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Proposed Methodology for the Use of Computer Simulation to Enhance Aircraft Evacuation Certification

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In this paper a methodology for the application of computer simulation to evacuation certification of aircraft is suggested. This involves the use of computer simulation, historic certification data, component testing, and full-scale certification trials. The methodology sets out a framework for how computer simulation should be undertaken in a certification environment and draws on experience from both the marine and building industries. In addition, a phased introduction of computer models to certification is suggested. This involves as a first step the use of computer simulation in conjunction with full-scale testing. The combination of full-scale trial, computer simulation (and if necessary component testing) provides better insight into aircraft evacuation performance capabilities by generating a performance probability distribution rather than a single datum. Once further confidence in the technique is established the requirement for the full-scale demonstration could be dropped. The second step in the adoption of computer simulation for certification involves the introduction of several scenarios based on, for example, exit availability, instructed by accident analysis. The final step would be the introduction of more realistic accident scenarios. This would require the continued development of aircraft evacuation modeling technology to include additional behavioral features common in real accident scenarios.

I. Introduction

EVACUATION simulation using computer models has been underway for at least 30 years [1–3], one of the first models being developed by the U.S. Federal Aviation Administration (FAA) in the early 1970s [4,5]. Today, evacuation simulation is used in the certification of buildings [6] and passenger ships [7], yet they have no formal role in the certification of aircraft. Part of the difficulty in utilizing evacuation models for the certification of aircraft is that there is no framework or procedure set out for the use of computer models for this purpose. This paper attempts to define such a framework. It should be noted that all the views presented in this paper are solely those of the author.

Until such a framework is in place, it is unlikely that the aviation industry will voluntarily adopt the use of computer simulation for evacuation certification analysis. Hence it is essential that effort be directed towards producing an acceptable framework for the application of aircraft evacuation models to the regulatory environment.

An underlining philosophy adopted by the author in defining this framework is that it is not sufficient to simply replace the current status quo of a one-off full-scale live evacuation demonstration with an equivalent computer simulation. Whereas this may make evacuation certification a safer and more efficient process, computer modeling should also improve the certification process by providing the aviation community and the passengers that use the aircraft something more than what the current simple one-off testing provides.

II. Current Evacuation Certification Process

Aviation regulators attempt to enforce and maintain safety standards through a set of essentially prescriptive rules that have evolved over time. In Europe they are known as Joint Aviation Requirements (JAR) [8], whereas in the U.S.A. the rules are known as the Federal Aviation Regulations (FAR) [9]. An example of one of the rules that has evolved over time relating to aircraft evacuation safety is the so-called "60-foot" rule. The rule appears in the FAR [i. e., 25.803 (f) (4)] [9], and there is an equivalent ruling in the JAR. The JAR rule states:

"For an airplane that is required to have more than one passenger emergency exit for each side of the fuselage, no passenger emergency exit shall be more than 60 feet from any adjacent passenger emergency exit on the same side of the same deck of the fuselage, as measured parallel to the airplane's longitudinal axis between the nearest exit edges [8,9]."

These prescriptive regulations specify design rules that must be followed in the design of all commercial passenger aircraft carrying more than 44 passengers. Compliance with these rules can easily be visually checked by inspectors both during design, by viewing aircraft scale drawings, and when the first aircraft rolls off the production line.

In addition to these prescriptive rules is a performance based requirement commonly known as the "90 second certification test" [10]. Compliance with this rule is demonstrated by performing a full-scale evacuation demonstration. The demonstration is performed in darkness, utilizing only half of the normally available exits and a population which satisfies an age and gender mix specified in the FAR/JAR rules, selected by the manufacturer and approved by the regulatory authority. Crew and passengers do not know before hand which exits will be made available. The test involves evacuating all passengers and crew to the ground (using slides if they are fitted) within 90 s if the aircraft is to pass the performance test. A complete video record is made of the event including behavior within the cabin and at the exits. The video recordings of the evacuations are a valuable source of data concerning the performance level achieved during these types of certification evacuations. This paper addresses the full-scale evacuation demonstration (or trial) component of the certification process and not the entire certification process.

A. Difficulties with the Current Certification Process

The evacuation certification trial is only intended to provide a measure of the performance of the aircraft under an artificial benchmark evacuation scenario. It is not intended to be a predictor of the aircraft performance under plausible or realistic accident scenarios. As such, it could be argued that the certification trial may provide a false sense of security to the traveling public (and parts of the aviation industry), who may assume that if the aircraft is certified, it must be "safe." What the current certification trial does achieve is a

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way of comparing the evacuation performance of different aircraft under a set of identical, if somewhat artificial, scenario conditions.

There are several difficulties with the current 90 s trial. There is considerable threat of injury to trial participants. Published statistics for the periods 1972 and 1991 reveal that a total of 378 volunteers (or 6% of participants) sustained injuries ranging from cuts and bruises to broken bones [11]. In October 1991 during the McDonnell Douglas evacuation certification trial for the MD-11, a female volunteer sustained injuries leading to permanent paralysis.

Another difficulty is the lack of realism inherent in the 90 s evacuation scenario. Volunteers are subject neither to trauma nor to the physical ramifications of a real emergency situation such as smoke, fire, and debris and so the certification trial provides little useful information regarding the suitability of the cabin layout and design or the cabin crew procedures in the event of a real emergency. The Manchester disaster of 1985, in which 55 people lost their lives, serves as a tragic example. The last passenger to escape from the burning B737 aircraft emerged 5.5 min after the aircraft had ceased moving, while 15 years earlier in a U.K. certification trial, the entire load of passengers and crew evacuated the aircraft in 75 s [12,13]. In the certification trial, while passengers may be keen to exit as quickly as possible, the behavior exhibited is essentially cooperative, whereas in real accident situations the behavior may become competitive under certain circumstances.

