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Prioritizing risks via several expert perspectives with application to runway safety

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ABSTRACT

Factor hierarchies have been widely used in the literature to represent the view of an expert of what factors most contribute to reliability or safety. The methods for rating and aggregating the influences across a set of expert-elicited factors to risk or reliability are well known as multiple criteria decision analysis. This paper describes a method for distinguishing levels of risk across a set of locations via the use of multiple factor hierarchies. The method avoids averaging across experts and is thus useful for situations where experts disagree and where an absence of expert consensus on the causative or contributing factors is important information for risk management. A case study demonstrates using seven expert perspectives on the airport-specific factors that can contribute to runway incursions. The results are described for eighty towered airports in the US. The expert perspectives include differing relative emphases across the following set of factors: airport geometry, operations, weather, geography, and days since last safety review. Future work is suggested to include human factors issues as pilot-and-controller communications styles at airports.

1. Introduction

Safety assurance programs are critical to management and operations of large-scale systems. In order to improve and maintain safety, a program must commit to continuous analysis and learning throughout the system lifecycle. Sidney Dekker emphasizes the importance of accurate reporting and accountability in order to maintain quality, improve safety, and "[stay] just ahead of the constantly changing nature of risk" [1]. As Dekker describes, systems analysis is not only about looking in the rear-view mirror at a situation, but "accountability is about looking ahead. Not only should accountability acknowledge the mistake and the harm resulting from it. It should lay out the opportunities (and responsibilities!) for making changes so that the probability of such harm happening again goes down" [1]. In this way, risk and safety programs help to reduce the occurrence and adverse effects of hazards across a distributed system.

Practically every real-world systems engineering problem is characterized by uncertain or imprecise knowledge and limited resources [2]. Ensuring these resources are effectively allocated is key to maintaining accountability for safety and quality assurance. Proper assessment and monitoring of the potential safety risks to a system and their impact on system operation is critical in determining an appropriate resource allocation. No single methodology or perspective is sufficient for solving complex risk problems [3]. Multiple stakeholders, each with different viewpoints and objectives, are inherent in most systems, and optimization of one objective usually comes at the expense of not optimizing another [4,5]. Thus, when evaluating system risks with regard to resource allocation, one must take into account the multiple stakeholder perspectives on the issues and problems the system brings about. Tsang et al. [6] discuss the importance of considering multiple perspectives in assessing a safety-critical system. As they describe, each stakeholder frequently has a different perspective on the parameters and risk factors related to the system. Without taking into account multiple stakeholder perspectives on a system, performing an effective risk reduction program is impossible. Lambert and Sarda [7] describe, "this stage is important as it recognizes that … scenarios are associated to components of the systems beyond those that are identified directly. The use of indirect relationships will thus expose non-obvious vulnerabilities" [7]. Lambert and Sarda further describe that, through examining multiple perspectives to a problem, one is able to identify interdependencies in the system structure.

This paper develops and tests a methodology for identifying, organizing, and aggregating potential risks to a safety-critical system in order to formalize a prioritization scheme for protection

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against a hazard. The methodology developed here is designed to (i) avoid false consensus of varying expert views by illuminating the effects of multiple complementary perspectives on system organization, and (ii) address the process of decision-making under stakeholder-specific assessments of risk factor relationships. The methodology is examined with respect to multiple layered stakeholder perspectives in order to address potential contention among stakeholders and to effectively allocate program resources. The effects of varying perspectives on the identification of and relationships among system risks and the ensuing results on hazard prioritization are analyzed.

The methodology is applied to a case study allocating training meetings to improve airport runway safety. This paper addresses the runway safety problem by identifying indicator and causative factors by airport and thereby prioritizing which airports warrant training or intervention by the program safety office. The methods demonstrated in this paper will be applicable across a variety of complex systems and sources of risk. The generalized characteristics and needs of this problem are described in the following sections.

2. Background

The approach of this paper will adopt elements of existing methods described in this review of literature and contribute the innovation of *layered stakeholder perspectives* in developing multiple models of hazard to a system. Considerable insight will be achieved by varying the perspective on relevant risk factors and the relationships thereof, building on the following earlier efforts. Theory, methods, and previous efforts on assessing and organizing potential risks to a large-scale system are described below, with our extension to the runway safety problem to be described in subsequent sections. In particular, this section motivates our distinguishing of risk at locations across a distributed infrastructure via multiple hierarchical modeling perspectives and factor hierarchies.

2.1. Risk assessment and management.

The identification and organization of a system's risks and objectives is a crucial task when considering a complex risk problem with multiple dimensions of resource allocation. Several investigators, including Haimes [3], Keeney and Raiffa [8], and others [9–13], suggest the implementation of a hierarchical organization of risk factors and objectives to echo the hierarchical nature of many organizational and technological systems. A hierarchical organization of factors allows for the synthesis of qualitative and quantitative evidence [14]. As Haimes [3] describes, another valuable aspect of the hierarchical organizational framework is its ability to evaluate risks as they apply to subsystems and their corresponding contributions to the system as a whole. Haimes illustrates this benefit by recommending the use of hierarchical holographic modeling (HHM) and risk filtering, ranking, and management (RFRM) for identifying key risk factors to a system [3,15].

2.2. Systems analysis and risk identification.

The major phases of the RFRM process are: (i) scenario identification through HHM, (ii) scenario filtering, (iii) bicriteria filtering and ranking, (iv) multicriteria evaluation, (v) quantitative ranking, (vi) risk management, (vii) safeguarding against missing critical items, and (vii) operational feedback [3]. HHM, the first phase of the RFRM process, is a key step in the risk assessment process, as it attempts to identify and organize all possible risks to a system based on multiple possible perspectives and aspects of the system. This holistic approach provides a mechanism with which to identify and structure possible scenarios surrounding a system. The remaining phases of the RFRM process, which consists of evaluating risks against a variety of criteria, filter the risks to those most crucial to system performance. Resulting from the RFRM is a manageable set of risks that should receive the most focus when performing a risk assessment on a system [3,15,16,43].

Similar to the hierarchical organization of sources of risk is the hierarchical nature of objectives, as discussed by Keeney and Raiffa [8]. Following Manheim and Hall [17], MacCrimmon [18], and Miller [19], among others, Keeney and Raiffa suggest organizing system objectives in a hierarchical fashion using methods of specification and means-ends. These methods structure objectives in terms of higher-level objectives and their constituent subobjectives. Each set of subobjectives acts as a means to an end, where the "end" is the higher-level objective. By dividing objectives in this manner, they state, one is able to identify where focus should lie in order to achieve the broad objectives by working up the hierarchy to the overall goal of the project or system. Keeney and Raiffa [8] emphasize that this hierarchical construction must include all aspects of each higher-level objective as subobjectives. This is a crucial step to insure that all objectives are properly identified and accounted.

Similar to the HHM described above, Keeney and Raiffa emphasize that, although having an excess of objectives can be overwhelming and confusing, one should not discard too many objectives so that the remaining hierarchy is sparse and unrepresentative. Also similar to the criteria in the RFRM process above, a test of importance determines whether an objective should be included in the hierarchy. This test, developed by Ellis [20], indicates that one should ask oneself whether she/he would change her/his course of action if a particular objective were excluded. If one believes the overall best course of action may be altered, the objective should be included in the hierarchy; otherwise, it should not [8]. The hierarchical processes described here are influential in identifying and organizing risk factors.

2.3. Use of expert evidence and the incorporation of multiple stakeholders.

Once the appropriate risk factors are identified and organized, they must be aggregated/synthesized in order to create meaningful results. Many methods exist to evaluate the likelihood of a particular event occurring. Most, if not all, methodologies involve the generation of explicit probabilities. This is especially relevant in cases involving the use of quantitative risk analysis, which is becoming increasingly prevalent in real-world safety programs. A practical way to represent these likelihoods is to use objective probabilities, those derived from frequencies of events in historical data or statistical analysis. However, when these sources do not exist or when supplementary information is desired, likelihoods are developed from subjective probabilities, those derived from the elicitation of expert evidence [3].

