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Research on the Aviation Accident Importance Analysis Based on the Bow-tie model

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Abstract To efficiently and directly display the relationship between causes and consequence of the aviation accident, the constructing method of aviation accident's Bow-tie model are provided. Using the probabilities of basic events and control events in the model, the computational methodology is suggested to compute the possibility of each consequence, which can present the quantitative relation between hazards and consequences of the aviation accident. After the merits and demerits were analyzed, the traditional important measures are extended to the aviation accident importance analysis. Based on that, a new kind of aviation accident important measure is proposed, and its solution are suggested as well. Finally, the feasibility and property of the proposed measure and suggested solution are testified by the example of tire burst accident.

Keywords Aviation safety, Accident, Bow-tie model, importance analysis, tire burst

1 Introduction

Due to fast development, the aviation safety has become a large challenge to global aviation business. If global aviation business works at the current developing speed and accident rate, the global aircraft's accidents in next fifteen years would be as much as double of present. So, it is a prominent and vital thing to promote the aviation safety level continuously[1]. Practices have proved that researching aviation accident and then proposing countermeasures is a feasible and efficient method to promote aviation safety. The method mainly includes gathering and teasing all kinds of aviation accidents and unsafe incidents, exploring and extracting the inner-laws concealing in them, and proposing measures, recommendations and steps to prevent accident happening and control unsafe incident deteriorating into accident[2].

Currently, many researchers have proposed quantitative and qualitative models to research and analyzing these aviation accidents and incidents, many of those had obtained preferable effect[3-6], but there still exist lots of problems need to overcome. For example, the Fault Tree analysis(FTA) and Event Tree Analysis(ETA) are two important graphical tools in traditional safety analysis fields. Respectively, FTA displays the relation between basic events and top event, and the top event probability can be computed by the Boolean operation and basic events' probabilities. While ETA displays the relation between initial event and outcome event, and the outcome's possibility can be computed based on the model[7-8]. Nevertheless, applying the FTA and ETA into analyzing aviation accident cannot point out the direct relation between hazards and consequence of accident, and the countermeasures proposed by them are not targeted and intuitively enough. Recently, a synthesis of FTA and ETA, the Bow-tie model, creates between FTA and ETA is an excellent "best of both world" solution in accident analysis[9-10]. The model takes the top event as the critical event to connect the basic events and outcome events of accident, and it breaks through the barriers between basic events and outcome events so that one can find and understand the relations between hazards and consequences of accident easily. Based on that, some researchers have analyzed accident's outcomes quantitatively by combining mathematic tools, and proposed many targeted preventive and mitigate countermeasures. So to speak, the Bow-tie model overcome many shortcomings of traditional accident analyzing methods[11-12], e.g. insufficiency quantification, highly fragmented and less intuitive and

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targeted, et al., and it has provided a new way in accident analysis and risk assessment.

The Bow-tie model and its solutions are new focus in accident analysis field, so there are many scholars and literatures to research it and its application[11-15]. However, considering the cost, time and personality, it is a multiple-object optimization problem to generate countermeasures to prevent or mitigate aviation accidents, and it need analyze the importance of every basic event and control event to make targeted and pointed countermeasures. To considering and weighing the importance of every basic event and control event comprehensively, the important analysis methodology of the aviation accident Bow-tie model is needed to research. Through the importance analysis, some quantitative references to propose collectively and targeted accident's countermeasures can be obtained.

The remainder of the article is organized as follows. Section 2 reviews the Bow-tie model theory and discusses how the model be applied in aviation accident analysis. Section 3 proposes two new aviation accident important measures and suggests their computational methodology. Section 4 testifies the feasibility and property of proposed measures and suggested solution by taking the tire burst accident as an example. Finally, some analyzed conclusions are obtained through the example. Specially, a new thought to generate the preventive and mitigate countermeasures of aviation accident are suggested among them.

2. The Bow-tie model and its solution

The Bow-tie model theory was firstly proposed by the SHELL company in 1990s[9]. It displays the whole development process of accident by means of a diagram(Figure 1), which reflects how the hazards of accident do result in the risk and how the risk does evolve to the accident's consequences. Now, the Bow-tie model has been used popularly in risk management, risk analysis, risk assessment and the presentation of the safety barriers, and it has obtained remarkable results[11,15-20]. Generally, the Bow-tie model is composed of two parts, the Fault tree(FT) in the left and the Event tree(ET) in the right. The FT involves all the events induce to the accident, which are defined as basic events or unexpected events, and these events are connected by the logical gates. While the ET defines all the consequences of the accidents, many mitigate and remedy measures are display in the model. That is ,combing with the ETA and FTA, the Bow-tie model displays the basic events and consequences of accident in a diagram, and which presents the causes and results of accidents by a visible mean[15,18].

