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Work Package 2

Task 2.3

A Methodology and Procedure for the Introduction of Aircraft Evacuation Simulation to the Aircraft Certification Process

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GLOSSARY

AASK	Aircraft Accident Statistics and Knowledge database
AIRBUS	AIRBUS Deutchland
ASET	Available Safe Egress Time
BWB	Blended Wing Body
CAMI	Civil Aerospace Medical Institute
CFR	Code of Federal Regulations
CU	Cranfield University
D	Deliverable
DG TREN	Directorate General Transport & Energy
ETF	ETF/SNPNC
FAR	Federal Airworthiness Rules
FSEG	Fire Safety Engineering Group
IMO	International Maritime Organisation
JAA	Joint Aviation Authority
JAR	Joint Airworthiness Rules
RSET	Required Safe Egress Time
SOF	Sofréavia
SRG	CAA/SRG
UOG	University of Greenwich
VAA	Virgin Atlantic Airways
VERRES	VLTA Emergency Requirements Research Evacuation Study
VLTA	Very Large Transport Aircraft
WP	Work-Package

EXECUTIVE SUMMARY

In this document we suggest a methodology for the application of computer simulation to the certification of aircraft. While the approach is intended to address the requirements of Very Large Transport Aircraft, it is applicable to all aircraft types. The methodology suggested here involves the use of computer simulation, historic certification data, component testing and full-scale certification trials. The proposed methodology sets out a protocol for how computer simulation should be undertaken in a certification environment and draws on experience from both the marine and building industries.

Along with the suggested protocol, a phased introduction of computer models to certification is suggested. Given the sceptical nature of the aviation community regarding any certification methodology change in general, this would involve as a first step the use of computer simulation in conjunction with full-scale testing. The computer model would be used to reproduce a probability distribution of likely aircraft performance under current certification conditions and in addition, several other more challenging scenarios could be developed. The combination of full-scale trial, computer simulation (and if necessary component testing) 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. Once further confidence in the technique is established, the second step would only involve computer simulation and component testing. This would only be contemplated after sufficient experience and confidence in the use of computer models have been developed.

The third step in the adoption of computer simulation for certification would involve the introduction of more realistic accident scenarios into the certification process. This would require the continued development of aircraft evacuation modelling technology to include additional behavioural features common in real accident scenarios.

Finally, computer based aircraft evacuation models – together with reliable data - have the potential to be used for aircraft certification and provide manufacturers, operators and regulators a means of assessing novel designs, procedures and accident scenarios associated with VLT and BWB (Blended Wing Body) aircraft.

1. INTRODUCTION

In this document we suggest a methodology for the application of computer simulation to the certification of aircraft, with particular emphasis to Very Large Transport Aircraft (VLTA). Given the current state-of-the-art in aircraft evacuation modelling, the proposed methodology is reliant on the use of reliable evacuation data in the form of historic certification data and component testing. This report should be read in conjunction with two earlier reports from Verres Work Package 2 which; reviewed the current state-of-the-art in aircraft evacuation modelling and data availability (WP2.1, see APPENDIX A) [1] and applied the current leading aircraft evacuation model (airEXODUS) to an application involving a VLTA (WP2.2, see APPENDIX B) [2].

Before embarking on this discussion it is useful to review the current regulatory process. Regulators attempt to enforce and maintain safety standards through a set of essentially prescriptive rules that have evolved over time. In Europe they are know as Joint Aviation

Requirements (JAR) [4] while in the USA the rules are known as the Federal Aviation Regulations (FAR) [3]. An example of one of the rules that has evolved over time relating to aircraft evacuation efficiency is the so-called "60-foot" rule. The rule appears in the FAR (i.e. 25.803 (f) (4)) [3], 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."[3,4]

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'* [5]. Compliance with this rule is demonstrated by performing a full-scale evacuation demonstration. The demonstration is performed with a representative cross-section of the travelling public (age and gender distribution), in darkness and utilising only half of the normally available exits. 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 seconds if the aircraft is to pass the performance test. A complete video record is made of the event including behaviour within the cabin and at the exits. The video recordings of the evacuations are a valuable source of data on the performance level achieved during these types of certification evacuations. The certification performance test is only intended to provide a measure of the performance of the aircraft under an artificial benchmark evacuation scenario. It is not intended to predict the performance of the aircraft under a realistic accident scenario. However, it allows the performance of different aircraft to be compared under a set of identical – if somewhat artificial – scenario conditions.