It may be argued that the inclusion of simulated fire conditions or reduced visibility due to fire smoke is too complex to include within certification trials and even if they could be reliably represented, would further increase the chance of injury to participants and so should be excluded from consideration. However, it is difficult to justify why the certification trial makes use of half the available exits, usually on one side of the aircraft. Providing all exits on one side of the aircraft bears little resemblance to realistic accident scenarios [14–19].

Identifying a population to be used in the one-off certification trial is a difficult task. Given the other prescriptive certification requirements, the number of people successfully evacuated in the trial sets the maximum number of people that the aircraft will be able to legally and by implication, "safely" carry in commercial service. To have any relevance, the test population should be (and indeed is intended to be) representative of the traveling public. The evacuation certification trial assumes that each passenger is socially unconnected to other passengers. In reality, passenger behavior during evacuation may be influenced by the presence of traveling companions and the nature of the social bond that exists between traveling companions. Analysis undertaken using data from past accidents [14–19] suggests that a significant proportion of passengers travel with a "companion" [14]. The frequency of passengers traveling within groups, the size and composition of the groups, and the nature of the group dynamic during emergency evacuation situations may have significant implications for not only evacuation certification but also safety procedures and cabin crew training. However, this important component of evacuation dynamics is excluded from the certification trial.

Another factor related to the population that is ignored by the certification trial is the presence of passengers with disabilities. As people with disabilities are not represented in the certification trial, their impact on evacuation efficiency, whatever that may be, is not measured. As it is not measured, it cannot be factored into the maximum passenger head count. Yet clearly, people with disabilities fly and each disabled passenger counts as a fully ambulant passenger in the head count of the maximum number of passengers the aircraft is legally permitted to carry. Furthermore, experimental trials undertaken by the FAA suggest that passengers with disabilities can require more than twice as much time (dependent on the nature of the disability) as able bodied passengers to evacuate, unaided, from an aircraft [20]. This may have a significant impact on evacuation efficiency and hence the maximum passenger capacity of the aircraft, but is ignored in the certification process and in the subsequent operation of the aircraft.

On a practical level, the aircraft evacuation time is a stochastic variable. Thus, if the evacuation is repeated (with or without the same passengers) under the same conditions, the evacuation time will be different. To understand the likely performance of the aircraft under the trial conditions, it is therefore necessary to repeat the evacuation a number of times thereby generating the envelope of evacuation performance. As only a single evacuation trial is stipulated by the certification requirements, there can be at best limited confidence that the test, whether successful or not, truly represents the evacuation capability of the aircraft. In addition, from a design point of view, a single test does not provide sufficient information to arrange the cabin layout for optimal evacuation efficiency and does not even necessarily match the types of configuration flown by all the potential carriers.

Another difficulty is the artificial and prescriptive time that is imposed on the certification requirement as the time available for safe egress. This is set to 90 s, irrespective of the type of aircraft. The adoption of 90 s is argued to be related to the expected time to reach flashover, and hence nonsurvivable conditions, within an aircraft subjected to a postcrash fire. This "one size fits all" rationale is intended to apply to a 50 seat, high wing turbo prop aircraft designed and manufactured 30 years ago and an 800 seat, double deck, jet engine aircraft circa 2005. This requirement, which is at the very heart of the evacuation certification process, is of questionable scientific and engineering validity.

Finally, each full-scale evacuation demonstration can be extremely expensive. For instance an evacuation trial from a wide-body aircraft costs in the vicinity of $2 million U.S. [11]. Although the cost may be small in comparison to development costs, it remains a sizable quantity.

III. Aircraft Evacuation Models

One of the first computer based evacuation simulation tools to appear in the open literature was an aircraft evacuation model, developed by the FAA in the early 1970s known as the GPSS model [4,5]. The model was designed to run on the massive mainframe computers of the day, the concept of desktop computers not being developed until the 1980s. The software was written using IBM's General Purpose Simulation System (GPSS) language. Unfortunately, this model failed to capture the imagination of engineers and regulatory authorities of the day, perhaps due to the limitations of the computers of the time or limitations in its modeling capabilities. As a result the entire discipline of aircraft evacuation modeling fell dormant for almost 20 years.

In the interim period, the most significant developments in computer based evacuation modeling technology occurred in the building industry, which has been the driving force for much of the development in evacuation modeling technology. This was partially driven by the desire of architects to continually implement novel concepts in building design. As these designs challenged the traditional bounds of size and space utilization they also challenged the scope of the traditional prescriptive building regulations. Increasingly, engineers and regulatory officials were faced with the dilemma of demonstrating in some manner that these new concepts in building design were safe and that the occupants would be able to efficiently evacuate in the event of an emergency.

Within the building industry, research into quantifying and modeling human movement and behavior has been underway for at least 30 years. Today it is estimated that there are over 30 different evacuation models in use for the design and certification of buildings [1]. More recently, evacuation models have been adopted by the maritime industry for design and certification [21,22] with the International Maritime Organization (IMO) setting out guideline procedures for the use of evacuation simulation for the certification of passenger vessels [7].