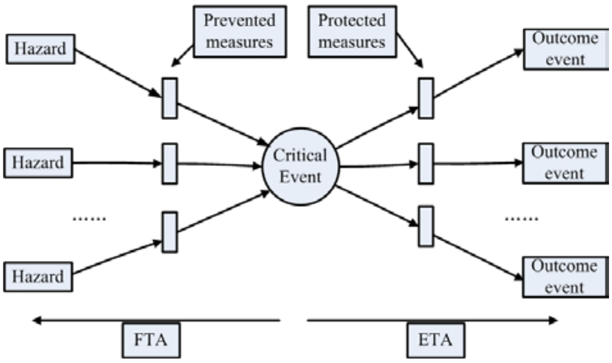

Fig.1. The schematic diagram of the Bow-tie model

2.1 Construction of the Bow-tie model

Because Bow-tie model is made up by the FT and ET, a series of methods are used to build the Bow-tie model based on FTA and ETA.

Generally, most of these methods depend on the experts knowledge and experience, these methods are simple and feasible but they are also strong subjective and difficult to quantified. To overcome these problems, some new methods to build the Bow-tie model were proposed[17,18,21,22]. On the whole, these modeling principles can be concluded as follows.

(1) The top event of FT is the initial event of FA, it is the critical event of the model as well.

(2) The FT and ET are connected by the common critical event.

(3) All identified accident causations and basic events are located in the left of the model.；

(4) The accident consequence are located in the right of the model.

(5) All the branches in the left always gather to the critical event, and in the right all the consequences are extended from the critical event.

In the Bow-tie model, the hazards can be identified by the FT and the consequence can be analyzed by the EA. Further, the model can be conveniently used to carry out the risk analysis and assessment of the accidents. So a comprehensive Bow-tie model should have capability to propose a series risk management measures, namely, some barriers to prevented the top level risk happening are listed in the left of the model, and some mitigated countermeasures are listed in the right of the top event, all these countermeasures are used to prevent or mitigate unexpected consequences induced by the top even[23].

2.2 Probabilistic solution of the outcome event

The quantitative solutions of FT and ET can be represented by logical operation and probabilities of events, the solution of the Bow-tie model are suggested based on these solutions as well[12, 24-25]. For the sake of clearness in the recital, a typical Bow-tie model(Fig.2) is taken as an example to introduce the computational method. Generally, events of the Bow-tie model can be classified as the basic event(BE), the critical or event (CE), the intermediate event(IE), the control event(SE) and the outcome event(OE).

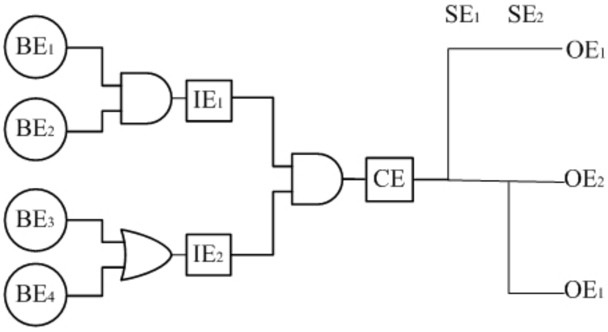

Fig.2 The sketch map of the typical Bow-tie model

If we suppose that BEs and CEs of the Bow-tie model are independent and their probabilities are known, the probability of IE can be computed by the logical operation. For example, the probability of IE composed by logical “and” gate can be computed by Eq.(1)

$$p_{\mathrm{OR}}^{IE} = \prod_{i=1}^{n} p_i^{BE} \tag{1}$$

and the probability of IE composed by the logical “or” gate can be computed by Eq.(1)

$$p_{\mathrm{AND}}^{IE} = 1 - \prod_{i=1}^{n} (1 - p_i^{BE}) \tag{2}$$

where n is the number of BEs involved in the logical "and" and "or" gate. p_i^{BE} is the probability of the ith basic event BE_i. Of course, many logic gates are existed in the FT, the probabilistic results can be computed by responding logical operations. That is, the CE's probability, p^{CE} of the Bow-tie model can be computed by using probabilities of all BEs according the logical gates step by step.

The important target of the Bow-tie modeling is to analyze the possibility of outcome events. If we take probability theory to evaluate the possibility p_i^{OE} of outcome event OE_i, we can suggested the computational equation as

$$p_i^{OE} = \sum_{k=1}^{l} p^{CE} \prod_{j=1}^{m} f(p_j^{SE}) \tag{3}$$

where l is the number of the branches existing between the critical event CE and the outcome event OE_i, and if the SE is happening, $f(p_j^{SE}) = p_j^{SE}$, else, $f(p_j^{SE}) = 1 - p_j^{SE}$.