There are several difficulties with the current 90 second trial. There is considerable threat of injury to trial participants. Between 1972 and 1991 a total of 378 volunteers (or 6% of participants) sustained injuries ranging from cuts and bruises to broken bones [6]. 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-second evacuation scenario. Volunteers are subject neither to trauma nor to the physical ramifications of a real emergency situation such as smoke, fire and debris, 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 minutes after the aircraft had ceased moving, while 15 years earlier in a UK certification trial, the entire load of passengers and crew evacuated the aircraft in 75 seconds [7,8]. In the certification trial, while passengers are keen to exit as quickly as possible, the behaviour exhibited is essentially co-operative, whereas in real accident situations the behaviour may become competitive. Even if complex issues of fire etc are excluded from consideration, relatively simple issues such as exit selection are far from realistic. Providing all exits on one side of the aircraft bears little or no resemblance to realistic accident scenarios.

On a practical level, as only a single evacuation trial is necessary for certification requirements, there can be 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.

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 $US2 million [6]. While the cost may be small in comparison to development costs, it remains a sizeable quantity.

A primary driver for the development of aircraft evacuation models is to augment and eventually replace 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, GPSS [1]) have been developed to address these needs. These models have been discussed in detail in the report for WP2.1 [1] (see APPENDIX A). It is worth noting that evacuation models designed to address 90-second certification applications have access to a plethora of data, in the form of video footage of previous 90-second certification trials, upon which behaviours within the model can be derived and key model parameters set.

Evacuation modelling for accident reconstruction is considerably more demanding than certification modelling. Some models have been developed in an attempt to simulate real emergency evacuation scenarios (e.g. airEXODUS, ARCEVAC, GOURARY, DEM, MACEY see [1] for details). An air accident as defined within JAR and FAR is:

> *"An occurrence associated with the operation of an aircraft that takes place between the time any person boards the aircraft with the intention of flight and all such persons have disembarked, where any person suffers death or serious injury, or the aircraft received substantial damage."* [9].

Modelling real (incident or accident) emergency evacuation is far more complex than certification modelling for a number of reasons. Firstly, 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 [10], in another, the cabin may remain intact but passengers may be subjected to a mild threat of smoke [11]. The aircraft could be on its landing gear in one scenario [12] but may have partial failure in another [11]; the aircraft may be partially immersed in water as in the case of a runway overrun [13], etc. Thus the range of human behaviour that needs to be modelled is far more extensive than that found in the certification scenario.

Furthermore, reliable data on human behaviour and performance under these realistic accident scenarios is more difficult to obtain. There are fewer sources of accurate quantitative information on human performance in emergency evacuation situations. Unlike, 90-second certification trials there are no video recordings of the unfolding evacuation upon which behaviour 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 and data from contrived experimental trials.

2. A CRITICAL EVALUATION OF AVIATION EVACUATION MODEL DATA

Any modelling approach used for certification purposes will be heavily reliant on evacuation data. This data will be composed of a variety of different sources namely, historic certification data, component testing, experimental trial data and accident data. It is apparent from the earlier review of evacuation model capabilities (see WP2.1 [1] – APPENDIX A) that a large quantity of data is available for use in evacuation models. In this section we summarise the findings of the previous report and suggest what additional data is required for certification applications of evacuation modelling.

2.1. Current Data Requirements

As has already been described, the nature of the intended simulation scenario determines the quantity and quality of data required to perform the simulation. While there is a large amount of data available from certification trials and controlled experiments there are still gaps in these data sets that need to be addressed.

One of the most significant components of evacuation models concerns the manner in which the model represents the exiting process. To simulate this accurately requires data, either from certification trials or from experiments. The trial data best represents the conditions found in certification trials while experimental data has the potential to represent conditions found in real emergency evacuations through the use for example, of the competitive evacuation experimental protocols. From the study of video footage of these trials or experiments it is possible to extract passenger exit hesitation time distributions and exit flow rates that can be used by the model developers to define the passenger performance at the various exits.

In considering the data required for the simulation of certification trials, a considerable amount of exit hesitation time data has been extracted from certification trial video footage [14,15]. This data has been collected by FSEG and is based on data provided by the aircraft manufacturers. While more raw data may exist, it has not been made available to FSEG for analysis. For example, data for the upper deck Type-A exit is scarce, as data only exists for one evacuation in which the crewmember behaved in an assertive manner. No data at all exists for Type-A upper deck exits with in-between assertion level and unassertive cabin crewmembers.

In amendment 25-88 [16], the JAA and FAA introduced two new types of exit. They were the Type-C and Type-B. The classification of these exits was based not only on exit dimensions but also on requirements for exit passageway widths, cabin crewmember jump seat placement, the provision of assist spaces, escape slide capacity and total exit preparation times. At present, no data exists on exits classified as Type-B or Type-C at the time of certification. However, in order to better represent the variation in performance of various sizes of Type-I exits, the Type-I exit data has been categorised according to the dimensions of the exit, i.e. of Type-I, Type-C or Type-B dimensions.