In contrast, only a handful of aircraft evacuation models have been reported in the open literature [2,3]. One of the earliest evacuation models still in use and constantly under development is the airEXODUS evacuation model [2,3,23–28]. Although it is not the purpose of this paper to review aircraft evacuation modeling technology (readers wishing an overview of evacuation modeling should consult one of the state-of-the-art reviews on the subject [1–3]), the airEXODUS aircraft evacuation model will be briefly described as an example of the technology currently in use by the aviation industry. Readers wishing a more detailed description of the software should examine one of the many publications describing the software and its applications [2,3,23–28].

The airEXODUS aircraft evacuation model is part of a suite of software tools designed to simulate the evacuation of large numbers of people from a variety of complex enclosures. Development of the EXODUS concept began in 1989 [23] and today, the family of models consists of buildingEXODUS [29], maritimeEXODUS [30], and airEXODUS [2,3,23–28] for the built, maritime, and aviation environments, respectively. airEXODUS is designed for use in aircraft design, compliance with 90 s certification requirements, crew training, development of crew procedures, resolution of operational issues, and accident investigation.

The EXODUS software takes into consideration people–people, people–fire, and people–structure interactions. It comprises five core interacting submodels: *passenger*, *movement*, *behavior*, *toxicity*, and *hazard* submodels. The software describing these submodels is rule based, the progressive motion and behavior of each individual being determined by a set of heuristics or rules. These submodels operate on a region of space defined by the geometry of the enclosure. The model tracks the trajectory of each individual as they make their way out through the geometry, or are overcome by fire hazards such as heat, smoke, and toxic gases. Each of these components will be briefly described in turn.

The geometry of the aircraft can be defined manually or read from a computer aided design using the DXF format. Internally the entire space of the geometry is covered in a mesh of nodes that are typically spaced at 0.5 m intervals. The nodes are then linked by a system of arcs. Each node represents a region of space typically occupied by a single passenger. The movement submodel controls the physical movement of individual passengers from their current position to the most suitable neighboring location or supervises the waiting period if one does not exist. The movement may involve such behavior as overtaking, side stepping, seat jumping, or other evasive actions. The hazard submodel controls the atmospheric and physical environment. It distributes predetermined fire hazards such as heat, radiation, smoke, and toxic fire gases throughout the atmosphere and controls the opening and closing times of exits. The toxicity submodel determines the effects on an individual exposed to toxic products distributed by the hazard submodel. These effects are communicated to the behavior submodel which, in turn, feeds through to the movement of the individual.

The passenger submodel describes an individual as a collection of defining attributes and variables such as gender, age, maximum unhindered fast walking speed, maximum unhindered walking speed, response time, agility, etc. Each passenger can be defined as a unique individual with their own set of defining parameters. Cabin crew members require additional attributes such as range of effectiveness of vocal commands, assertiveness when physically handling passengers, and their visual access within certain regions of the cabin. Some of the attributes are fixed throughout the simulation whereas others are dynamic, changing as a result of inputs from the other submodels. Passengers with disabilities may be represented by limiting these attributes.

The behavior submodel determines an individual's response to the current prevailing situation on the basis of his or her personal attributes and passes its decision on to the movement submodel. The behavior submodel functions on two levels, global and local. The local behavior determines an individual's response to the local situation, e.g., jump over seats, wait in queue, etc., whereas the global behavior represents the overall strategy employed by the individual. This may include such behavior as exit via the nearest serviceable exit, exit via most familiar exit, or exit via their allocated exit. As certain behavior rules, for example, conflict resolution and model parameters, for example, passenger exit hesitation times, are probabilistic in nature, the model will not produce identical results if a simulation is repeated. In studying a particular evacuation scenario, it is necessary to repeat the simulation a number of times to produce a distribution of results.

A unique feature of airEXODUS is its use of 90 s certification data [24,31] to specify certain model parameters such as the passenger exit delay time. This particular attribute characterizes two stages of the exiting process, the exit hesitation time and the exit negotiation time. In virtually all cases, the passengers exhibit a hesitation at the exit, before negotiating it. Typically, this starts when an outstretched hand first touches the exit. The latter time considers the amount of time taken to pass through the exit. Details concerning the exit hesitation time data used in airEXODUS may be found in [24,31].

A primary driver for the development of aircraft evacuation models is to augment and eventually replace the full-scale certification trial component of the current certification process. In this application the model is intended to simply replicate the live certification trial and if possible to address the identified problems and shortcomings of the certification process. Several models (e.g., airEXODUS and GPSS, see [3] for details) have been developed to address these needs. It is worth noting that evacuation models designed to address 90 s certification applications have access to a plethora of data, in the form of video footage of previous 90 s certification trials, upon which behaviors within the model can be derived and key model parameters set.

Evacuation modeling for accident reconstruction is considerably more demanding than certification modeling. Some models have been developed in an attempt to simulate real emergency evacuation scenarios (e.g., airEXODUS, ARCEVAC, GOURARY, DEM, MACEY, see [3] for details).

Modeling real (incident or accident) emergency evacuation is far more complex than certification modeling for a number of reasons. First, intrinsic variability in real emergencies leads to a myriad of different possible evacuation scenarios. For example, whereas in one emergency evacuation the aircraft fuselage may expose the cabin interior to a life threatening fire [32], in another, the cabin may remain intact but passengers may be subjected to a mild threat of smoke [33]. The aircraft could be on its landing gear in one scenario [34] but may have partial gear failure in another [33]; the aircraft may be partially immersed in water as in the case of a runway overrun [35], etc. Thus the range of human behavior that needs to be modeled is far more extensive than that found in the certification scenario.