And the probability of ith outcome event OE_i can be represented by the function of probabilities of n basic and m control events, which can be listed as Eq.(4).

$$p_i^{OE} = f(p_1^{BE}, p_2^{BE}, ..., p_n^{BE}, p_1^{SE}, p_2^{SE}, ..., p_{m\times l}^{SE}) = f(\boldsymbol{p}^{BE}, \boldsymbol{p}^{SE}) \tag{4}$$

Taking the typical Bow-tie model displayed in Fig.2 as the example, the probabilities of basic event BE_1, BE_2, BE_3, BE_4 are assumed as p_1^{BE}, p_2^{BE}, p_3^{BE} and p_4^{BE}, there are two outcome events OE_1 and OE_2 and three branches. The control events responding to the outcome events are SE_1 and SE_2, and their probabilities can be represented as p_1^{SE} and p_2^{SE}, so the probabilities that the control events would not happening are $1 - p_1^{SE}$ and $1 - p_2^{SE}$, so the outcome event OE_1 can be computed by Eq.(5)

$$p_1^{OE} = [p_1^{SE} p_2^{SE} + (1 - p_1^{SE})(1 - p_2^{SE})] \bullet \{p_1^{BE} p_2^{BE} [1 - (1 - p_3^{BE})(1 - p_4^{BE})]\} \tag{5}$$

the outcome event OE_2 can be computed by Eq.(6)

$$p_2^{OE} = (1 - p_1^{SE}) p_2^{SE} \bullet \{p_1^{BE} p_2^{BE} [1 - (1 - p_3^{BE})(1 - p_4^{BE})]\} \tag{6}$$

Of course, the probabilities of outcome events composed other logical gates can be computed by practical logical structure in the same way, and you will ignore that for this article. In a general way, the more serious the outcome event is, the more attention is paid to.

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3 Aviation accident importance measure and solution

3.1 The aviation accident importance measure

There are many importance measures in traditional reliability analysis, such as the Birnbaum importance measure[26], the criticality importance measure[27], the Fussell-Vesely importance measure[28-29] and the risk achievement worth[30], et.al. Each of them represents the contribution of basic event to the top event of the system in responding respective. Though they can be extended and used in the aviation accidents importance analysis, there are still some limitations and drawbacks in them[31]. Borgonovo and Apostolakis[31-33] have proposed a differential importance measure in 2003, the importance measure solved the significant limitation of the present importance measure, including the nor normalized and inconvenient for comparing. So a new aviation accident importance measure based on that will be proposed to measure the effect of the basic event or control event on the outcome event of the aviation accident.

For easily expressing, the probability of one outcome event in the aviation accident is represented as P_s^{OE} (where s represents the number of outcome events in the accident model), and probabilities of the basic event, the control event are defined as P_{Xi} , so according to the differential importance measure proposed by Borgonovo and Apostolakis, the aviation accident importance measure can be defined as

$$I_{s/i}^{\mathrm{DIM}} = \frac{\partial P_s^{OE} / \partial P_{Xi}}{\sum_{j=1}^{n} \partial P_s^{OE} / \partial P_{Xj}} \qquad （7）$$

According to reference[31] and the aviation accident model built in the above content, some properties are listed in the following if basic events and control events are independent respectively.

Property 1. Additivity. The joint importance measure of some basic events and control events can be added by their independent importance measures, e.g.

$$I_{s/i,j,\ldots,l}^{\mathrm{DIM}} = I_{s/i}^{\mathrm{DIM}} + I_{s/j}^{\mathrm{DIM}} + \ldots + I_{s/l}^{\mathrm{DIM}} \qquad （8）$$

Property 2. Normalization. To pointed outcome event, sum of the importance measures of involved basic events and control events equals 1, e.g.

$$I_{s/1}^{\mathrm{DIM}} + I_{s/2}^{\mathrm{DIM}} + \ldots + I_{s/n}^{\mathrm{DIM}} = 1 \qquad （9）$$

where n is the total number of basic events and control events involved in the given outcome event.

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The new importance measure $I_{s/i}^{\mathrm{DIM}}$ in Eq.（7） represents the effect of the variation of basic event or control event's probability on the probability of the outcome event. In fact, two cases in the following are needed to consider, e.g.

Case 1. It is assumed that the variations of the probabilities of every basic or control event are same.

$$H_1: \quad dP_{Xj} = dP_{Xk}, \quad \forall j,k = 1,2,...,n$$

Case 2. It is assumed that the gradients of the probabilities of every basic or control event are same

$$H_2: \quad \frac{dP_{Xj}}{P_{Xj}} = \frac{dP_{Xk}}{P_{Xk}}, \quad \forall j,k = 1,2,...,n$$

Two aviation importance measures $I_{s/1}^{\mathrm{DIM\_H1}}$ and $I_{s/1}^{\mathrm{DIM\_H2}}$ are defined as follows

$$I_{s/i}^{\mathrm{DIM\_H1}} = \frac{\partial P_s^{OE} / \partial P_{Xi}}{\sum_{j=1}^{n} \partial P_s^{OE} / \partial P_{Xj}} \tag{10}$$

$$I_{s/i}^{\mathrm{DIM\_H2}} = \frac{\partial P_s^{OE} / \partial P_{Xi} / P_{Xi}}{\sum_{j=1}^{n} \partial P_s^{OE} / \partial P_{Xj} / P_{Xj}} \tag{11}$$

3.2 Solution of the aviation accident importance measure

In term of the definition in Eq.(7), it is likely to think of that the differential method can be used to compute the aviation accident importance measure. Due to its limitation, the differential method is feasible to solve relative easy aviation model. However, most aviation accident models have complex structure, enormous scales and includes large number of basic and control events, so the differential methodology is difficult to obtain the aviation accident importance measures, and other methods are needed.