Other exit type/assertiveness categories are also not represented within the FSEG database. Namely, any data for Type-C or Type-B exits as defined by amendment 25-88 [16]. Those exits of Type-B dimensions, Type-C dimensions and Type-I dimensions all with unassertive cabin crewmembers. Also, data for floor level exits without slides is lacking from the database. Furthermore, some exit types would benefit from additional data to better define the exit hesitation time distributions. These include: Type-B dimensions, Type-C dimensions and Type-I dimensions all with in-between assertion level cabin crew (2 evacuations only per category) and the Type-I dimensions exit with assertive cabin crew (1 evacuation only).

Certainly, data can and should be made available to the research community and extracted from future certification trials to help fill the data shortfall however, there are unlikely to be sufficient certification trials to completely satisfy this requirement. Targeted manufacturer component testing offers a possible way to plug the data gap. However, to be valid, this testing must be done under strict certification conditions.

Other data that would be useful for certification analysis includes, passenger flow rates in aisles for different seating configurations, slide times, flow rates from specific passageway and cross aisle configurations, flow rates from evacuations in which cabin crewmember impede flow through the exit.

For more realistic scenarios involving possible accident situations, there is a wide array of data that requires a systematic collection strategy. The collection of this data differs from that of certification data as the experiments can be undertaken using competitive behaviour protocols that attempt to simulate accident conditions. It must be emphasised that such data should be collected for both wide and narrow body aircraft configurations. This data includes, passenger exit hesitation times for different exit and crew assertiveness combinations, exit flow rate data, passenger aisle movement rates for different cabin orientations, passenger movement rates on staircases for different cabin orientations, passenger aisle/staircase movement rates in smoke for different cabin orientations, impact of cabin luggage on evacuation efficiency, frequency of aisle swapping, passenger instigated redirection to alternative exits, etc. In addition, in the analysis of accident scenarios, passenger cultural differences may be an important factor and so should be examined both in accident analysis, such as through the AASK database (see references [17,18]) and in controlled experiments.

Furthermore, it would be a valuable exercise to compare passenger exit hesitation time data collected from certification trials with the equivalent data collected from competitive evacuation trials. Some have assumed that this data may be significantly different however, until a detailed systematic analysis is undertaken this will not be known for certain. It is the belief of the authors that there are unlikely to be significant differences in this data, especially for situations involving assertive crew. If this were shown to be true, this would be a tremendous advantage, as it would justify the use of certification data in accident analysis.

Existing data from experimental studies performed by CAMI and Cranfield may help to bridge some of the data gap. Unfortunately, the data that has been published in the literature is not presented in an appropriate form for integration into evacuation models. Typically, published literature summarises qualitative features, perhaps providing an overall measure of performance such as a flow rate or an average time for a specific action. Data in this form is not usually sufficient to satisfy the requirements of model developers. For example, data in the form of distributions of measured quantities would be more valuable. Where appropriate, this data should be re-analysed and presented in a form that will satisfy the model developers. Ideally, in future, when new experiments are undertaken the needs of the model developers should be considered in order to gain the maximum benefit from the experiment.

Cabin crew play a vital role in managing the evacuation process. As such, their behaviour and influence should be included within evacuation models. Analysis of video recordings from 90-second certification trials and transcripts of interviews with cabin crew following accidents has provided insight into this interaction and allowed complex models to be developed. However, more information is required to improve these models, in particular in real accident situations. Analysis of evidence from accidents involving dense irritant smoke suggests that the effectiveness of cabin crew at redirecting is severely reduced in real emergency evacuations [10]. Currently, research at FSEG using the AASK database is attempting to determine the significance of the qualitative differences in cabin crew effectiveness between real emergency evacuations and 90-second certification trials [19,20]. While this is useful, quantitative data is required. This can only be achieved through controlled full-scale experimentation. Such a study could provide useful data for both evacuation models and safety regulators.

Numerous studies have shown that exit hesitation time data is dependent on passenger physical characteristics of age, gender and size. If sufficient data were collected it would be possible to specify the exit hesitation time distribution not as simply a probability distribution but as a probability distribution dependent on these physical attributes. This would require considerably more data than currently exits and a concerted effort between the various experimental facilities to co-operate in the generation of such data.

Finally, with the exception of anecdotal data from accident investigations, very little data is available concerning passenger/crew performance in evacuation situations involving ditching or situations involving cabin ruptures. Experimental data relating to these type of incidents could be collected and used in evacuation models.