The development of probabilities requires *expert evidence*, rather than *expert opinion*. Although these two terms are frequently used interchangeably, Kaplan emphasizes the fact that this should not be the case—that the two are distinct concepts. What is desired is the objective information an expert can provide about the topic, not subjective thoughts on the subject [21]. Acquiring accurate expert evidence is not a trivial task, and once the evidence is available, analytically incorporating it into analysis is difficult [22]. There are several difficulties with taking into account expert evidence.

First, as Tversky and Kahneman note, are the *availability* and *retrievability* biases, which state that experts are often prone to overestimate the probabilities of recent occurrences. A similar phenomenon exists when an expert may recall an experience with which she/he has a personal connection more quickly or vividly than others due to its higher level of personal salience [23]. Biases such as these must be taken into account when incorporating expert evidence into quantitative analysis. Second, expert evidence on the operation of a system is not always entirely accurate. Paté-Cornell and Guikema illustrate this occurrence for probabilistic modeling of a system in which there is a terrorist threat to the United States. They discuss the possibility to rank terrorist threats according to various metrics. The authors note that the ordered rankings derived from these analyses do not always meet with expert intuition [24]. Instead, experts often overestimate some threats at the expense of underestimating others. Expert evidence, although a key piece in the development of a quantitative portrayal of a system, should be used as a supplement to objective evidence from historical records and statistical analysis.

Multiple stakeholders are inherent in any system. Thus, when evaluating a system, one must take into account multiple stakeholder perspectives on the issues highlighted by the system. Without taking into account multiple stakeholders perspectives on a system, an effective risk reduction program is impossible. Lambert and Sarda [7] stress the importance of considering multiple perspectives to highlight nonobvious relationships and interdependencies between system components. Tsang et al. [6] begin to consider the stakeholders, problem scope, and driving parameters of a systems analysis. One of the key contributions of the paper is the increased ability to define early in the lifecycle the plural aspects and perspectives of the benefits and costs of a risk program for rare and extreme events [6].

The papers discussed above provide the foundation for a layered-methods approach to the risk in a large-scale system, where efforts will be made to aggregate risk factors by incorporating expert evidence. Although each of the above papers is influential to the study of risk and multi-objective tradeoff analysis, there is an opportunity to add to the above works as follows. The above works emphasize the creation, organization, and aggregation of system risks. Although Tsang et al. [6] emphasize the importance of multiple stakeholder perspectives, these effects are neither fully quantified nor related to aggregation of risk factors. This paper thus builds on the efforts described above by analyzing multiple hierarchies of risk factors representing layered stakeholder perspectives as they relate to the risk of runway incursions. The problem combines aspects from several other problems in that it adds multiple stakeholder perspectives on system modeling and analysis. Specifically, a key method that will be adapted from Haimes [3] and others [8,17–19] is the use of hierarchical method to identify and organize risk factors. An extension of the method to incorporate multiple stakeholder perspectives is presented in the following sections.

3. Methodology

This section introduces a multiple-layer approach to the incorporation of varying perspectives in the identification of potential risks to a system. A key element of the approach is the integration of multiple stakeholder perspectives into the existing risk identification methods discussed in Section 2. The integration of additional perspectives is crucial, as determining precise, agreed-upon values can be impossible [25]. The approach thus allows for varying perspectives across a variety of different stakeholders in order to account for varying beliefs on the emphasis of and relationships among potential risks to a system, thereby avoiding false consensus. The effects of layered stakeholder perspectives, indexed SR-A, SR-B, SR-C, etc., on the identification and organization of risk factors will be analyzed.

The approach described in this paper follows a multiple step process, as illustrated in the flow diagram in Fig. 1. The administrator of the process begins by determining which stakeholder experts to inquire and convene these stakeholders for a safety working group. Once the working group is formed, relevant risk factors should be collected from all stakeholders. The stage, which is analogous to a *brainstorming* phase, should include a discussion of historical data on the hazard system to determine specific perspectives. Stakeholders should then be spatially separated in order to avoid false consensus and input from other stakeholders. The approach proceeds by assessing hierarchical factor relationships according to each individual expert in parallel. The administrator then performs one or more method of factor aggregation to incorporate the varying perspectives of each stakeholder. The approach concludes with the re-gathering of the experts and the assessment of variance in stakeholder perspective. The administrator should share all charts and results generated with the working group for feedback and discussion. The administrator should use the discussion along with the analysis itself to determine which results are most significant to the system being studied. Results of the process will likely vary based on the administrator since different administrators may use different sets of data or may employ different scientific experts or stakeholders.

Hazard reduction is especially crucial for transportation systems. Runway safety in particular is of key concern of regulatory agencies, including the US National Transportation Safety Board (NTSB) and the US Federal Aviation Administration (FAA). Runway incursions, or near-misses, are a common metric for evaluating runway safety. A runway incursion is formally defined as the erroneous presence of an object on the runway [26]. Situations involving incursions are extreme events—they are rare but dangerous, as they have the potential to interfere with aircraft take-offs and landings, possibly by way of collisions [27,42]. Incursions are precursors to aviation accidents and have become more frequent since fiscal year 2007 [26]. Accidents such as incursions are, as Dekker states, "no longer accidents at all. They are failures of risk management" [1].

The rate of incursions often differs by airport. In the United States, airports with high incursion rates are selected for three-day evaluation and training sessions with regional and national authorities. The goal of these training meetings is twofold: (1) "to address existing runway safety problems and issues" and (2) "to identify and address potential runway safety issues" [28,29]. As is frequently the case, resource limitations constrain the number of safety training meetings that can be performed. Ensuring these

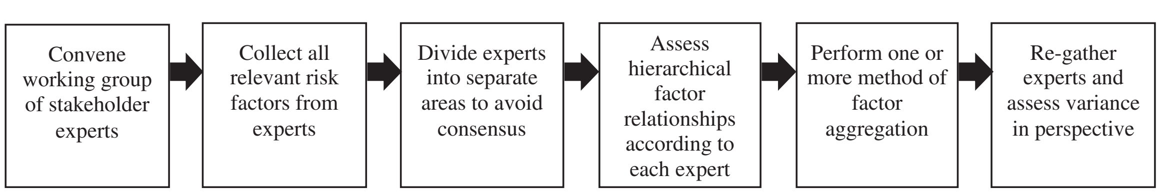

Fig. 1. Flow chart of approach of paper incorporating multiple expert perspectives into factor hierarchies.

resources are properly allocated is key to maintaining accountability for safety and quality assurance. It is thus important that such evaluation and training resources be allocated systematically where need is greatest and where they can be most effective to reduce incursions.

In order to prioritize which airports should receive training and other program interventions, it is necessary to develop an understanding of the runway safety system and, in particular, the potential causes and ramifications of runway incursions. This is not a trivial task, as the runway incursion problem is a complex one for which there is no single cause. Factors that may influence the probability of a runway incursion occurring vary greatly in type, from those pertaining to runway layout and identification to navigation and communication among pilots, drivers, and controllers [30]. This section illustrates the process by which factors are identified and filtered to a manageable set.

To begin, factors that could have an influence on runway incursions are identified using the HHM process described in Section 1 [3]. Factors are then filtered to those most critical to the runway safety problem using the RFRM process, also described above. The filtering process involves the elicitation of expert evidence to determine which factors are most likely to lead to an incursion and thus should remain in the analysis. Analysis is then performed on the remaining factors to ensure that no key factors were unintentionally filtered out. Each step of the HHM and RFRM process is not discussed in detail here; the factors identified for use in this analysis are those remaining after the RFRM process. Table 1 shows the runway incursion factors that are considered in this analysis. These factors are assigned identification markings of RIF-01 through RIF-23, in no particular order.

Factors in the table vary greatly in type and degree of impact on a runway incursion. Many factors used in this analysis were developed through previous efforts focusing solely on identifying the causes of runway incursions [30]. Several additional factors were added for this analysis to account for further complexities in the runway safety system. The newly added factors are indicated in italics in the table and are discussed further in the coming paragraphs.