Furthermore, reliable data on human behavior and performance under these realistic accident scenarios are more difficult to obtain. There are fewer sources of accurate quantitative information on human performance in emergency evacuation situations. Unlike 90 s certification trials there are no video recordings of the unfolding evacuation upon which behavior can be identified and model parameters set. As such information regarding the evacuation is limited to the testimonies of surviving passengers, crew, and rescue workers (e.g., accident reports [32–35] and the Aircraft Accident Statistics and Knowledge (AASK) database [14–19]) and data from contrived experimental trials (e.g., [36]). These types of data have also been used in the development of airEXODUS.

Before computer models can reliably be used for certification applications it is essential that they undergo a range of validation demonstrations. Although validation will never prove a model correct, confidence in the models predictive capabilities will be improved the more often it is shown to produce reliable predictions [37].

The airEXODUS evacuation model has successfully undergone a range of validation trials. These trials have focused on reproducing the certification performance of a range of both wide and narrow body aircraft [2,3,23–28]. The success of this model in predicting the outcome of previous 90 s certification trials is a compelling argument of the suitability of this model for evacuation certification applications, at least for derivative aircraft. For aircraft involving truly "new" features it is suggested that evacuation models in conjunction with component testing of the new feature will be necessary. Examples of new features include a new exit type or an established exit configuration placed at a sill height surpassing that previously used. In both these examples it is assumed that sufficient data do not exist that would allow a reliable representation within the evacuation model. In these cases, the combination of computer model and component testing offers a sensible and reliable alternative to full-scale live evacuation trials.

IV. Use of Evacuation Models for Certification Applications

As stated in the Introduction, it is not sufficient to simply replace the current status quo of a one-off full-scale live evacuation demonstration with computer modeling. Computer modeling should improve the certification process by addressing the many identified shortcomings of the current certification process. In addition to the safety, efficiency, and cost issues, these revolve around the specification and definition of the evacuation scenario and the evaluation of the outcome of the scenario.

A. Current Evacuation Certification Scenario

An aircraft evacuation scenario, be it real accident, computer generated simulation, or live full-scale experiment, is made up of the three key components addressing the aircraft, the crew, and the passengers. These three components consist of the following main attributes:

1. Aircraft Specific Components:

a) Aircraft configuration specification: This typically consists of the cabin layout such as number of main aisles, width of main aisle (s), cross aisle clear width, positioning of monuments within the cabin, seating configuration, number and type of exits, exit locations, exit configuration, etc. In accident scenarios, this may include information regarding possible ruptures to the cabin and damage to the cabin interior fittings.

b) Aircraft exit availability: This component addresses which exits will be available during the evacuation. This may be affected by the nature of the accident scenario as exits may change their state of availability during a scenario and cabin ruptures may provide passengers with additional exiting opportunities.

c) Aircraft environmental specification: This consists of issues associated with the orientation of the aircraft, lighting levels, the presence of debris within the cabin, whether the cabin is exposed to water, and the nature of the cabin atmosphere with regard to heat, smoke, and toxic gases.

2. Crew Specific Components:

a) Number of Crew: This component concerns the number of crew who will be able to assist in the evacuation. This is not necessarily the number of crew on board and so can be affected by the accident scenario.

b) Crew Behavior: This component concerns the nature of the tasks that the crew will be assigned to undertake and the ability of the crew to undertake their assigned tasks. Issues such as performance of the crew in identifying suitable exits to be used during the evacuation, speed at which the exits are made ready, level of assertiveness displayed by the crew at exits, and the ability of the crew to manage the crowd dynamics are an essential part of this component. The nature of the crew behavior is likely to be affected by the severity of the accident scenario.

3. Passenger Specific Components:

a) Passenger population distribution: This component considers the nature of the evacuating population, that is, the passengers. It consists of a description of the age and gender of the population, the physical ability of individual members of the population, and the nature of the social affiliation between passengers (e.g., presence of family groups). This component is likely to be affected by the nature of the accident scenario as passengers may be killed or injured. Other aspects of the population such as knowledge/experience of flying and culture may also be factors to be considered.

b) Passenger behavior: To a certain extent this component is linked to the nature of the passenger population distribution and will be influenced by the nature of the scenario. It consists of the type of behavior exhibited by the passenger population. Passenger behavior can vary from the type of noncompetitive compliant behavior typically exhibited in standard 90 s certification trials to competitive behavior such as seat jumping and aisle swapping typically found in

Table 1 Current evacuation certification scenario specification and its typical representation with computer models

Scenario	Component	Current evacuation certification scenario	Typical computer model setting for certification scenario
Aircraft specific components	Aircraft configuration specification	Standard production aircraft, usually fitted to maximum passenger configuration.	Cabin layout and exit specification as specified by aircraft CAD drawings.
	Aircraft exit availability	One exit from each exit pair, typically all exits down one side of the aircraft.	As in certification setting.
	Aircraft environmental specification	Normal orientation, darkness/emergency lighting and no fire products.	Data used in models to represent passenger and crew performance consistent with certification setting and ideally derived from past certification trials.
Crew specific components	Number of crew	Normal number of crew specified by the operating standards for the specific aircraft.	If crew are explicitly represented within the model, then number of crew as required by certification conditions.
	Crew behavior	The crew are typically selected from the launch customer and would normally be assumed to be well experienced.	The crew would typically be assumed to be assertive and the generalized exit ready times derived from past certification trials would normally be imposed.
Passenger specific components	Passenger population distribution	The specific age and gender mix are dictated by the evacuation certification requirements. People with disabilities are excluded from the population as are the very young and the very old. The population would also generally be made up of unattached individuals.	Data used in models consistent with certification requirement.
	Passenger behavior	Passengers generally exhibit a non-competitive compliant behavior. The presence of groups (if they exist) do not generally exert an influence on the evacuation. Generally optimal or near optimal passenger exit usage achieved.	As the passengers generally follow the instructions of the crew, the passenger exit selection is typically set to optimal.

severe accident situations. Part of passenger behavior is the passenger exit selection. This behavior dictates the overall exiting strategy exhibited by the passengers in selecting which exits to use during the evacuation. This can be categorized into essentially one of three basic types, overall optimal exit, nearest exit, or case specific suboptimal exit selection.