2.2. Future Data Requirements for VLTA and BWB aircraft

VLTA pose considerable challenges to designers, operators and certification authorities. VLTA designs currently being considered are capable of carrying 800+ passengers with interiors consisting of two aisles and two full-length passenger decks. Other more radical concepts consist of a Blended Wing Body (BWB) design, involving one or two decks with possibly four or more aisles. The drive for increased efficiency, passenger capacity and aircraft size is balanced by the need to maintain, and if possible, improve current safety standards. One of the highest safety priorities for aircraft designers and regulators alike concerns the evacuation efficiency of aircraft design. Questions concerning seating arrangement, nature and design of recreational space, the number, design and location of internal staircases, the number, location and type of exits, the number of cabin crew required, their seating locations and the nature of the cabin crew emergency procedures are just some of the issues that need to be addressed. Computer models offer a means of addressing these issues but only if the data requirements of these models can be meet.

The massive increase in passenger capacity and aircraft size being suggested also challenge some of our preconceptions in equipment design and crew emergency procedures. For instance, in order to efficiently complete an evacuation, will it be necessary to extend emergency procedures to the marshalling of those passengers evacuated to the ground? Imagine a situation with 800 passengers on the ground, possibly on one side of the aircraft. What impact will they have on fire fighting and rescue operations? Who should take responsibility for the grounded passengers? Should evacuation procedures be developed that allow passengers to travel between decks before exiting the aircraft? How will crew communicate effectively to control such an evacuation on a single deck and between decks? Will the proximity of multiple emergency slides have a detrimental effect on evacuation efficiency and safety? Can exits be safely spaced further apart than the current arbitrary 60 foot limit [21] What impact will this have on evacuation times and survivability?

If BWB aircraft become a reality, should designs incorporate continuous solid cabin partitions along the length of the aircraft? Should these cabins have cross aisles linking each cabin section?

Will it be sufficient to simply have exits in the forward and aft sections of the aircraft? Can the largest exits currently available cope with passenger flow arising from four or five main aisles? Do we need to consider new concepts in exit design, perhaps introducing three or four lane exits? How efficient can a three or four lane exit be in evacuating passengers? Should the main aisles be made wider to accommodate more passengers? How much time is actually required for safe egress from a BWB aircraft? Does the 90-seconds concept have any relevance to VLTA and BWB aircraft?

While there are currently no VLTA flying, the A380 has been labelled a VLTA by some. The A380, while physically the largest passenger aircraft currently planned does not represent a massive increase in passenger capacity, at least for its standard configuration. The standard passenger seating capacity of the A380 is reported to be 550 passengers in a three class configuration [22] however, significantly greater seating capacity options are possible, with 822 passengers being suggested for the single class configuration [23]. This is compared with the B747-400 that carries 416 in a three class configuration with a reported maximum of 660 for the single class configuration [23]. Another feature of the A380 is that it has two passenger decks positioned one on top of the other. This in itself is not unusual or novel as the B747 has flown with an upper deck for many years. While it may be debated whether the new Airbus A380 should be classified as a VLTA, the number of passengers that are seated on the upper deck make the A380 different to existing aircraft.

With the upper deck comes the need to evacuate passengers using the upper deck exits and slides. A feature of upper deck exits is that the exit slides are much longer than those of more ‘standard’ exits. For example, on the B747 the upper deck sill height is **7.8** metres and on the A380 it is set to be **8.1** metres above the ground [23]. One assumption concerning the use of high sill height exits is that passengers would hesitate longer at the upper deck exit before they jumped onto the slide compared to lower height main deck exits. While there is very little data concerning the use of upper deck slides under certification evacuation conditions, what data that is available suggests that this is not the case, and that passenger exit hesitation delays while slightly longer are similar to those of more standard exits [14,24]. Clearly, more research in the form of component testing is required to generate the required data (see Section 2.1).

In addition to higher sill heights, longer exit slides and large numbers of passengers located on upper decks, VLTA double deck aircraft can possess one or more staircases. Again, in itself this is not a new concept as the B747 has flown for many years with a staircase connecting the two decks. While evacuation procedures for VLTA may not require the use of the staircase(s) in order to pass an evacuation certification trial, it is desirable that staircase design be appropriate for evacuation situations. Emergency evacuation scenarios may develop where it is necessary or desirable to evacuate all or some passengers down the stairs and out the main deck exits rather than out the upper deck exits. While less likely, accident situations may also develop where it is necessary to move some passengers to the upper deck and out the upper exits. While this may not be a problem for existing aircraft, the sheer number of passengers located on the upper deck of VLTA configurations makes this an issue worth investigating.