One of the newly added factors for this analysis is the number of *hot spots*, RIF-08, which is a measure of the number of locations at an airport where many incursions have occurred in the past and are likely to occur in the future. The concept of the hot spot in the network of airport runways is a reflection of the concept of the point of conflict in the network of highways [31]. Just as points of conflict are locations where traffic incidents are likely to occur, hot spots are pinpointed locations where runway incursions or accidents are likely to occur. These geometrical oddities in the runway layout may be the result of several runways intersecting in a central location, very closely aligned runways, short taxi routes from the runway to the terminal, or other runway geometry issues. Since each hot spot is a potential location of an incursion, the greater the number of hot spots at a particular airport, the more likely the airport is to experience an incursion.

The *intersection-operations (per year)* factor (RIF-11) another newly added factor, is defined as the number of runway intersections multiplied by the number of operations per year at a particular airport. This factor provides an additional level of complexity to the analysis of the runway incursion problem and reflects a further manifestation of the points of conflict concept with regards to highway safety. The intersection-operations factor combines a measure of runway traffic and geometry just as the Federal Highway Administration (FHWA) combines highway traffic and geometry by measuring the number of vehicles through intersections and points of conflict [31]. The number of *incursions per intersection-operation* (RIF-14) notes an additional level of complexity by combining a measure of traffic failures along with runway traffic and geometry.

Factors RIF-18 through RIF-21 account for variation in weather and geography across airports, as these factors have been shown to have an influence on the risk of incursions [32]. Research by the US Department of Transportation (US DOT) Federal Motor Carrier Safety Administration (FMCSA) on the causes of incidents in other safety-critical transportation systems (specifically, commercial motor vehicles, or CMVs) shows that weather events, such as snow and rain, have adverse effects on the performance of safety operators [32]. As this analysis is focused on the on-the-ground operations and incursions considered in this analysis take place on the ground, involving vehicle drivers as well as pilots, the airport runway system is analogous to a safety-critical ground transportation system, and it is thus logical and imperative to include weather factors RIF-18 to RIF-21. For this analysis, a *freezing day* is defined as a day with temperatures below 32 °F (0 °C), and a *hot day* is defined as a day where the temperature reaches a point above 90 °F (32 °C).

The FMCSA study further shows that CMV operators do not perform as well in the dark as they do during the day, as they are not able to see potential dangers as well in the night [32]. RIF-22, the *variation in day length*, is added to account for this risk factor. RIF-22 measures the difference in the length of daylight at a particular airport on the summer solstice, the longest day of the year, and the winter solstice, the shortest day of the year. This accounts for the fact that areas with long periods of darkness during a stretch of the year are more prone to incursions than those were the length of daylight remains long or consistent throughout the year.

The *variation in day length* factor is also important from a psychological perspective. The effects of seasonal affective disorder (SAD) on human performance are extreme. It has been shown that people are less willing to work to do their jobs correctly and therefore more likely to make errors during the winter, perhaps due to cold temperatures or little daylight. Areas where the effects of SAD are the most dire are those with extremely short days in the winter and long days in the summer. Thus, the variation in day length accounts for this psychological concept as well [33].

For ease of analysis, several aggregate factors are defined as the composition of other factors. First, *general airport geometry*

Table 1
Runway incursion factors developed in this analysis (denoted by italics) or adopted and modified from variety of sources as described in the narrative.

RIF-01	General airport geometry
RIF-02	Crossing runways
RIF-03	Intersections
RIF-04	T-intersecting runways
RIF-05	Intersecting runway safety areas
RIF-06	Taxiways crossing many runways
RIF-07	Close thresholds
RIF-08	*Hot spots*
RIF-09	Cumulative airport geometry counts
RIF-10	Airport operations (per year)
RIF-11	*Intersection-operations (per year)*
RIF-12	Incursions (per year)
RIF-13	Type A or B incursions (per year)
RIF-14	*Incursions per intersection-operation*
RIF-15	Incursions per 10^5 operations
RIF-16	Activity percentages
RIF-17	Days since last safety review
RIF-18	*Yearly snowfall (average)*
RIF-19	*Rainy days per year (average)*
RIF-20	*Freezing days per year (average)*
RIF-21	*Hot days per year (average)*
RIF-22	*Variation in day length*
RIF-23	Other information

(RIF-01) is defined as the number of the following attributes at an airport: closely aligned runways, parallel runways, short taxi routes, and bullseye formation. Each of the factors making up the general airport geometry aggregate factor is a binary variable, measuring whether an airport has or does not have the attribute in question. Second, *cumulative airport geometry counts* (RIF-09) is defined as the combined number of runway intersections, T-intersecting runways, intersecting runway safety areas, taxiways crossing many runways, close thresholds, and hot spots at an airport. Different from the binary variables that make up the general airport geometry factor, each factor considered in the cumulative airport geometry counts represents a count of the number of the attribute in question at an airport. Third, the final factor in the table, *other information* (RIF-23), is an aggregate factor used to account for several certifications and basic features an airport may have, including an associated flight school and a federal contract tower. These factors are shown in Table 2 and are discussed further in the coming sections.

The list of factors included in the analysis has the potential to change as new possible causes of incursions are identified. Other factors that could have an effect on runway incursions include airport culture, management style, method of communication, and others. Although such psychological factors play a role in causing incursions, they are filtered out for this analysis, as they are nearly impossible to measure in a fair, quantifiable manner. The list in Table 1 is the filtered list (on which the RFRM process is complete), and any factors previously filtered out of the analysis can be added back in at a later date if deemed necessary. Similarly, the list can be filtered down further if some factors are deemed minimally important to causing incursions.

The factors affecting the incursion rate at an airport should be understood from multiple perspectives. Since the relationships among factors vary among stakeholders, each stakeholder is allowed a different view on the organization of relevant factors along with the inclusion/emphasis of the factors themselves. The approach is thus able to account for and compare different stakeholder opinions and biases while avoiding aggregating all stakeholder perspectives.

A key feature of the approach is to allow each stakeholder to have varying perspectives on contributing factors and the hierarchical relationships associated with these factors. The approach allows the stakeholders to have varying opinions on (1) the factors included/emphasized in the analysis, and (2) the relationships among emphasized factors. The difference of perspective can be characterized as follows, where preferences and allowed to vary in several ways.

Multiple hierarchical representations are developed based on complementary structurings of the data, risk factors, and objectives. The factor hierarchies created here are motivated by the HHM and RFRM philosophies discussed in Section 2 [3,15]. The RFRM process filters the original list of factors to those deemed most influential on the analysis, and the multiple hierarchical factor representations provide a way to filter the factors even further, past the point where all stakeholders agree on the level of significance of each factor. Multiple hierarchies allow for the different stakeholder perspectives. Stakeholders are thus able to present their perspectives on the factors that have the greatest influence on the occurrence of runway incursions. There may be some factors from the list in Table 1 that were not filtered out through the RFRM process but that have little influence on the occurrence of runway incursions. Multiple hierarchies allow experts to recognize this fact and filter the list further, selecting which factors to emphasize in their particular hierarchy. Similarly, an expert may add in factors that were filtered out or omitted completely in the HHM and RFRM process. This step serves as verification that necessary perspectives are included and the analysis is being formed correctly.

The key contributions of the complementary hierarchies are twofold: (1) to identify and examine the role of each factor in the overall airport runway system, and (2) to demonstrate and allow for the perspectives of multiple experts and stakeholders on the runway safety problem. Methods for rating and aggregating factors in a hierarchical organization are well known in the field [e.g., [2–4,8,24]] and thus will not be discussed in detail. Rather, results from one such method are analyzed to demonstrate the effects of multiple stakeholder perspectives on the hierarchical organization of risk factors. This paper thus demonstrates agreement on factor aggregation and disagreement on factor organization.