Changing the selection of any of these parameters will change the nature of the evacuation and the likely outcome of the evacuation. In effect, changing these parameters and hence the scenario is equivalent to changing the nature of the question that is being posed. The current evacuation certification scenario and its representation within a computer model such as airEXODUS is described in Table 1.

B. Selecting Evacuation Certification Scenario(s) Representative of Reality

Although the nature of the current full-scale certification trial may be limited due to practical considerations, this is not necessarily the case for computer simulations. Unlike the certification trial, evacuation models have the capability of examining many different types of evacuation scenario by varying the specification of aircraft, crew, and passenger specific components of the scenario definition. What scenario should be considered for certification by computer model? Should the current certification scenario be maintained or should a range of scenarios be considered? Perhaps a selection of the most likely evacuation scenarios should be considered or simply the most severe likely evacuation scenario or scenarios?

The selection of suitable evacuation scenarios should be guided by analysis of past accident data, from, for example, one of the several accident databases that are available [15–17]. Furthermore, any new scenario(s) selected for evacuation certification purposes should be supported by reliable data, drawn either from past certification or published experimental trials. For example, it may be desirable to include scenarios in which the aircraft specific component "aircraft environmental specification" is altered to represent an aircraft fuselage that has an adverse orientation due to the partial loss of landing gear. However, as sufficient data do not currently exist to reliably represent the likely changes in passenger performance and behavior, this should be excluded from consideration until further research provides the necessary data.

Here we consider one aspect of the scenario specification that can be guided by accident analysis and can be supported by existing data sources. We will focus on the aircraft specific component of exit availability. From analysis undertaken using the AASK database [18], an investigation of 42 accidents suggests that in approximately 67% of these accidents, an exit availability of 50% or more was achieved. Thus, as the most frequently occurring exit availability involves 50% or more of the exits, it would appear to be reasonable to require 50% exit availability in certification evacuation scenarios. This is in line with current certification practice. However, this argument ignores the fact that a significant minority (33%) of the accidents investigated had less than 50% exit availability, resulting in a more challenging evacuation scenario. This would appear to be an important observation that could be represented in the certification scenario. In addition, the data suggest that the available exit distribution for small (i.e., aircraft with three exit zones) and large aircraft (i.e., aircraft with four exit zones) is different, with smaller aircraft having a greater tendency than larger aircraft to have less than 50% of their exits available during an emergency evacuation. Thus the certification scenario could be sensitive to the size of the aircraft, that is, whether the aircraft had three or four exit zones.

Furthermore, accident analysis suggests that over half (55%) the accidents investigated involve a cabin section in which no exits were available. And of the accidents in which there were more than 50% of the exits available, almost half of these (43%) involve a cabin section in which no exits were available. Thus, even if we adopt a 50% rule, it does not follow that this should involve one exit out of each exit pair as in the current certification practice. A potentially more challenging exit combination, while maintaining the 50% exit availability condition that is also consistent with the observed exit availability, for small aircraft, would involve both exits in one location being available and a single exit being available in one other location. Suitable likely combinations of exits based on observed frequencies in decreasing order of likelihood include the following:

1) A single forward exit, both overwing exits, and no exits in the aft section available.

2) Both forward exits, a single overwing exit, and no exits in the aft section available.

3) Both forward exits, no exits in the overwing section, and a single aft exit available.

4) A single forward exit, no exits in the overwing section, and both aft exits available.

5) No exits in the forward section, a single overwing exit, and both aft exits available.

This type of criteria for selecting exit availability could be used in determining the exit combinations to be used in certification analysis by a computer model. This change would make the certification process more representative of reality without the burden of performing additional experimental studies to collect passenger performance data.

By varying the specification of aircraft, crew, and passenger specific components of the scenario definition in this way, a range of more representative certification scenarios can be identified and introduced into the certification by simulation process. It is further suggested that consideration of likely failure modes should also be considered. Thus, in addition to simulating the "optimal" passenger exit selection, examination of likely "what if" scenarios, such as passengers selecting to use their nearest exit could be considered. These are likely to be aircraft specific and depend on the nature of the aircraft geometry.

Furthermore, unlike certification using the full-scale demonstration, certification by simulation allows the possibility of performing many repeat simulations for any particular scenario thereby producing a range of results for any given scenario or collection of scenarios. Indeed, it may even be argued that rather than simply testing a single interior layout configuration, each layout flown by a carrier could be tested by computer simulation.

In this way evacuation simulation provides better insight to the performance capability of the aircraft under a range of scenarios.

C. Acceptance Criteria

Regardless of the accident scenario selected for certification testing, how do we determine that an aircraft has met the pass/fail criteria, how do we establish the "deemed to satisfy" requirement? In the current certification protocol a clear pass/fail criteria is applied. Either the outcome of the certification test is sub-90 s, in which case the aircraft passes, or it is over 90 s in which case the aircraft fails. As only a single trial is performed this criteria is fairly straightforward to apply and interpret.