Currently, the CFR 25 aviation regulations are silent on the issue of staircase design [3,4]. This omission could lead to the development of sub-optimal conditions during an evacuation should the staircase be needed as a means of escape. As an example, the height of a stair riser and the depth of a stair tread are known to be important factors in determining the ease of use and efficiency of staircase design. Additionally, the requirement for handrails that separate a wide staircase into lanes has long been recognised as essential in building and marine regulations [25,26]. It is recognised that central handrails enable passengers to use the entire width of the staircase during an emergency evacuation as opposed to 'hugging' the walls close to the outer handrails. Handrails are mandatory in building codes as they provide support to occupants and serve as guides for people whose vision may be impaired due to smoke and/or lighting failure [26]. In addition, within building codes it is recognised that to be effective the handrails must be within reach of staircase users [26]. Therefore building codes mandate that handrails must be within 30 inches of the "natural path of travel" [26]. Onboard marine vessels the requirement for handrails is of even more importance as marine vessels are subject to dynamic and static changes in pitch and roll. Similar situations could develop on aircraft that have crashed and have gear failure.

Aircraft staircase design has been studied in previous research undertaken by the FAA Civil Aerospace Medical Institute (CAMI) in 1978. The staircases that were investigated were very narrow having an effective width of 20 inches. As such the passengers evacuated in single file and used the handrails extensively. Unfortunately, the staircase width used in these experiments is simply not relevant for staircases that are expected to accommodate two or more passengers simultaneously. While there are no specific rules addressing staircases in the CFR, special conditions were specified for the certification of the B747. These conditions do not specify staircase design constraints but state objectives that should be meet by good staircase design, e.g. stairs must be safe, must work in adverse attitude conditions etc.

3. THE USE OF EVACUATION MODELS FOR CERTIFICATION APPLICATIONS

Before computer models can reliably be used for certification applications they must undergo a range of validation demonstrations. While 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.

The success of at least some aircraft evacuation models (e.g. airEXODUS in [1,27,28,29,30,33]) in predicting the outcome of previous 90-second certification trials are compelling arguments of the suitability of these models for evacuation certification applications - at least for derivative aircraft. For aircraft involving truly 'new' features 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 does 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.

However, it is not sufficient to simply replace full-scale testing of aircraft with a combination of computer modelling and component testing. While this may make testing the aircraft a safer and more efficient process, computer modelling should also improve the certification process i.e. provide the aviation community and the passengers that use the aircraft something more than the simple one-off testing provides. If we are to rise to this challenge it is essential that we begin to question some of our current preconceptions concerning certification.

3.1. What constituents a certification scenario?

When examining the possible use of aircraft evacuation models for certification purposes, we must first establish what will be the nature of the certification scenario. An aircraft evacuation scenario – be it real accident, computer generated or live full-scale experiment - is made up of the following six key components:

- ***Aircraft configuration specification:*** consisting of cabin layout, exit configuration and exit availability.
- ***Aircraft environmental specification:*** consisting of the orientation of the aircraft and the nature of the cabin atmosphere with regard to heat, smoke and toxic gases.
- ***Crew behaviour:*** consisting of the number and role of cabin crew, level of assertiveness displayed by the crew at exits and the exit ready times.
- ***Passenger population distribution:*** consisting of the nature of the evacuating population, either a standard 90 second population or other mix of passengers including for example injured/disabled passengers.
- ***Passenger behaviour:*** consisting of standard 90 second type non-competitive behaviour or accident specific competitive behaviour (e.g. seat jumping, aisle swapping, etc).
- ***Passenger exit selection:*** consisting of which exits the passengers will attempt to utilise during the evacuation, this can be categorised into essentially one of three basic types, optimal exit, nearest exit, or case specific sub-optimal exit selection.

Changing the selection of any of these parameters will change the outcome of the evacuation. In effect, changing these parameters is equivalent to changing the nature of the question that is being posed. Computer simulations used to represent current 90 second certification scenarios would typically consist of the following settings:

- ***Aircraft configuration specification:*** cabin layout and exit specification given by aircraft drawings exit availability determined by standard 90 second protocol.
- ***Aircraft environmental specification:*** normal orientation, darkness/emergency lighting and no fire products.
- ***Crew behaviour:*** assertive crew and generalised exit ready times.
- ***Passenger population distribution:*** standard 90 second population distribution.
- ***Passenger behaviour:*** standard 90 second type non-competitive behaviour.
- ***Passenger exit selection:*** optimal exit selection.

Evacuation models have the capability of examining many different types of evacuation scenario. 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? The selection of suitable evacuation scenarios could be guided through analysis of past accident data – from for example one of the several accident databases that have been developed [17,18,34,35,]. For example, the analysis of past accidents can suggest which exit combination is most likely to occur. This could be used to assist in selecting the number and location of exits to assess in the certification trial. In addition, it is suggested that consideration of likely failure modes should also be considered. In addition to simulating the "optimal" scenario it is important to simulate likely "what if" scenarios that may occur. These are likely to be aircraft specific and depend on the nature of the aircraft geometry.