The Monte-Carlo method is popularly applied into computing most traditional importance measures in system reliability analysis, so we can consider applying the method to extend the traditional importance measures to aviation accident importance measures. Based on that, an feasible and efficient method to obtain the proposed aviation accident importance measure can be suggested by the method.

Taking the Birnbaum importance measure I_i^B as an example, which can be transformed as the effect of outcome event's probability change as the ith basic (control) event changes. So the Birnbaum aviation accident importance measure $I_{s/i}^B$ can be defined as

$$I_{s/i}^B = \frac{\partial P_s^{OE}}{\partial P_{Xi}} = f(1_i, \boldsymbol{p}^{BE}, \boldsymbol{p}^{SE}) - f(0_i, \boldsymbol{p}^{BE}, \boldsymbol{p}^{SE}) \tag{12}$$

where s is the sequence number of outcome event, and i is the sequence number of the basic or control event.

The Birnbaum aviation accident importance measure can be obtained by computing the partial derivative of the probability of outcome event to that of basic event or control event[33] ,it can also be represented as $I_{s/i}^B$

$$\begin{aligned} I_{s/i}^B &= E\{\Phi(1_i, \boldsymbol{BE}, \boldsymbol{SE}) - \Phi(0_i, \boldsymbol{BE}, \boldsymbol{SE}) = 1\} \\ &= P\{\Phi(1_i, \boldsymbol{BE}, \boldsymbol{SE}) - \Phi(0_i, \boldsymbol{BE}, \boldsymbol{SE}) = 1\} \end{aligned} \tag{13}$$

where $\boldsymbol{BE}$ and $\boldsymbol{SE}$ are all basic and control events except the ith event, and $\Phi(\bullet)$ represent the sth outcome event is happen or not as the basic events and control events are given, when the outcome is happen, it equals 1, else it equals 0.

According to Eqs.(7) and (9), the computational formulae can be derived under two cases H_1 and H_2

$$I_{s/i}^{\text{DIM\_H1}} = \frac{\partial P_s^{OE} / \partial P_{Xi}}{\sum_{j=1}^{n} \partial P_s^{OE} / \partial P_{Xj}} = \frac{I_{s/i}^{B}}{\sum_{j=1}^{n} I_{s/j}^{B}} \qquad (14)$$

$$I_{s/i}^{\text{DIM\_H2}} = \frac{\partial P_s^{OE} / \partial P_{Xi} / P_{Xi}}{\sum_{j=1}^{n} \partial P_s^{OE} / \partial P_{Xj} / P_{Xj}} = \frac{I_{s/i}^{B} P_{Xi}}{\sum_{j=1}^{n} I_{s/j}^{B} P_{Xj}} \qquad (15)$$

It is easy to find from Eqs.(13)-(15) that the Monte-Carlo method is a feasible and effective method to compute the aviation importance measure of complex aviation accident. That is, the aviation accident importance measure $I_{s/i}^{\text{DIM\_H1}}$ and $I_{s/i}^{B}$ both represent the contribution of *i*th basic event on outcome's probability in case that all the basic events' probabilities changes are same, and the aviation accident importance measure $I_{s/i}^{\text{DIM\_H2}}$ represents the contribution in case that the change rate are same.

4. Case analysis

Tire is the important part composed the aircraft landing gear system, which is crucially important to guarantee the safety in aircraft's taking off and landing phases. Once the tire bursts, the serious consequence will happened quite possibly and endanger the aircraft safety. Historically, hazards induced the tire burst are widely distributed in many fields, including factors caused by personal, environment, and component failure. On the other hand, the consequences result from the tire burst are serious, which even could lead to fatal crash accident. Thus, the tire burst accident were analyzed in this section, and its Bow-tie model will be built, the basic event or the control event which have more effect would be researched and quantified. Based on that, a new generating mechanism of aviation accident countermeasures is proposed.

4.1 Model construction

4.1.1 Hazard analysis

Through analyzing historical aviation accidents[35-36], three kinds of failures can directly induced to tire burst, e.g. the tire failure, the wheel failure and the brake system failure. Further, the tire failure was result from basic events including low charge pressure, inflatable mouth fracture, tire excessive wear and quality problem, et al. Among them, the basic event of low charge pressure can be due to the responsibility for maintenance, and the tire can be due to the responsibility for producer, both of them can be classified as the mechanism fault caused by human error. The wheel wearing would give rise to not only the wheel failure but also the tire failure. There are four reasons causing the wheel fault, including Hub crack, the gear chipping, brake disc chipping and the hot melting. Among them, the gear chipping probably results from the brake pad's filling by mistake, and the brake disc chipping is a structure problem, the hot melting is a design problem. There are lots of reasons causing the brake system failure, such as foreign body existing in brake ducts, fault of the air bleed valve, fault of the inertial sensor, et.al. what's more, the air leakage caused by tire overheating also can lead to tire burst. All above reasons can act each other and cause the accident happening.

It is not difficult to find the human factors, the mechanical factors, the environment factors causing the tire burst accident. So if we

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control the above hazards, a series of countermeasures must be suggested from the aspects of human, components and environment.