The use of multiple hierarchies allows the large list of factors generated in Table 1 to be filtered to a manageable set. As Miller argues [34], the maximum number of objects one can have in working memory at one time is in the range of seven plus or minus two. That is, it is difficult for the human brain to comprehend or compare too many objects at once. Similarly, including too many factors can be troublesome and difficult to comprehend on a cognitive level, so they must be filtered down further than the list in Table 1 based on expert evidence/multiple stakeholder perspectives.

Just as there are multiple perspectives on a system such as runway safety, there are an unlimited number of possible factor hierarchies. Seven organizational factor hierarchies are discussed in this analysis, each illustrated by a different hierarchical representation of factors. Hierarchies represented in this section are chosen to reflect vastly different stakeholder perspectives, indexed SR-A, SR-B, SR-C, SR-D, SR-D, SR-E, SR-F, and SR-G. The analysis in the following sections would be altered significantly if the hierarchies were changed (i.e., if the hierarchies reflected increased agreement upon emphasized factors). The factor hierarchies are displayed in the following figures. The bold factors are those emphasized in the specific hierarchy.

For the creation of the hierarchies and the ensuing analysis, several aggregate factors are defined as the composition of previously defined features. Aggregate factors include *general airport geometry* (RIF-01), *cumulative geometry counts* (RIF-09), and *other information* (RIF-23). Aggregate factors are useful to show the generality of the hierarchies. The remainder of the factors shown in the factor hierarchies maintain their previous

Table 2
Definitions of aggregate incursion factors to be used in factor hierarchies for characterizing risk of runway incursions.

Code	Aggregate Factor	Definition
RIF-01	*General airport geometry*	Number of the following attributes: closely-aligned runways, parallel runways, short taxi routes, bullseye formation
RIF-09	*Cumulative airport geometry counts*	Cumulative counts of the following attributes: runway intersections, T-intersecting runways, intersecting runway safety areas, taxiways crossing many runways, close thresholds, hot spots
RIF-23	*Other information*	Number of the following attributes: airport certifications, flight school, federal contract tower

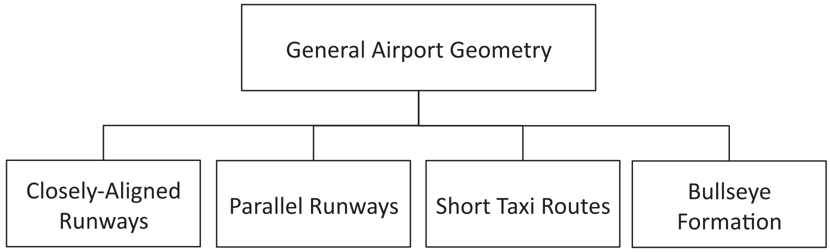

Fig. 2. Factors related to *general airport geometry*, to be used in factor hierarchies.

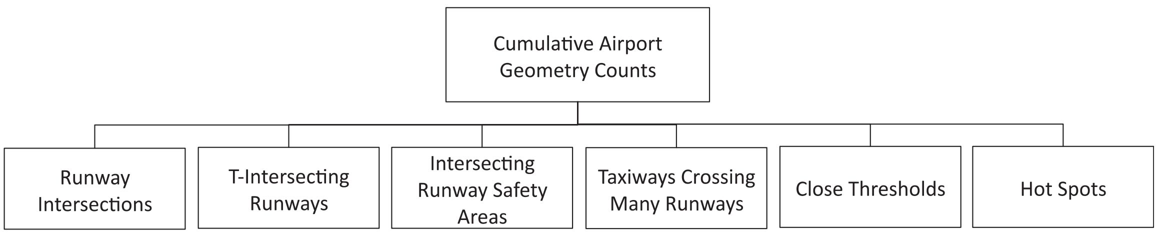

Fig. 3. Factors related to *cumulative airport geometry*, to be used in factor hierarchies.

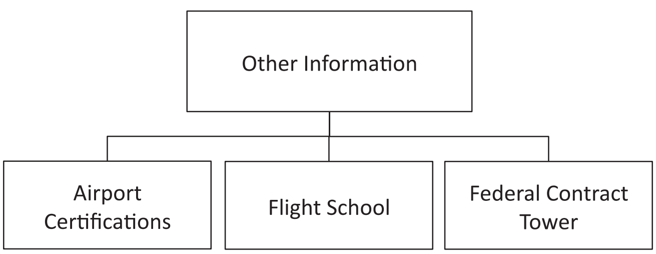

Fig. 4. Factors related to *other information*, to be used in factor hierarchies.

definitions. Figs. 2–4 illustrate the hierarchical decompositions of each of the aggregate factors and the subfactors that are combined in their formations. These organizational structures are implicit in each of the factor hierarchies discussed below.

This paper considers the following factor hierarchies, where each hierarchy corresponds to a potential perspective of one stakeholder or group of stakeholders on the runway incursion problem. The hierarchies introduced here are realistic descriptions of potential scenarios, based on experience of the FAA Office of Runway Safety and attending safety meetings with stakeholders and runway safety experts.

Fig. 5 shows *Hierarchy H01: General Hierarchy*, based on the perspective of stakeholder SR-A. Runway incursion factors are divided hierarchically based on their categorization as *airport geometry*, *airport operations*, *days since last safety review* (history of safety training meetings), and *other information*. The factors in this hierarchy, like those in all hierarchies to be discussed, are airport-specific and vary from airport to airport. This hierarchy represents the perspective of a stakeholder or group of stakeholders with little additional information as to the relative importance or emphasis the factors should receive. Each of the lowest level factors is shown in bold, representing the fact that this stakeholder believes each factor should be considered in the analysis, possibly to ensure relevant data is not lost or forgotten. Stakeholder SR-A is unfamiliar with the intricacies of the runway safety system and therefore unwilling to make irrational judgments as to which factors should be emphasized in the analysis.

Fig. 6 shows *Hierarchy H02: Emphasis on Specific Counts*. H02 represents the point of view of stakeholder SR-B, who emphasizes runway incursion factors describing specific counts in the analysis. Stakeholder SR-B emphasizes the criticality of airport geometry and operations, likely the result of a belief that a complex airport runway system is likely to experience many incursions.

Fig. 7 shows *Hierarchy H03: Emphasis on Operations and Incursions*. H03 shows the perspective of stakeholder SR-C, who is most concerned with the impact of the number of operations and incursions at an airport in the past year. Although H03 has fewer factors, it adds to the analysis by incorporating a perspective based solely on an airport's past experiences with regards to operations and incursions.

Fig. 8 shows *Hierarchy H04: Extension to Include Weather and Geography*, based on the perspective of stakeholder SR-D. This hierarchy adds to *Hierarchy H01: General Hierarchy* and incorporates the additional weather and geography factors created for the purpose of this analysis. These factors, yearly snowfall, rainy days per year, freezing days per year, hot days per year, and variation in day length, provide a method of incorporating the effects of the airport location on the number of runway incursions it experiences in a given year.

Fig. 9 shows *Hierarchy H05: Emphasis on Weather and Geography*, based on the perspective of stakeholder SR-E. H05 emphasizes the weather and geographical features along with the number of operations and incursions at an airport in the past year. This hierarchy would be useful when little data on airport structure and geometry exists, as operation/incursion data and weather/geography data are typically more readily available than other, more qualitative factors such as airport geometry.

Fig. 10 shows *Hierarchy H06: Emphasis on Factors that Can Be Affected by a Safety Meeting*, held by stakeholder SR-F. H06 emphasizes only the factors in the incursions sub-category since those are the factors directly impacted by a safety meeting.

Fig. 11 shows *Hierarchy H07: Emphasis on Factors that Cannot be Affected by a Safety Meeting*, based on the perspective of stakeholder SR-G. This final hierarchy is equivalent to the inverse of hierarchy H06. Although it may not be the realistic to omit incursion factors from the analysis altogether, it is more realistic to include factors other than solely those relating to incursion rates. Stakeholder SR-G broadens her/his viewpoint by emphasizing a vastly different factor hierarchy than those upheld by the previous stakeholders.