Furthermore, unlike full-scale testing, evacuation models allow 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 should 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.

3.2. 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? For a particular scenario should the requirement stipulate that ***every*** simulation be sub-90 seconds? Or should the distribution mean or the 95 percentile result be sub-90 seconds? In the hypothetical example provided (see Figure 1), 950 of the 1000 simulations (i.e. 95%) produced an evacuation time less than 90 seconds. Should this aircraft configuration be deemed to pass or fail the certification criteria?

An interesting example of this dilemma was shown in a recent report to the UK CAA [29] concerning the validation of the airEXODUS model. In this example, the aircraft achieved an actual certification performance of 83.7 seconds with a mean airEXODUS predicted evacuation time of 82.7 seconds. While 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% less than 90 seconds) 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.

Any aircraft configuration will produce a range of evacuation times over a number of tests, some of which may well be over the certification maximum of 90 seconds. Under the current 'make or break' single test regime, a single performance result is selected from this '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 second 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 could be repeated. This provides a better indication of the performance capability of the aircraft.

It has been argued by some that to achieve parity with the current certification process, 100% of the generated simulations should produce times less than 90 seconds 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 modelling analysis. As part of this methodology it would still be necessary to first generate the evacuation time distribution using many repeat simulations. This would generate the probability space of possible evacuation times for the aircraft configuration under the selected certification scenario. From this probability distribution a single evacuation time would be selected at random and deemed to be the certification performance of the aircraft. This in essence is equivalent to the current practice of performing only a single trial for certification. 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 modelling 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 re-define 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 endeavouring to produce a more meaningful measure of aircraft evacuation performance.

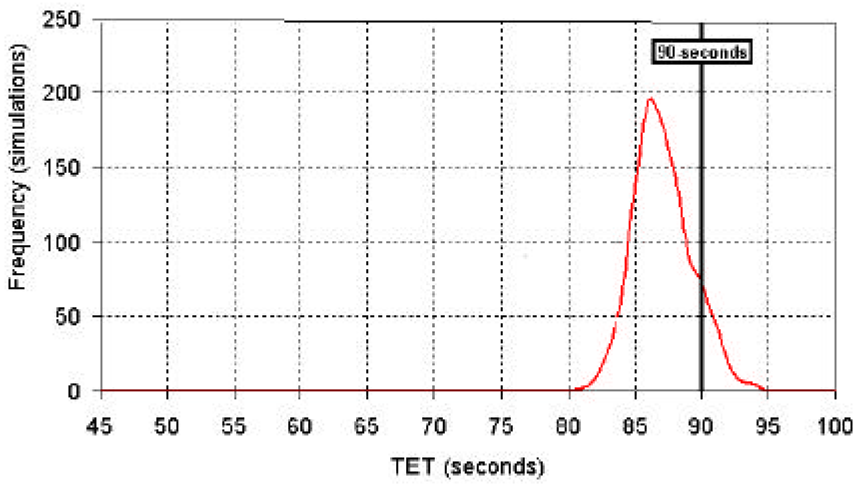

Figure 1: Numerically generated evacuation time distribution (frequency Vs evacuation time) for a particular scenario for a hypothetical aircraft configuration.

This raises the question, does the "magic number" 90 seconds have any actual meaning under these circumstances?

3.3. 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 pre-defined acceptable amount of time. In the U.K. for public buildings this turns out to be the “magic number” 2.5 minutes. 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 while the RSET may be the time required for the occupants to vacate the structure. Put simply, the ASET must be greater than the RSET. 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 evacuation and fire models are being used to assist in the determination of both the ASET and the RSET. 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 half way 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 second “magic number” used in the aviation industry while the RSET can be determined by computer simulation [1,31]. 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 are prescribed in a similar way to the current 90 second certification trial. The ship design must pass all four benchmark scenarios in order 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 should be considered for aviation.

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 allow easy verification and reproduction of the submitted results [1,31,32]. These requirements include the specification of:

- the variables used in the model to describe the dynamics, e.g. walking speed of each person;
- the functional relation between the parameters and the variables;
- the type of update used within the model;

- 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;
- 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 should require a similar level of documentation.

3.4. Suggested Certification Methodology

As in the marine and building industries, it is essential that a protocol be developed for the acceptable use of computer simulations for aircraft certification applications. However, it is essential to note that such a methodology is not intended to replace the entire certification process. Existing testing such as slide inflation testing, door opening times, etc would still be required as would compliance with prescriptive rules. The protocol is only intended as an alternative to the current full-scale evacuation demonstration.