4.1.2 Consequence analysis

If the tire bursts, the aircraft would not be controlled in its proper direction, and it would run off the runway, or turn on its side, even cause fatal crash by the pilot's hurry mistake operation. According the historical datum, consequences caused by the tire burst can be classified as follows.

(1) Termination of task, and aircraft stopped safely.

(2) Aircraft Slightly damaged

(3) Aircraft Seriously damaged

(4) Fatal crash

Except that the first consequence, the later three consequences all result in property loss or casualties. Through analyzing many accidents caused by the tire burst, four control measures, such as starting the emergency brake system, keep away the obstacles, such as aircraft, building, et al., installing the separation net, starting the fire emergency systems, can be adopted to control and mitigate the happening of the above unsafe consequences. And if they are not play an effective role, the corresponding serious consequence would happen probably.

4.1.3 Bow-tie model

Based on historical information and analyzed results, the Bow-tie model are built as Fig.3.

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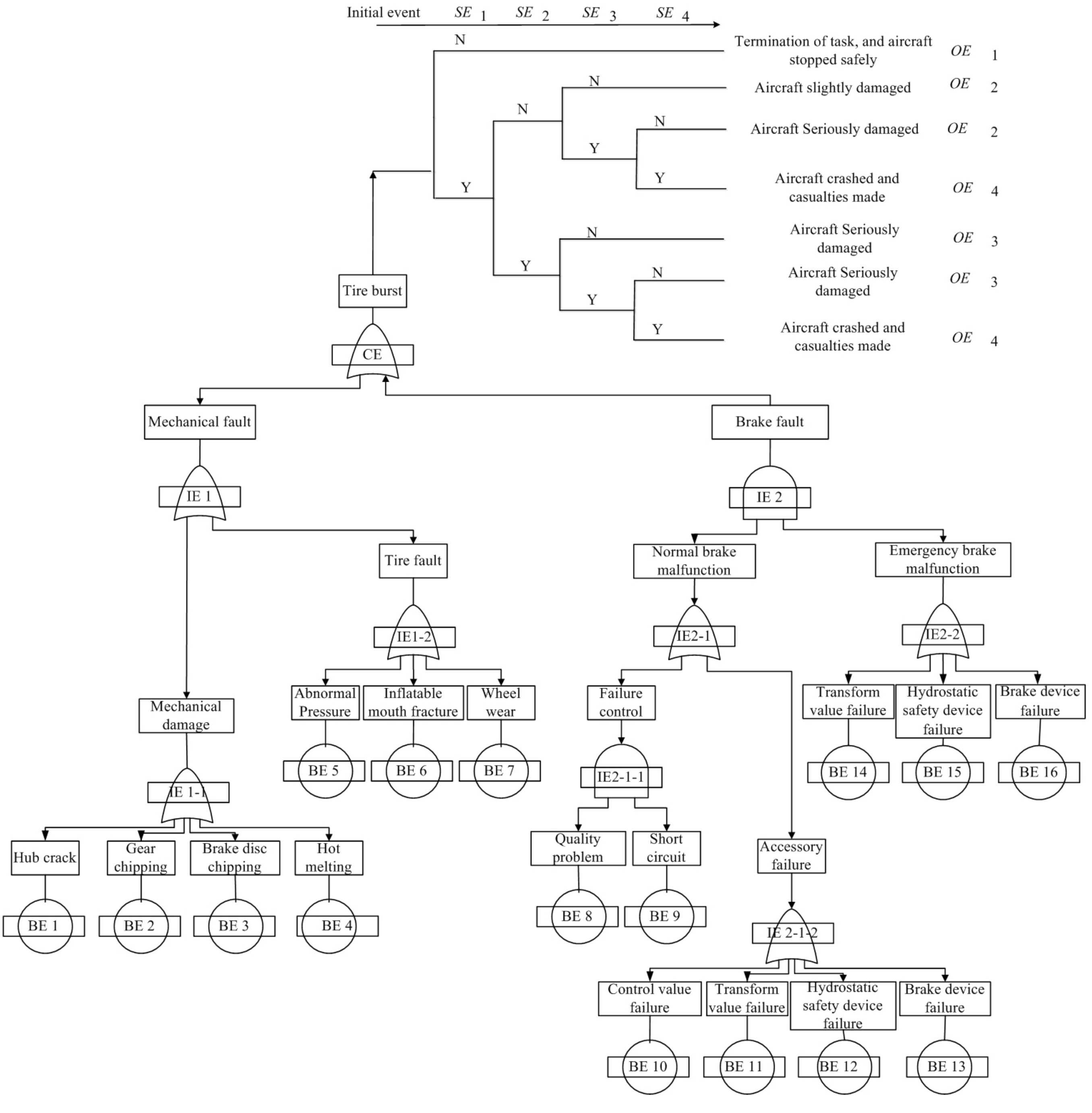

Fig.3. The Bow-tie model of aircraft's tire burst accident

There are 16 basic events in the failure tree of the above Bow-tie model, and the critical(top) event are leaded to by some inertial events composed of different logical gates and these basic events. After the critical(top) had happened, four accident's consequences would be induced due to the effects of different subsequent countermeasures. In regarding to the previous mentioned, four controlled events are SE_1: Starting the emergency brake system, SE_2: Keep away the obstacles, SE_3: Installing the separation net, SE_4: Starting the fire emergency systems. Table 1 lists all the basic events and their probabilities, while probabilities of four control events are determined by experts due to they are difficult to quantify, and the four probabilities of control events are assumed as 0.25, 0.27, 0.20 and 0.15.