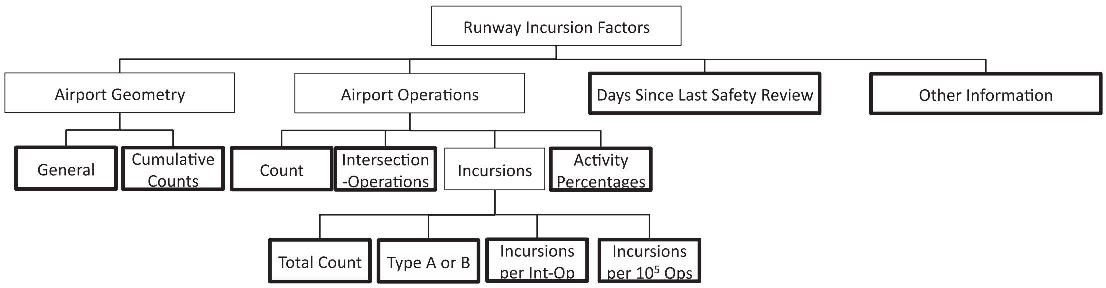

Fig. 5. Hierarchy H01: General, airport-specific hierarchy, representing a complementary perspective on the organization and emphasis of runway incursion factors for prioritization of airports for risk of runway incursion.

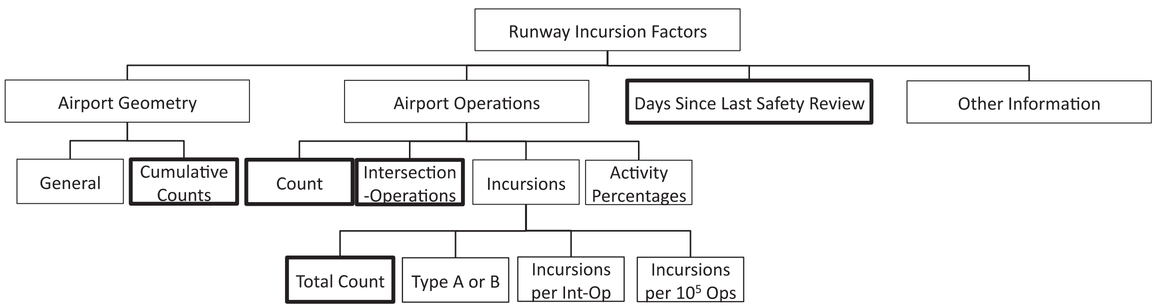

Fig. 6. Hierarchy H02: Emphasis on specific counts, representing a complementary perspective on the organization and emphasis of runway incursion factors for prioritization of airports for risk of runway incursion.

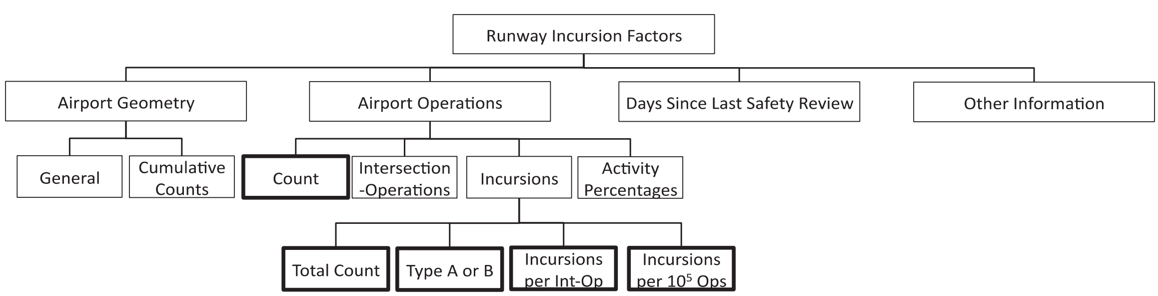

Fig. 7. Hierarchy H03: Emphasis on operations and incursions, representing a complementary perspective on the organization and emphasis of runway incursion factors for prioritization of airports for risk of runway incursion.

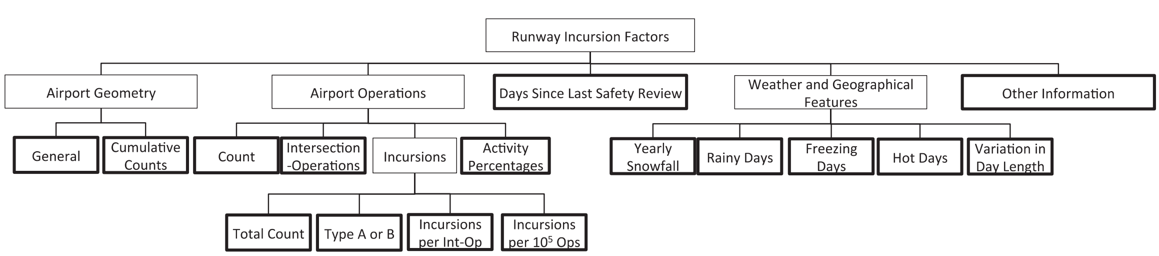

Fig. 8. Hierarchy H05: Emphasis on weather and geographical features, representing a complementary perspective on the organization and emphasis of runway incursion factors for prioritization of airports for risk of runway incursion.

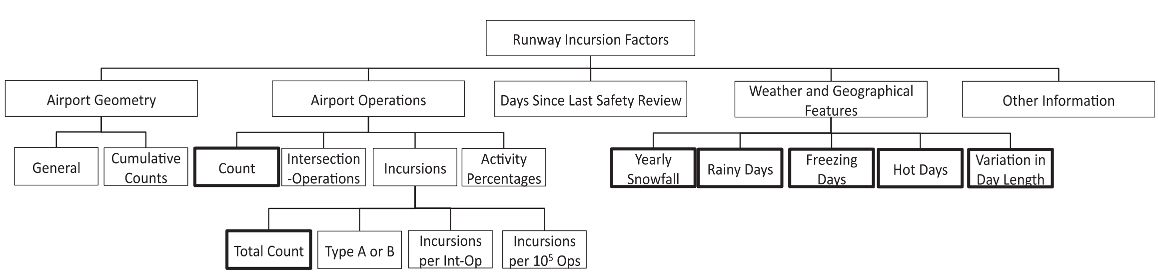

Fig. 9. Hierarchy H04: Extension to include weather and geographical features, representing a complementary perspective on the organization and emphasis of runway incursion factors for prioritization of airports for risk of runway incursion.

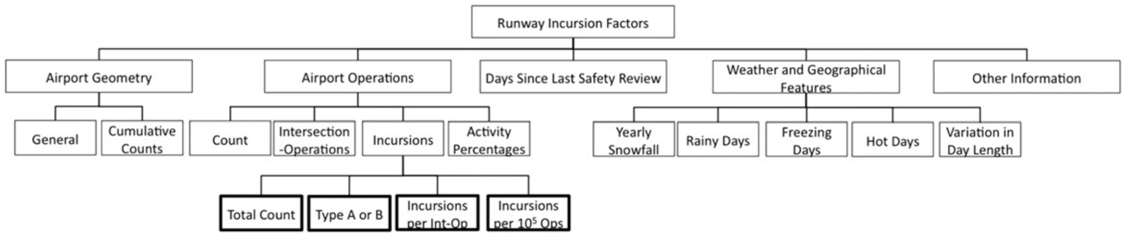

Fig. 10. Hierarchy H06: Emphasis on factors that can be affected by a safety meeting, representing a complementary perspective on the organization and emphasis of runway incursion factors for prioritization of airports for risk of runway incursion.

