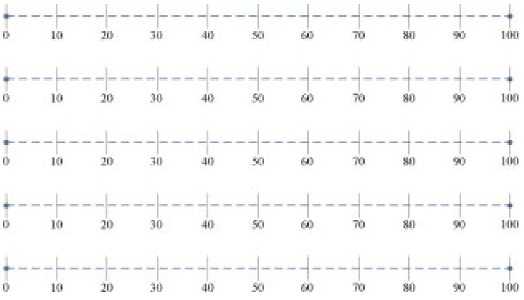
(1) Very Low = ( ) ~ ( ) points

(2) Low = ( ) ~ ( ) points

(3) Medium = ( ) ~ ( ) points

(4) High = ( ) ~ ( ) points

(5) Very High = ( ) ~ ( ) points



The second part comprised 57 questions, representing corresponding potential risks. Taking the first four questions for example:

Question: How do you think the following ATC-related risk factors influence aviation safety?

Risk factors	Very Low	Low	Medium	High	Very High
1. Leadership of supervisor	☐	☐	☐	☐	☐
2. Esprit de corps	☐	☐	☐	☐	☐
3. Working atmosphere	☐	☐	☐	☐	☐
4. Staffing shortage conditions	☐	☐	☐	☐	☐
.					
.	☐	☐	☐	☐	☐
.					

3. The third part comprised five questions surveying respondent gender, age, educational level, years of work experience, and affiliation and title.

Question: Please answer your demographic statistics in the following questions:

(1) Gender: ☐Male ☐Female
(2) Age: __________ years old
(3) Education level: ☐Elementary school ☐Junior high school ☐Senior high school
☐B.S. degree ☐Master degree or above
(4) Work experience of ATC-related jobs: ___________ years
(5) Affiliation:______________________; Title: ______________________

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