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Tab.1. Basic events of Bow-tie of aircraft's Tire burst accident

NO.	Basic event	Probability	NO.	Basic event	Probability
BE1	Hub crack	0.000000317000	BE9	Short circuit	0.000001200000
BE2	Gear chipping	0.000000537000	BE10	Control value failure	0.000002400000
BE3	Brake disc chipping	0.000002680000	BE11	Transform value failure	0.000003600000
BE4	Hot melting	0.000030400000	BE12	Hydrostatic safety device failure	0.000002800000
BE5	Abnormal Pressure	0.000001200000	BE13	Brake device failure	0.000013000000
BE6	Inflatable mouth fracture	0.000035000000	BE14	Transform value failure	0.000032000000
BE7	Wheel wear	0.000006700000	BE15	Hydrostatic safety device failure	0.000028000000
BE8	Quality problem	0.000000370000	BE16	Brake device failure	0.000007000000

Using the equations in section 2.2 and the datum inTable.1, The probabilities of the consequences due to tire burst can be computed as Fig.4.

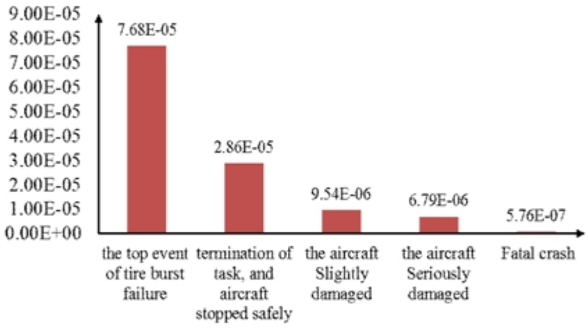

Fig.4. The probabilities of consequences caused by the tire burst

Fig.4 displays that probability of top event of tire burst failure is 7.68E-5, and the probabilities of the outcome events are sorted as follows, the fatal crash is the lowest, which is 5.76E-7, the aircraft seriously damaged and slightly damaged are taken second and third place, the highest probability is the termination of task, and aircraft stopped safely, which is 2.86E-5. It is consistently that the computational results with the practical facts.

4.1.4 Importance analysis

In practices, there are three serious consequences need to prevent and avid, e.g. the aircraft seriously damaged, the aircraft slightly damaged, and the fatal crash. To judge if the proposed prevent and control measures are most suitable and reasonable, the aviation accident importance analysis need to carry out. Thus, the importance analysis methodology in above sections are taken, and the computational results had been obtained and displayed in the Fig.5-7 respectively.

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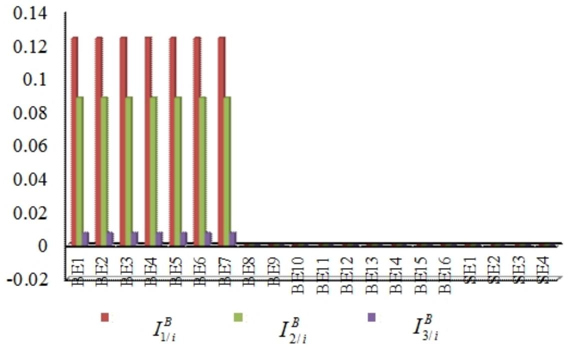

Fig.5. The computational results of the Birnbaum importance measure of the tire burst accident

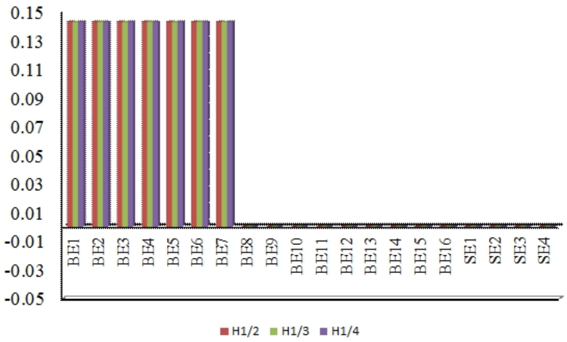

Fig.6. The computational results of the aviation accident importance measure $I_{s/1}^{\mathrm{DIM\_H1}}$ of the tire burst accident

It is obviously in Fig.5 and Fig.6 that BE1-BE7 are the most important events of the tire burst accident, and the results of other events are relatively lower, which testifies that the Birnbaum importance measure and the differential importance measure $I_{s/1}^{\mathrm{DIM\_H1}}$ are only relative to the structure and location of the basic or control event in the model but their probabilities. Due to the values are not normalized, the Birnbaum importance measures shown in Fig.5 are difficult to compare each other. From the results in Fig.6, it is easily to compare the importance of different events.