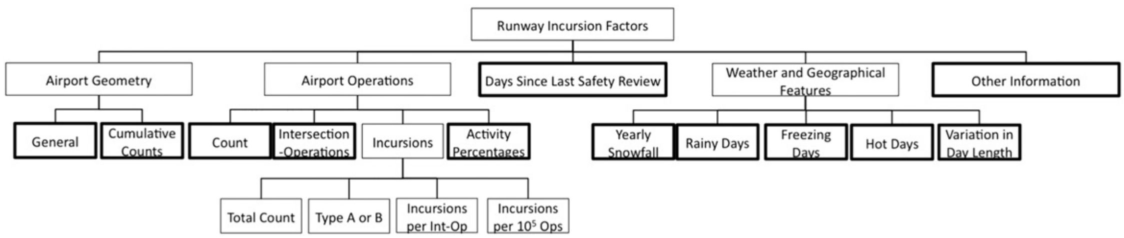

Fig. 11. Hierarchy H07: Emphasis on factors that cannot be affected by a safety meeting, representing a complementary perspective on the organization and emphasis of runway incursion factors for prioritization of airports for risk of runway incursion.

Table 3
Quantitative definitions of *high*, *moderate*, and *low* ratings for each factor to be used in the multiple factor hierarchies.

Factor	High rating	Moderate rating	Low rating
General airport geometry	3 or more of: closely aligned runways, parallel runways, short taxi routes, bullseye formation	1–2	0
Cumulative airport geometry counts	3 or more of: intersections, T-intersecting runways, intersecting runway safety areas, taxiways crossing many runways, close thresholds, hot spots	1–2	0
Airport operations	155,000 or more operations	70,000–154,999 operations	0–69,999 operations
Intersection-operations	250,000 or more intersection-operations	1–249,999 intersection-operations	0 intersection-operations
Incursions	4 or more incursions	1–2 incursions	0 incursions
Type A or B incursions	1 or more incursions	N/A	0 incursions
Incursions per intersection-operation	1.0×10^{-5} or more incursions	$0-1.0\times10^{-5}$ incursions	0 (or undefined) incursions
Incursions per 10^5 operations	2.5 or more incursions	0–2.5 incursions	0 incursions
Days since last safety review	1025 or more days	625–1024 day	0–624 day
Yearly snowfall	More than 45 in.	30–45 in.	Fewer than 30 in.
Rainy days	More than 130 day	70–130 day	Fewer than 70 day
Freezing days	More than 150 day	125–150 day	Fewer than 125 day
Hot days	More than 20 day	10–20 day	Fewer than 10 day
Variation in day length	More than 6 h30 min	5 h45 min–6 h30 min	Fewer than 5 h45 min
Other information	2 or more of: 139 certification, flight school, federal contract tower	1	0

Other perspectives and factor hierarchies could be admitted in future efforts.

4. Results and discussion

The methods of this paper provide insight into safety training programs by employing layered stakeholder perspectives in the identification and synthesis of potential risks to the system. A single perspective on the runway safety problem (or other hazard protection system) insufficiently accounts for the variety in stakeholders. This section discusses implementation of the several factor hierarchies and illuminates what is gained by considering the additional perspectives. Results of the runway safety demonstration are discussed and analyzed below.

Methods of implementation of factor hierarchies in both weighted and unweighted methods are well known in the literature [2–4,8,24]. Several methods of aggregation have been performed with regard to this problem [35], where this paper employs one such method to implement factor hierarchies and determine a ranking of airports at risk of runway incursion.

A *high*/*moderate*/*low* scale is used to rate factors based on their potential to contribute to increased rates or severities of runway incursions. High, moderate, and low ratings are determined based on factor values from the data. The thresholds for high, moderate, and low are quantitative values approximately based on the top quartile, middle 50%, and bottom quartile of airports. That is, the thresholds are set for each factor so that approximately 25% of airports have a *high* rating, approximately 50% have a *moderate* rating, and approximately 25% have a *low* rating. This approach, which is utilized in several methods of factor aggregation, is designed so that a higher rating indicates a higher risk of runway incursion. The high, moderate, and low rating scales for each factor are shown in Table 3.

The several factor hierarchies along with the high/moderate/low factor rating system are implemented through an adaptation of the analytic hierarchy process (AHP) to aggregate and rank airports by risk of runway incursions. The several deficiencies of AHP relative to multiattribute utility theory are well known [36]. This paper avoids one of these deficiencies by the use of rating scales. Another method than AHP could be used for aggregation of the factors assembled for this paper. The AHP as adapted for this paper is complementary to a combinatorial model such as a fault or event tree or Bayesian network [37,39,41]. It uses expert-elicited values on the relative significance of each factor as well as each factor rating in leading to an incursion, allowing factors for which there may have been disagreement as to their importance to be assigned varying weights in the overall prioritization scheme.

Factor weights are used to show which factors are most important in contributing to the overall objective, the reduction of runway incursions. These weights are derived as follows. The expert inputs a value as the relative significance of factor X over factor Y in contributing to a runway incursion. If factor X is more likely to contribute to an incursion than factor Y, the expert enters a positive integer value between 2 and 10 reflecting the magnitude of the difference. If factor X is less likely to contribute to an incursion than factor Y, the expert enters a positive rational value between 0 and 1 reflecting the magnitude of the difference. A value of 1 indicates that the two factors are equally significant in contributing to an incursion. The value of the importance of factor Y over factor X is equal to the reciprocal of the value indicated for the relative significance of factor X over factor Y, reducing the number of expert-elicited pair-wise comparisons necessary.

Only factors on the same tier of the hierarchy are directly compared in this manner. For example, *airport geometry* and *airport operations* would be directly compared, whereas *airport geometry* and the number of *incursions* would not. Similarly, the total *number of operations* would be directly compared to the *activity percentages* but not to the number *of type A or B incursions*.

Once these values are determined for each set of factors, values are normalized within the tier. In order to derive global weights of a factor on the lowest level, the relative weights of each of the factors on the tiers above are multiplied together. For example, multiplying the relative weight of the *airport geometry* factor by the relative weight of the *general airport geometry* factor gives the global weight of the *general airport geometry* factor. Similarly, to attain the global weight of *type A or B incursions*, we multiply the relative weights of *airport operations*, *runway incursions*, and *type A or B incursions*. The process for determining the global weight of factor i is shown in Eq. (1). In this formulation, ω_i is the global weight of factor i with respect to all other factors emphasized in the hierarchy, ω_{ij} is the relative weight of factor j (where factor i is a subfactor of factor j), and factor i is on the τ-th tier of the hierarchy:

$$\omega_i = \prod_{j=1}^{\tau} \omega_{ij} \tag{1}$$

scale-level weights, which are evaluated for each factor, represent how much worse a *high* rating is than a *moderate* or *low* rating for a factor. Scale-level weights are computed once for each factor, whereas factor-level weights are computed for each hierarchical organization of factors. The calculation of the scale-level weights is similar to the first step in the calculation of the factor weights. For each factor, the expert inputs a value (integer or rational number) based on whether one rating is more or less significant in contributing to incursions than another. These values are then normalized, yielding scale-level weights for each factor. Scale-level weights are only evaluated on bottom tier factors. For this analysis, let $\theta_i(k)$ be the scale-level weight for factor i with respect to rating k, where $k \in$ {high, moderate, low}.

Once expert evidence is gathered and factor-level and scale-level weights are calculated, each airport is assigned a scale-level weight for each factor based on whether the airport has a high, moderate, or low rating for the factor. Each airport is then assigned a total score, s, by multiplying the score for each risk factor by the factor weight (i.e., multiply the score for the yearly snowfall by the normalized factor weight for yearly snowfall) as shown in Eq. (2), where N is the total number of factors emphasized in the hierarchy under consideration:

$$s = \sum_{i=1}^{N} \omega_i \theta_i(\kappa) \tag{2}$$

airports are then ranked according to their overall scores, where a higher score indicates increased justification to perform training or other intervention. This process allows for airports to be prioritized based on their number of significant factors with high ratings. Airports with high ratings for significant factors are ranked towards the top of the list and thus prioritized for safety meetings. Airports with high ratings for less significant factors are not prioritized since having a high rating in these factors does not substantially increase the risk of incursion.