When undertaking computer simulations of evacuation performance, the results are generally stochastic, each time the simulation is run, a different result can be produced, even if the initial conditions have not changed. In using the airEXODUS model for certification applications, typically 1000 repeat simulations are produced for a given scenario [27]. The results can then be presented as a frequency (probability) diagram which shows the likelihood that a particular evacuation time will be produced. This approach provides considerably more information regarding the aircraft performance than a single one-off test. However, how are we now to determine whether or not the aircraft design meets the certification requirement? For a particular scenario should the requirement stipulate that *every* simulation be sub-90 s? Or should the distribution mean, 95 percentile result, or some arbitrarily higher percentile be sub-90 s?

An example of this dilemma was demonstrated in a recent report to the U.K. Civil Aviation Authority (CAA) [27] concerning the validation of the airEXODUS model. In this example, the aircraft under consideration achieved an actual certification performance of 83.7 s with a mean airEXODUS predicted evacuation time of 82.7 s. Although these times represent the out of aircraft time for the passengers, the actual certification on-ground time for the passengers and crew was such that the aircraft clearly passed the certification requirement. However, of the 1000 simulations performed using airEXODUS for this aircraft, three or 0.3% are predicted to marginally fail the certification requirement. If the mean rule (i.e., 50% of cases produce evacuation times less than 90 s) or the 95% rule were adopted the aircraft would clearly satisfy these requirements and be considered acceptable. However, if the 100% requirement were adopted the aircraft would not be considered acceptable. As this aircraft is considered to be acceptable (on the basis of the single actual certification trial result) perhaps the deemed to satisfy limit should be placed at 0.3%? If this general approach were considered viable, the logical extension would require that all of the past aircraft that have undergone the certification process would need to be assessed using computer simulation and a suitable acceptance level derived from this analysis.

This situation is not unique to results produced by computer simulation, but applies equally to results produced by real full-scale trials. In reality, any aircraft configuration will produce a range of evacuation times over a number of repeat tests. Some of the results may well be over the certification maximum of 90 s while some may be under the 90 s. Unfortunately, under the current certification protocols, this important performance information is ignored as only a single trial is performed. In effect, under the current "make or break" single test regime, a single performance result is selected at random from the "unknown" distribution of possible evacuation times and put forward as the certification performance. The aircraft will pass as long as the result is below the 90 s threshold. It is impossible to know whether or not the outcome is a fair reflection of the aircraft's evacuation capability. In contrast, the multiple tests enabled by computer simulation generate a distribution of times, reflecting what would happen if the full-scale evacuation scenario could be repeated. This provides a better indication of the performance capability of the aircraft.

It has been argued by some in the aviation industry that to achieve parity with the current certification process, 100% of the generated simulations should produce times less than 90 s to pass. Clearly, this would not achieve parity with the current certification process. For those who wish to achieve some form of parity with the current certification process, an alternative approach may be to generate only a single evacuation time from the modeling analysis. This in essence is equivalent to the current practice of performing only a single certification trial. Using this approach the same acceptance criteria could be applied to the numerically generated certification time as that applied to the full-scale trial generated certification time. In this way, the modeling process would replicate the current certification process where only a single evacuation time is put forward and so provides a means to circumvent the need to redefine acceptable performance. However, a significant downside of this methodology is that a considerable amount of potentially useful information regarding the performance of the aircraft is disregarded. Rather than attempting to achieve parity with the current standard the industry should be endeavoring to produce a more meaningful measure of aircraft evacuation performance. Clearly, all the stakeholders in the aviation safety community need to agree on a sensible acceptance criterion.

This issue raises the question; does the "magic number" 90 s have any actual meaning under these circumstances?

D. Experience from Other Industrial Sectors

Internationally, throughout the building industry, similar issues are being addressed through the replacement of the old prescriptive building requirements with performance based regulations. Prescriptive building regulations the world over suggest that if we follow a particular set of essentially configurational regulations concerning travel distances, number of exits, exit widths, etc., it should be possible to evacuate a building within a predefined acceptable amount of time. In the U.K. for public buildings this turns out to be the "magic number" 2.5 min.

Part of the risk analysis process involves the concept of the available safe egress time or ASET and required safe egress time or RSET. For a particular application the ASET may be based on the time required for the smoke layer to descend to head height whereas the RSET may be the time required for the occupants to vacate the structure. Put simply, the ASET must be greater than the RSET (plus a case specific safety factor). The circumstances of the scenario under consideration dictate both the ASET and RSET and several scenarios may need to be examined before any conclusions can be reached. As part of this risk analysis process credible fire scenarios (including fire loads, fire evolution, fire size, etc.) are postulated along with credible evacuation scenarios (including number and type of people, occupant response characteristics, etc.). Computer based fire and evacuation simulation tools are then used to determine the ASET and RSET, respectively. In this way evacuation models are providing a means by which the complex interacting system of structure/environment/population can be assessed under challenging design scenarios.

Recently in the marine industry a halfway house approach has been adopted. Rather than use the building industries ASET/RSET approach, IMO have adopted as draft guidelines a methodology where the ASET is set by a prescriptive limit, similar in concept to the 90 s magic number used in the aviation industry whereas the RSET can be determined by computer simulation [3,7]. To determine the RSET the submitted design is subjected to four benchmark scenarios each evaluated by computer simulation. The precise nature of the benchmark scenarios is prescribed in a similar way to the current 90 s certification trial. The ship design must pass all four benchmark scenarios to be deemed to satisfy the requirement. Furthermore, IMO have acknowledged that a distribution of evacuation times will be produced for any single evacuation scenario. As a result, they have adopted the 95% rule described above.