Such a protocol should address the following five key issues:

(i) 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. The cases examined in the recent report on the validation of the airEXODUS aircraft evacuation model [33] could form the basis of such validation/demonstration cases.

(ii) Simulation protocols
It is necessary to specify the manner in which the simulations are to be run and the nature of the core results must 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.

(iii) The Scenarios to be Investigated
The number and nature of the scenario(s) to be investigated must be specified. For example, a range of scenarios could be considered which includes the standard 90 second scenario as a base case and additional scenarios drawn from accident analysis as suggested in section 3.1. The scenario specification should specify the six key components as identified in section 3.1.

(iv) The Acceptance Criteria
Due to 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 outlined in section 3.2.

(v) 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 numerical technique and data used - and provide a means of reproducing the analysis in some way. The approach adopted by International Maritime

Organisation discussed in section 3.3 provides the basis for developing such a system for aviation applications.

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

3.5. Suggested use of models for certification

In suggesting the use of computer models for aircraft certification we must be mindful of the point made earlier that it is not sufficient to simply replace full-scale testing of aircraft with a combination of computer modelling and component testing. While this may make testing the aircraft a safer and more efficient process, computer modelling should also improve the certification process i.e. provide the aviation community and the passengers that use the aircraft something more than the simple one-off testing provides.

While a methodology for the use of computer simulation for certification applications has been suggested in section 3.4, the nature of the scenarios to be considered for certification has not been finalised. It has been suggested that through the use of computer simulation a range of evacuation scenarios should be examined for certification purposes. As a first step in the process of developing these scenarios it is suggested that the current 90 second certification scenario be adopted as the basis for the computer analysis.

The success of evacuation models such as airEXODUS in predicting the outcome of previous 90-second certification trials is a compelling argument of the suitability of this model for predicting evacuation performance under certification conditions - at least for derivative aircraft (for example see [27,28,29,30,33]). These applications would simply involve the computer simulation being used to perform the full-scale evacuation demonstration. This could only be achieved for situations in which reliable data is available on which to base the evacuation simulation. For aircraft involving truly 'new' features – in which data is 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 does 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.

It has also been demonstrated through computer simulation that even though an aircraft may pass a single one-off certification trial, there may be a finite chance that the aircraft will fail to meet the requirements of the certification process if the trial were repeated a number of times [33]. This information is invaluable when attempting to assess the true evacuation performance of the aircraft. It provides insight into the design of the aircraft that can only be practically provided through evacuation simulation.

Thus, computer based aircraft evacuation simulation using the standard evacuation certification scenario has been shown to:

- be capable of reproducing the evacuation performance of aircraft, passengers and crew in full-scale certification trials,
- be a safer and more efficient process than full-scale evacuation trials,
- 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, and
- be capable of easily and efficiently investigating a range of relevant certification scenarios rather than a single scenario.

These capabilities provide the aviation community (passengers, crew, manufacturers, airlines, regulators) with significantly more than the current simple one-off testing procedure provides and thus should be considered a useful alternative to full-scale testing. Thus as an alternative to full-scale testing, aircraft evacuation models could be used to simulate the performance of the aircraft using the current single certification scenario. The simulations would be run using the outlined methodology and 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. If suitable data were not available to perform reliable simulations, than component testing in conjunction with simulations would be necessary to satisfy the certification process. All other prescriptive rules and requirements would still apply, the evacuation simulation simply replacing the final full-scale demonstration. This approach should be considered 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.

While the above approach would appear to be a logical first step to the introduction of computer modelling to certification, it may be considered too radical by some sectors of the aviation industry that are still sceptical 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 the recognised 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. In this alternative first step, the full-scale evacuation certification demonstration would be run in the usual manner. However, additional requirements could be introduced into the certification process involving computer simulation.

These could involve the use of the computer model to address several relevant evacuation scenarios. The first scenario would be the standard 90 second certification scenario. This would be simulated many times in order to establish a probability distribution of likely evacuation performance of the aircraft under certification conditions. Given that the computer models was set up to model 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 reference [33] for examples). This would serve two purposes, the first would be to further validate the modelling process and secondly, to better understand the performance of the aircraft under repeated trials.

In addition, several other simulated evacuation scenarios could be investigated. These could be based on data from accident investigation suggesting likely exit combinations but would not involve the introduction of more complex accident conditions (see section 3.1). As suggested previously, all the simulations would be run using the outlined methodology. If suitable data were not available to perform reliable simulations, than component testing in conjunction with simulations would be necessary to satisfy the certification process. All other prescriptive rules and requirements would still apply.

As a second step in the adoption of computer simulation for certification the full-scale trial could be dropped in circumstances where there was sufficient data on which to be confident in the modelling approach. This would only be contemplated after sufficient experience and confidence in the use of computer models had been developed.