The adaptation of the analytic hierarchy process (for purpose of demonstration in this paper) generates an ordering of airports by risk of runway incursions, where highly ranked airports are of greater risks of incursions than others. The process is repeated for each hierarchy of risk factors, and results are compiled into one chart and corresponding graph. Fig. 12 shows the highest, lowest, and median ranking of each airport across the seven hierarchies. In the graph, the vertical bar represents the range of rankings for each airport, where the top of the bar is the highest ranking and the bottom of the bar is the lowest ranking. The point in the center represents the median ranking, by which airports are sorted from highest to lowest. The difference between the highest, lowest, and median rankings shows an airport's sensitivity to change in hierarchy.

The method describes sensitivity to expert evidence and experience as follows. As the hierarchies differ from one perspective to another, the rank ordering of airports changes as well. The analysis demonstrates at which airports this change has the greatest effect on the ranking (those airports with the greatest difference from highest to lowest rankings, or with the longest vertical bars in the figures). Airports with smaller ranges of highest to lowest ranking are less sensitive to change in hierarchy, and one should thus feel more comfortable about the positioning of these airports. Similarly, airports with larger ranges of highest to lowest ranking are more sensitive to change in hierarchy—their ranking changes drastically from one perspective to another.

Of the top ten airports according to median ranking over all hierarchies using factor analysis with weights, the median rankings range from 2 to 13. The lowest high ranking of the top ten airports is nine, where five of the ten rank as highly as one. The lowest rankings range from 7 to 26, where the variation in ranking represents the sensitivity to change in hierarchy.

For example, airports A08 and A56 are ranked highly and have small ranges for the difference between the lowest and highest rankings. These airports are of highest risk of incursion since their median and high rankings are extremely high and there is little variation across hierarchies. Airport A29, on the other hand, has a high median ranking but is very sensitive to change in hierarchy. Although A29 ranks very highly according to the majority of hierarchies, it does rank as low as 76 according to one hierarchy. Although A29 ranks above A56 by median ranking, one may

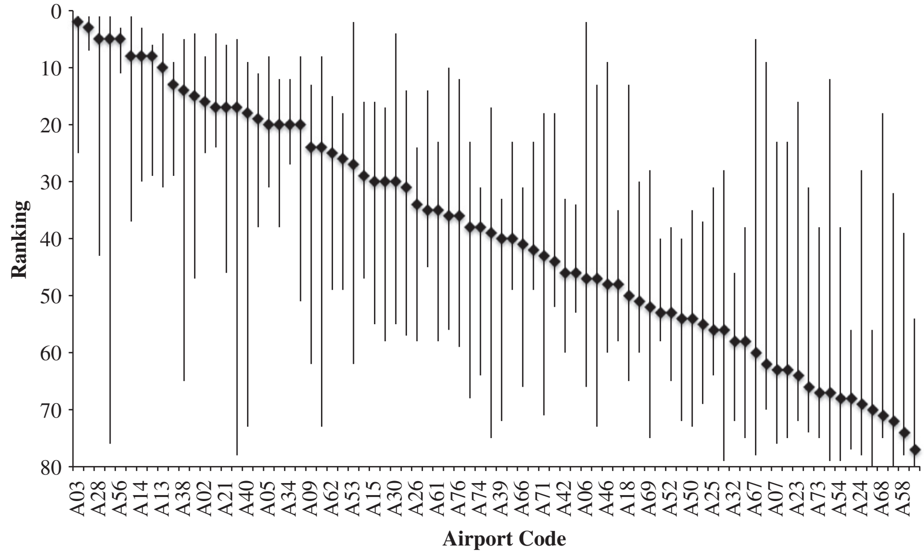

Fig. 12. Aggregation results using an adaptation of AHP, where sensitivity to stakeholder perspective is demonstrated by examining the difference between the highest and lowest ranking for an airport across each of the seven hierarchies.

Table 4
Summary of results from aggregation across seven hierarchical expert perspectives.

Airports with highest high rankings across seven expert perspectives	A03, A08, A28, A29, A11
Airports with highest median rankings across seven expert perspectives	A03, A08, A28, A29, A56
Airports with lowest median rankings across seven expert perspectives	A47, A58, A70, A68, A72
Airports with lowest low rankings across seven expert perspectives	A72, A47. A70, A54, A77

Table 5
Historical data and 95% confidence intervals on number of incursions per 100,000 operations.

Airport	Incursion rate	Lower bound on confidence interval	Upper bound on confidence interval
A06	1.730	1.047	14.530
A07	0.479	0	3.447
A09	0.753	0	4.850
A10	0.920	0	5.914
A12	0.936	0	6.025
A18	0.484	0	3.470
A20	0.494	0	3.513
A22	0	0	1.754
A23	0.543	0	3.740
A25	0.566	0	3.850
A27	0	0	1.754
A31	1.290	0.319	9.007
A39	0	0	1.754
A41	1.357	0.410	9.698
A42	1.081	0.070	7.121
A44	0	0	1.754
A48	0	0	1.754
A49	0	0	1.754
A50	0	0	1.754
A54	0.798	0	5.119
A55	0.810	0	5.194
A61	0	0	1.754
A67	2.962	6.0189	52.253
A68	1.509	0.641	11.450
A80	1.360	0.414	9.732

consider selecting A56 to receive a safety meeting before A29 since A29 is extremely sensitive to change in hierarchy. Further investigation of expert perspective or other methods of analysis could help determine which airport is of higher risk of incursion.

Similarly, airport A67 has a low median ranking of sixty but ranks as high as five according to one hierarchy. Airport A67 is thus relatively more sensitive to change in hierarchy, and, although it has a low ranking according to the majority of hierarchies, it could be ranked highly according to different perspectives. One would not feel as comfortable about the placement of this airport as, for example, A32. Airport A32 has a slightly higher median ranking than A67, but consistently ranks toward the bottom across all hierarchies. Both A67 and A32 would likely not receive safety meetings, but research into the cause of the high ranking for A67 could justify sending a safety team to A67 (if, for example, the hierarchy for which A67 has a high rating is deemed extremely important in determining the prioritization scheme).

Table 4 provides a summary of the results across the seven expert perspectives. The table shows the five most extreme airports in each of four categories that are evaluated across seven hierarchies: highest high ranking, highest median ranking, lowest median ranking, and lowest low ranking. Airports with highest high rankings and highest median rankings are of increased risk of runway incursions. Airports A02, A08, A28, and A29 fall in both of the first two categories (those with high highest rankings as well as high median rankings). These airports are of greatest risk of incursions, as they continually receive a high rank across the seven hierarchies. Airports A11 and A56 are of high risk of incursion as well but are more sensitive to change in hierarchy. Airports A11 and A56 should thus be prioritized second to the first group. Similarly, airports with lowest median rankings and lowest low rankings are of minimal risk of runway incursions and should not receive safety meetings. Although it is possible, there are no airports in the demonstration that fall into one of the high categories and one of the low categories. Should this be the case, any airport with both high and low rankings would exhibit extreme sensitivity to change in hierarchy and may not be deemed warranting of a safety meeting. Further inspection of the formation of the hierarchies could yield additional insight to why airports have drastically different rankings across hierarchies.

The benefits of the adaptation of AHP employed in this paper are evident when comparing the results with historical runway incursion data. Table 5 shows raw data on the number of incursions per 100,000 operations at a subset of the airports under consideration for this analysis. Fig. 13 displays the same incursion rates in a graphical format. Standard 95% confidence intervals on the incursion rates are displayed in the table and the figure.

Based on the historical data and confidence intervals shown in the table and the figure, airports A67 and A06 appear to be of higher risk of incursion than the others in this case study. Based purely on historical data, there is little or no difference in level of risk of the remaining airports. All other airports appear to have very little risk of incursion. Contrarily, neither A67 nor A06 are among the top five highest-risk airports according to the multi-factor elicitation method discussed in this paper. The developed method thus provides an additional level of analysis that is lacking when simply analyzing historical data.