A similar methodological approach to either the building or maritime industries could be considered for evacuation certification within the aviation industry.

Other disciplines such as the building and maritime industries accept computer based simulations as part of the certification process. These have adopted a common approach to the validation and verification of evacuation models that could easily be adapted for aviation applications. Furthermore, in the marine industry, specific documentation is required to be submitted along with the simulation results. This documentation is intended to demonstrate the credibility and appropriateness of the approach adopted and furthermore allows easy verification and reproduction of the submitted results [3,6,7]. These requirements include the specification of the following:

1) the variables used in the model to describe the dynamics, e.g., walking speed of each person;

2) the functional relation between the parameters and the variables;

3) the type of update used within the model;

4) the representation of stairs, doors, . . ., and other special geometrical elements and their influence on the variables during the simulation and the respective parameters quantifying this influence;

5) a detailed user guide/manual specifying the nature of the model and its assumptions and guidelines for the correct use of the model and interpretation of results should be readily available.

Certification analysis performed for the aviation industry using computer simulation could require a similar level of documentation.

V. Suggested Evacuation Certification Methodology

It is essential to note that the use of computer simulation is not intended to replace the entire existing evacuation certification process. Currently required testing such as those for slide inflation and door operation would still be required. Initially, compliance with prescriptive rules regarding cabin layout (e.g., type and location of exits, lighting, slide capacity, etc.) would also be required. The suggested methodology is only suggested as an eventual alternative to the current full-scale evacuation demonstration. To achieve this it is first necessary to define a framework for the use of computer simulation for evacuation certification applications and define an approach for the eventual adoption of computer simulation as part of the certification process.

A. Framework for the use of Computer Simulation for Evacuation Certification

As in the marine and building industries, it is essential that a framework be developed for the acceptable use of computer simulations for aircraft certification applications. The framework is intended to identify a systematic manner by which computer models are considered for use in certification applications and the manner in which the certification application is to be conducted and the results presented. Such a framework should address the following five key issues:

1. Model Validation and Demonstration Requirements

Before a model is used for a certification application it must be demonstrated that the model is capable of simulating the certification test with a specified degree of accuracy. Thus a battery of validation test cases must be defined. The cases examined in the recent report on the validation of the airEXODUS aircraft evacuation model [27] could form the basis of such validation/demonstration cases.

2. Simulation Protocols

It is necessary to specify the manner in which the simulations are to be run and the nature of the core results to be presented. This should include, for instance, the number of repeat simulations required, the nature of the data used in the simulations, the nature of the population to be used, etc.

3. Scenarios to be Investigated

The number and nature of the scenario(s) to be investigated must be specified. For example, the current certification scenario could be specified (as detailed in Table 1) and/or a range of scenarios drawn from accident analysis as suggested in Sec. IV.B could be considered. The scenario specification should specify the three key components as identified in Sec. IV.A.

4. Acceptance Criteria

Because of the probabilistic nature of the results produced from repeated simulations, it is essential that a rational acceptance criterion be developed. This should be based on meaningful statistical analysis as described in Sec. IV.C.

5. Supporting Documentation

The evacuation analysis must be supported by appropriate documentary evidence. This should provide a thorough justification for the analysis presented, covering both the modeling technique and data used, and provide a means of reproducing the analysis in some way. The approach adopted by IMO discussed in Sec. IV.D provides the basis for developing such a system for aviation applications.

B. Adoption of Modeling as Part of the Evacuation Certification Process

Although a framework for the use of computer simulation in certification applications has been suggested in Sec. V.A, the nature of the scenarios to be considered for certification has not been finalized. It has been suggested that through the use of computer simulation a range of evacuation scenarios should be examined for certification purposes based on accident analysis (see Sec. IV.B). Initially, it is suggested that the current evacuation certification scenario be adopted as the basis for the computer analysis. With the evacuation scenario defined, the adoption of computer models for evacuation certification could follow the steps outlined below.

1. Step 1: Replacing Full-Scale Evacuation Demonstration with Computer Simulation

Computer simulation is used to perform the standard certification evacuation demonstration in place of the full-scale demonstration. This would only be considered for situations in which reliable data are available on which to base the evacuation simulation. For aircraft involving truly "new" features, in which data are not available, it is expected that evacuation models in conjunction with component testing of the new feature will be necessary. Examples of new features include a new exit type or an established exit configuration placed at a sill height surpassing that previously used. In both these examples it is assumed that sufficient data do not exist that would allow a reliable representation within the evacuation model. In these cases, the combination of computer model and component testing offers a sensible and reliable alternative to full-scale live evacuation trials.

The analysis would follow the details as set out in the suggested framework (see Sec. V.A), in particular, only suitably validated models would be considered. It is argued that simulations performed in this manner would provide better insight into the actual performance capabilities of the aircraft by generating a performance probability distribution or performance envelope rather than a single datum.

This approach should be considered only as the first step in the process of introducing computer simulation to aircraft evacuation certification. As confidence in the technique develops, additional, more representative and demanding scenarios could be added to the certification process.

2. Alternative to Step 1: Step 1a, Computer Simulation and Full-Scale Evacuation Demonstration

Although the above approach would appear to be a logical first step to the introduction of computer modeling to certification, it may be considered too radical by some sectors of the aviation industry that are still skeptical of the capabilities of evacuation models. An alternative strategy would be to gradually phase in the use of evacuation models, using computer models to address some of the recognized failings of the current evacuation certification process. This would involve evacuation models being used in conjunction with full-scale evacuation demonstrations. Such an approach would provide two major benefits; it would improve the current certification process while allowing further confidence to be established in the use of aircraft evacuation models. The alternative to step 1 is defined in two parts, step 1a and step 1b.