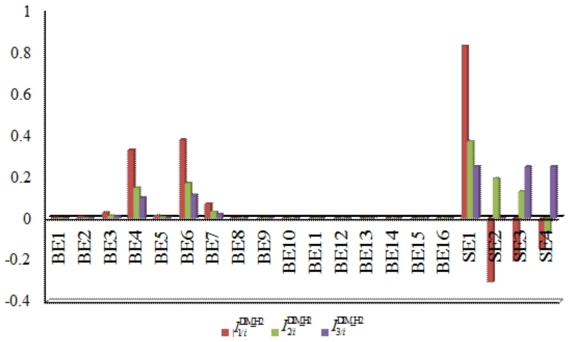

Fig.7. The computational results of the aviation accident importance measure $I_{s/1}^{\mathrm{DIM\_H2}}$ of the tire burst accident

The computational results of aviation accident importance measure $I_{s/1}^{\mathrm{DIM\_H2}}$ displayed in Fig.7 are different from the above two importance measures significantly. Those importance measures in Fig.7 show that the importance of basic events or control events are not

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only relative with their location and logical structure, but also with their probabilities. Taking the aircraft seriously damaged induced by the tire burst failure as an example, the importance ordering are SE1，SE2，BE6，BE4 and SE3, e.g. Starting the emergency brake system, keep away the obstacles, Inflatable mouth fracture, Hot melting and installing the separation net. Notably, some negative values exist in Fig.7 because the increasing of the probabilities of some control events are not positively related to the probability of the corresponding consequence. However, all the importance measures of fatal crash are positive values, which show the consistency to the physical truth.

Fig.7 displays that the most important events, like the hot melting, the Inflatable mouth fracture, should have most countermeasures from the aspects of design, maintenance and management. And the less importance events have relative less countermeasures. Specially, some controlled measures of outcome events are proposed to control some important and noticeable events are suggested in maintenance, logistic and management.

5.Conclusions

In the real world, it is very difficult to compute and obtain the probability of aviation accident's consequence. However, with the rapid development, many airline companies had collected mass data about aviation safety. Based on that and the Bow-tie model, a new computational methodology of aviation accident consequence probability are provided, and two aviation accident importance measures and solution are suggested. With the proposed methodology and measures, the importance of basic events or control events in aviation accidents can be judged properly and directly, which provided the useful reference and quantitative basis to design of safety and make countermeasures of the aviation accidents.

Of course, there are many difficulties in real aviation accident analysis. For example, there exists a great variety information in airline companies, which could make it very difficult to deal with and analyze. On the other hand, information of many concrete aviation accidents are few, dynamic and strong uncertain, thus it is more difficult to construct the accident model. Specially, it is intuitional in proposing prevented measures and controlled measures, how to validate the property and feasibility of proposed measures referring to quantitative analyzing results is a difficulty.

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References

[1] International Civil Aviation Organization. 2014-2016 Global Aviation Safety Plan[R]. Montréal, QC, Canada: ICAO, 2013

[2] Lars Harms-Ringdahl, Analysis of safety functions and barriers in accidents[J]. Safety Science, 2009, 47(10):353-363

[3] Khan, F., Abbasi, S.A. Techniques and methodologies for risk analysis in chemical process industries[J]. Journal of Loss Prevention in the Process Industries 1998,11, 261–277.

[4] Nima Khakzada, Faisal Khana, Paul Amyotte. Dynamic safety analysis of process systems by mapping Bow-tie into Bayesian network[J]. Process Safety and Environmental Protection. 2013, 91(1-2):46-53,

[5] Ahmed Badreddine, Taieb Ben Romdhane, Mohamed Aymen Ben HajKacem, et,al. A new multi-objectives approach to implement preventives and protective barrier in boe-tie diagram[J]. Journal of Loss Prevention in the process Industries. 2014,32,(9):238-253,

[6] Karin van Thienen-Visser, Dimmie Hendriks, Annemieke Marsman, et al. Bow-tie risk assessment combining causes and effects applied to gas oil storage in an abandoned salt cavern[J]. Engineering Geology. 2014, 168(1): 149-166

[7] Nivolianitou, Z.S.; Leopoulos, V.N.; Konstantinidou, M. Comparison of techniques for accident scenario analysis in hazardous systems[J]. Journal of Loss Prevention in the Process Industries, 2004, 17(6):467-475

[8] Skelt, S., Safety barriers: definition, classification, and performance[J]. J. Loss Prev. Process Ind. 2006,19(5): 494-506

[9] Couronneau, J.C., Tripathi, A., 2003. Implementation of the new approach of risk analysis in France[C]. In: Proceedings of the 41st International Petroleum Conference, Bratislava, Slovakia.,

[10] Linda J. Bellamy. Exploring the relationship between major hazard, fatal and non-fatal accidents through outcomes and causes[J]. Safety Science. 2015,71(2): 93-103

[11] Delvosalle, C., Fievez, C., Pipart, A., Debray, B. ARAMIS project: a comprehensive methodology for the identification of reference accident scenarios in process industries[J]. J. Hazard. Mater. 2006, 130 (3), 200-219.