Since runway incursions are rare events, data is sparse and inconclusive. Even when considering confidence intervals on the incursion rates, lack of sufficient data makes it difficult to ''rank'' the airports from highest risk of incursion to lowest risk of incursion. Any ordering that results from analysis of historic incursion data is a partial ordering due to the confidence intervals, meaning that most airports are tied. Although it is evident that airports A67 and A06 appear to be of higher risk of incursion than the others in this case study, shortage of data makes it difficult to determine which of the remaining similar airports are of high risk of incursion. It is also not certain that the apparent outliers (A67 and A06) are of consistently higher risk to incursion due to the scarcity of incursion data. The elicitation method described in this paper avoids this problem and successfully

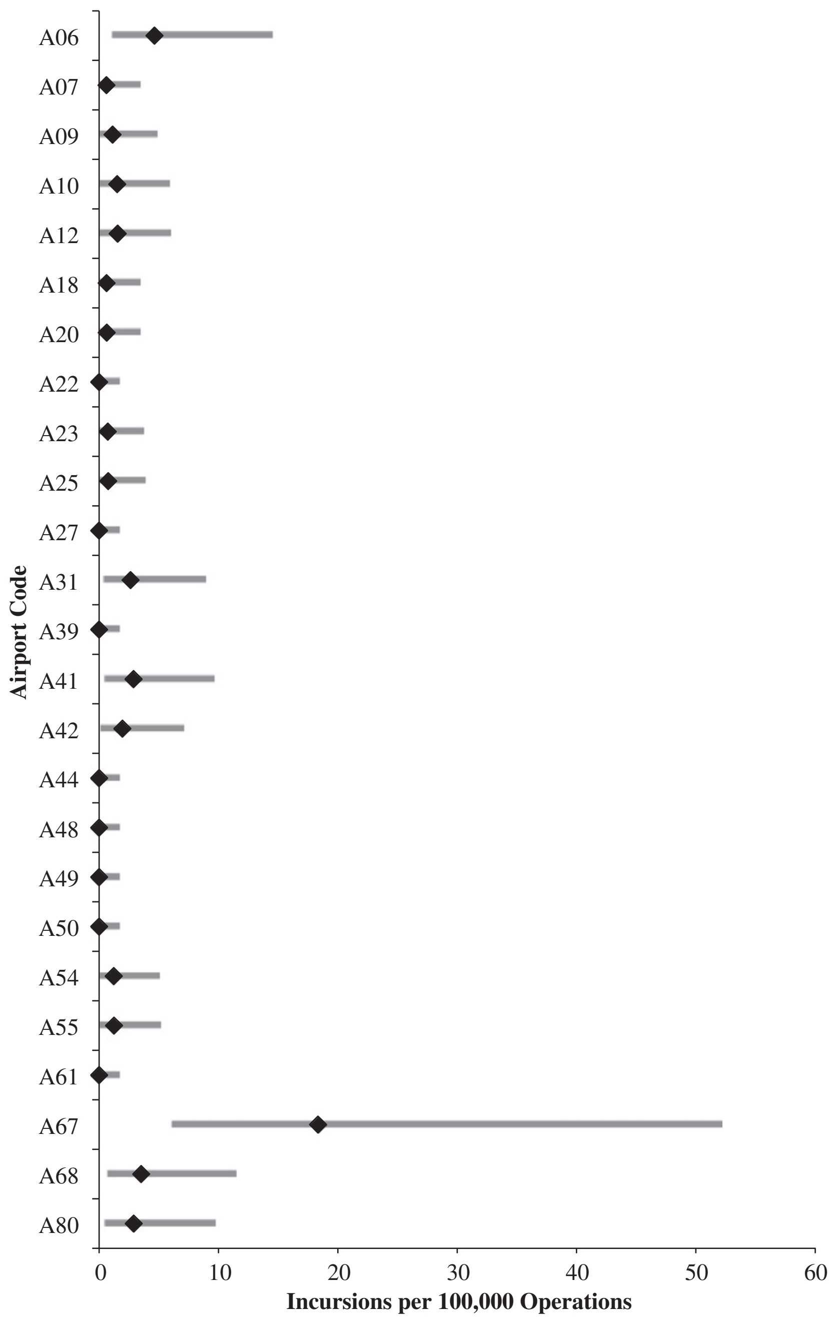

Fig. 13. 95% confidence intervals on number of incursions per 100,000 operations.

delivers meaningful results comparing airports relative to their risk of incursion.

5. Conclusions

This paper uses risk factors to prioritize sources of risk in large-scale systems, particularly by adding *layered perspectives on the emphasis of and relationships among relevant factors*. The paper has developed analysis to support prioritization of risk mitigation, adopting elements of previous hierarchical methods of organizing data and factors [3,8,18,19,46] as well as well known methods of ranking and aggregating risk factors by hierarchy [2–4,8,24]. The sensitivity to multiple expert perspectives on hierarchical relationships of risk factors along are explored. An application of the analysis is demonstrated to a real-world problem of critical worldwide importance to transportation safety.

In the case study, 23 runway incursion factors are organized into seven factor hierarchies to account for varying perspectives among stakeholders on the emphasis of and relationships among factors. Each of the seven hierarchies introduced represents a different perspective on the factors that should be emphasized in developing a prioritization of airports to receive safety meetings and the organization of/relationships among these factors. Several of the 23 factors are combined into three aggregate factors in order to simplify the hierarchies and the ensuing analysis.

The many available methods of aggregating factors and ranking airports based on any single factor hierarchy are not discussed in depth. One such method, an extension of the analytic hierarchy process, is implemented on each hierarchy in the case study. This method employs a *high/moderate/low* factor rating system and uses expert evidence on the relative significance of the factors to produce a weighted score for each airport. Sensitivity of results to change in hierarchy (and thus change in expert perspective) is evaluated to determine which airports are of highest risk of incursions and thus warrant receiving safety meetings.

Future effort will be useful to better select valid and useful perspectives of stakeholders as well as how to perform repeatable assessment of the uncertainties among stakeholders. The analysis discussed in this paper can thus be extended to include an infinite number of stakeholder perspectives. For example, firefighting or other emergency response teams could be useful perspectives to consider in the analysis. An *emergency preparedness* stakeholder would likely maintain a different belief as to the hierarchical organization of factors than the seven stakeholders emphasized here. Comparing the emergency preparedness or any other new stakeholder to the perspectives already discussed in this paper could yield additional insight to the allocation of safety trainings as applied to the runway incursion problem.

The analysis adjusts the aim of a prioritization to include the identification of essential information about key model parameters and factors. The importance of analyzing the consensus or non-consensus of key stakeholders in a safety training program is demonstrated as support for negotiation. Techniques such as these are frequently more useful in a negotiation scenario than traditional optimization strategies. This paper is followed by a submission to the *Journal of Risk Research* that describes a complementary method of prioritizing airports for risk of runway incursion [38]. Future work can be performed to relate the analysis to the theory of negotiation.

Just as incorporating further stakeholders would produce another layer of analysis, including additional runway incursion factors could be useful. The factors employed in this analysis account for a variety of possible conditions that could lead to a runway incursion. However, other factors, such as management style and airport culture, may make a difference in the analysis. Further work might include potential factors describing human behavior, relationships, or interactions. These "soft" factors are frequently critical in promoting runway safety and limiting incursions, but are extremely difficult or impossible to quantify for use in the analysis. Further efforts on identifying and quantifying cultural and management factors are suggested. Additional factors may be included in the hierarchies to reflect culture and management operations at each airport. Alternatively, investigation into the management styles at each airport could lead to airport-specific hierarchies where management of each factor is noted separately.

The findings of this paper are transferable to a variety of large-scale systems in which examining the impact of variation in perspective across several experts on factor organization would be useful. As multiple stakeholder perspectives are inherent in any system, the applicability of the method introduced in this paper extends to almost any problem [44,45]. For example, the development of a prioritization scheme for the locations of training meetings for hospital staff would benefit from the analysis. Similarly, the methods discussed in this paper could be applied to the prioritization of locations for supplies helpful in emergency response. Future work can be performed to deploy the results of this paper to other disciplines, both safety-critical and otherwise, and to automate the development of factor hierarchies via data-mining approaches such as described by [40].

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