In this alternative first step, the full-scale evacuation certification demonstration would be run in the usual manner. However, there would be an additional requirement to use computer simulation to perform repeated simulations of the certification trial conditions to produce a probability distribution of likely evacuation performance. Given that the computer model was set up to simulate the same situation as occurred in the actual full-scale trial, it would be expected that the data point from the full-scale certification trial would fall on the probability distribution produced by the computer simulation (see [27] for examples). The pass-fail criteria could then be based on both the actual result generated in the full-scale trial and the model predictions. This approach would provide a number of benefits, namely, 1) provides insight into the performance of the aircraft under repeated trials, 2) delivers improved confidence in the certification procedure, and 3) provides further validation of the modeling process.

As suggested previously, all the simulations would be run using the outlined framework. If suitable data were not available to perform reliable simulations, then component testing in conjunction with simulations would be necessary to satisfy the certification process. All other prescriptive rules and requirements would still apply, for example, slide inflation tests and door opening trials would still be required.

3. Alternative Step 1: Step 1b, Adopting the Sole Use of Computer Simulation for Evacuation Certification

The second part of the alternative first step involves dropping the full-scale certification demonstration in circumstances where there were sufficient data on which to be confident in the modeling approach. This would only be contemplated after sufficient experience and confidence in the use of computer models had been developed.

4. Step 2: Expanding the Nature of the Certification Scenario

The second step would involve expanding the nature of the certification scenario and perhaps introducing several certification scenarios. The set of scenarios would include the current standard certification scenario and in addition, several other simulated evacuation scenarios could be investigated. These could be based on analysis of past accidents and would be supported by reliable data, drawn either from past certification or published experimental trials, for example, scenarios involving likely exit combinations (see Sec. IV.B).

5. Step 3: Adopting Realistic Evacuation Scenarios and Performance Criteria

As a final step, the nature of the evacuation scenarios investigated in the certification process could be made more realistic, with the introduction of more credible accident scenarios. These could involve possible fire scenarios and would incorporate performance criteria rather than the current prescriptive 90 s criteria. The performance criteria could be set as in the building industry where fire models are used to specify for each scenario an ASET (see Sec. IV.D) and evacuation models would be used to determine the corresponding RSET. However, for this to become a reality, further effort must be directed towards the continued development of aircraft evacuation modeling technology to include additional behavioral features common in real accident scenarios and the generation of the necessary data. With the adoption of the ASET/RSET approach, some of the prescriptive rules regarding cabin configuration, such as the 60 ft rule [8,9], could be dropped.

VI. Conclusions

It has been suggested that evacuation models offer a possible alternative to the current practice of performing a single live full-scale evacuation demonstration as part of the evacuation certification process. Computer simulation potentially provides the aviation community (passengers, crew, manufacturers, airlines, regulators) with significantly more than the current practice of performing a one-off full-scale demonstration. It has been argued that computer based aircraft evacuation simulation:

1) is capable of reproducing the evacuation performance of aircraft, passengers, and crew in full-scale certification trials,

2) is a safer and more efficient process than the alternative full-scale evacuation demonstration,

3) provides improved insight into the actual performance capabilities of the aircraft by generating a performance probability distribution or performance envelope rather than a single datum, and

4) Is capable of efficiently investigating a range of relevant certification scenarios rather than a single scenario.

Although the introduction of computer models for aircraft evacuation will potentially solve some of the existing difficulties and shortcomings posed by current certification testing, it will introduce new questions, pose new challenges, and offer new opportunities that need to be addressed. However, by addressing these new challenges we may achieve our goal of producing safer aircraft.

One of these challenges concerns the existence and availability of data. To perform reliable simulations, evacuation models are reliant on data. The nature of the intended simulation will dictate the type and quantity of the required data, with accident reconstruction possessing the greatest challenges. For the simulation of the current certification scenario, much data already exist and have been analyzed while much more data are available and yet to be analyzed. However, more data are required and a concerted effort must be undertaken to collect and analyze the required data. This will require cooperation between manufacturers, regulatory authorities, and research groups.

A second challenge concerns the development and adoption of a framework for the application of aircraft evacuation models to the regulatory environment. As in the marine and building industries, it is essential that a framework be developed for the acceptable use of computer simulations for aircraft certification applications. Until such a framework is in place, it is unlikely that the aviation industry will adopt the use of computer simulation for evacuation certification analysis. An outline of such a framework has been suggested in this paper.

The third challenge involves the continued development of aircraft evacuation modeling technology to include additional behavioral features common in real accident scenarios. With this development, the third step in the adoption of computer simulation for certification could be taken. This would allow the introduction of more realistic accident scenarios into the certification process.

The final challenge facing all the stakeholders involved in aircraft certification, that is, regulators, approval authorities, accident investigators, manufacturers, airlines, unions, and ultimately the traveling public, is to develop a better understanding of the modeling technology being developed and with that understanding agree relevant certification protocols and standards. Here examples from both the building and maritime industries provide useful models upon which to base an aviation strategy. For this to have a proper perspective it is essential that all the stakeholders have a good appreciation of the current certification process and its limitations.

By adopting this approach we may achieve our goal of producing safer aircraft, which the industry claims they desire and the traveling public certainly deserves.

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