[12] Ferdous, R., Khan, F., Sadiq, R., Amyotte, P., Veitch, B., 2013. Analyzing system safety and risks under uncertainty using a Bow-tie diagram: an innovative approach[J]. Process Saf. Environ. Prot.2013,91(1): 1-18.

[13] Ferdous, R., Khan, F., Sadiq, R., Amyotte, P., Veitch, B. Handling and updating uncertain information in Bow-tie analysis[J]. J. Loss Prev. Process Ind. 2012,25(1): 8-19.

[14] Léger, A., Duval, C., Weber, P., Levrat, E., Farret, R., 2006. Bayesian network modeling the risk analysis of complex socio technical systems[C]. In: Workshop on Advanced Control and Diagnosis, ACD'2006.

[15] Markowski, A.S., Kotynia, A., Bow-tie model in layer of protection analysis[J]. Process Saf. Environ. Prot. 2011.89(4): 205-213.

[16] Delvosalle, C., Fievez, C., Pipart, A., Casal Fabrega, J., Planas, E.,Christou, M., Mushtaq, F. Identification of reference accident scenarios in SEVESO establishments[J]. Reliability Engineering and System Safety 2005.90(2-3), 238–246.

[17] Dianous, V.D., Fievez, C. ARAMIS project: a more explicit demonstration of risk control through the use of Bow-tie diagrams and the evaluation of safety barrier performance[J]. Journal of Hazardous Materials 2006,130(3), 220–233.

[18] Cockshott, J.E.. Probability Bow-ties a transparent risk management tool[J]. Process Safety and Environmental Protection 2005, 83(3), 307–316.

[19] Gowland, R. The accidental risk assessment methodology for industries (ARAMIS)/layer of protection analysis (LOPA) methodology: a step forward towards convergent practices in risk assessment?[J] Journal of Hazardous Materials 2006, 130(3), 307–310.

[20] Badreddine, A., Ben Amor, N.,. A dynamic barriersn implementation in Bayesian-based bow tie diagrams for risk analysis[C]. In: Proceedings of International Conference on Computer Systems and Applications, 2010. 1–8.

[21] Duijm NJ. Safety-barrier diagrams as a safety management tool[J]. Reliability Engineering and System Safety.94(2),331-341

[22] Markowski, A.S. Mannan, M.S., Bigoszewska, A., Fuzzy logic for process safety analysis[J]. Jouranl of Loss Prevention in the Process Industies. 2009, 26(6):695-702

[23] Yaneira E.Saud, Kumar Isranl, Jeremy Goddard. Bow-tie Diagrams in Downstream Hazard Identification and Risk Assessment[J]. Process Safety Progress. 2014, 33(1):26-35.

[24] Henley, E.J., Kumamoto, H. Probabilistic Risk Assessment and Management for Engineers and Scientists[M]. 2nd ed. New York:IEE Press, 1996

[25] American Institute of Chemical Engineers (AIChE). Guidelines for Chemical Process Quantitative Risk Analysis[M], 2nd ed. New York: AIChE, 2000.

[26] Barlow EB, Proschan FP. Importance of system components and fault tree events[J]. Stochastic Processes and their Applications. 1975; 3(2)153-173.

[27] Cheok MC, Parry GW, Sherry RR. Use of importance measures in risk-informed regulatory applications[J]. Reliability Engineering and System Safety. 1998; 60(3): 213-226.

[28] Vesely WE, Davis TC. Evaluations and Utilization of Risk Importances[S]. NUREG/CR-4377, Washington, D.C, 1985.

[29] Fussell J. How to hand calculate system reliability and safety characteristics[J]. IEEE transaction on Reliability. 1975; R-24(3): 169-174.

[30] Chadwell GB, Leverenz FL. Importance Measures for Prioritization of Mechanical Integrity and Risk Reduction Activities[C]. AICHE Loss Prevention Symposium. March 15, 1999, Houston.

[31] Borgonovo E, Apostolakis GE. A new importance measure for risk informed decision-making[J]. Reliability Engineering and System Safety. 2001; 72(2): 193-212.

[32] Borgonovo E. Differential, criticality and Birnbaum importance measures: An application go basic event, groups and SSCs in event trees and binary decision diagrams[J]. Reliability Engineering and System Safety. 2007; 92(10): 1458-1467.

[33] Borgonovo E. The reliability importance of components and prime implicants in coherent and non-coherent systems including total-order interactions[J]. European Journal of Operational Research. 2010; 204(3): 485-495.

[34] M.van der Borst, H. Schoonakker. An overview of PSA importance measure[J]. Reliability Engineering and System Safety. 2001,72()241-245

[35] WC Terryn. Accidents and Incidents Involving Military Aircraft(2000-present)[M]. cypt publishing, 2011.

[36] David Robert E. Location of Commercial Aircraft Accidents/Incidents Relative to Runways[R]. WASHINGTON DC: FEDERAL AVIATION ADMINISTRATION,1990