As a third 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. However, for this to become a reality, further effort must be directed towards the continued development of aircraft evacuation modelling technology to include additional behavioural features common in real accident scenarios. It is suggested that additional capabilities to explicitly represent the crew and their interactions with passengers should be developed. This should include the ability to simulate crew directed by-pass. Wherever possible these developments should be guided by evidence available from actual accidents. Additional capabilities relating to behaviours noted in actual accidents such as the ability for passengers to jump over seats and switch aisles should also be developed and where possible this development should be guided by actual accident analysis. As suggested in [2], this work is already underway but will require additional support if it is to develop to the point where it can be reliably used for certification applications.

4. CONCLUSIONS

As part of VERRES Work Package 2, it has been suggested that evacuation models offer a possible alternative to the current practice of performing a single live evacuation demonstration. While 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. In order 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 exists and has been analysed while much more data is available and yet to be analysed. However, more data is required and a concerted effort must be undertaken to collect and analyse the required data. This will require co-operation 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 suggested protocol be developed for the acceptable use of computer simulations for aircraft certification applications. Until such protocols are 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 protocol has been suggested in this document.

Along with the suggested protocol, a phased introduction of computer models to certification has been suggested. Given the sceptical nature of some in the aviation community regarding the capabilities of computer simulation, this would involve as a first step the use of computer simulation in conjunction with full-scale testing. The computer model would be used to reproduce a probability distribution of likely aircraft performance under current certification conditions and in addition, several other more challenging scenarios could be developed. In these cases, the combination of full-scale trial, computer simulation (and if necessary component testing) 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, and
- be capable of easily and efficiently investigating a range of relevant certification scenarios rather than a single scenario.

These capabilities provide the aviation community (passengers, crew, manufacturers, airlines, regulators) significantly more than the current simple one-off testing procedure provides. Once further confidence in the technique is established, the second step would only involve computer simulation and component testing. This would only be contemplated after sufficient experience and confidence in the use of computer models had been developed.

The third challenge involves the continued development of aircraft evacuation modelling technology to include additional behavioural features common in real accident scenarios. It is suggested that additional capabilities to explicitly represent the crew and their interactions with passengers should be developed. This should include the ability to simulate crew directed by-pass. Wherever possible these developments should be guided by evidence available from actual accidents. Additional capabilities relating to behaviours noted in actual accidents such as the ability for passengers to jump over seats and switch aisles should also be developed and where possible this development should be guided by actual accident analysis. With this development, the third step in the adoption of computer simulation for certification could be taken. This would involve the introduction of more realistic accident scenarios into the certification process.

Finally, the challenge facing all the stake holders involved in aircraft certification i.e. regulators, approval authorities, accident investigators, manufacturers, airlines, unions, and ultimately the travelling public, is to develop a better understanding of the modelling technology being developed and with that understanding specify relevant design 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.

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6. APPENDIX A

6.1. EXECUTIVE SUMMARY

This document is intended to review the state-of-the-art in aircraft evacuation modelling. As such, the document first reviews the methodologies available for evacuation modelling in general and then focuses on aircraft evacuation modelling. While some 30 evacuation models have been developed for the building industry, to date, there have only been approximately seven models proposed for the aviation industry. It should be noted that building evacuation models cannot easily and reliably be used for aviation applications. This is due in part to the unique behaviour exhibited by passengers and crew in aircraft evacuations and key structural features that differentiate aircraft from buildings. The discussion on aircraft evacuation modelling also addresses the state of validation/verification of these models. As part of this discussion, the data available for evacuation modelling analysis is also reviewed and suggestions made as to what data is still required. Finally, methodologies for the use of evacuation modelling in the building and maritime industries are discussed and possible aircraft certification procedures are suggested. This document represents the main deliverable for Task 2.1 of the Verres European Union funded project and begins to address the issues of Task 2.3.

6.2. Introduction – The main types of evacuation models

This report is a review of evacuation modelling with a particular focus on models used to simulate evacuation from aircraft. The review describes the various methods available to simulate evacuation from any enclosure, be it a building or aircraft (see Section 6.3.1), the models that are currently available to simulate aircraft evacuation (see Section 6.3.3), the data requirements of these models and the sources of this data (see Section 6.5) and finally suggests a procedure for applying aircraft evacuation models to certification applications (see Section 6.7).

Before embarking on this discussion it is necessary to define and distinguish between the types of application that aircraft evacuation models can be used for. The distinction between these application areas is made early as it has an impact on the nature of the model used to service these different areas, and the quality and quantity of reliable data required to define the model and ultimately validate the model.

Currently there are two main areas of application for aircraft evacuation models. These are for design/certification and for accident reconstruction. Each of these two areas will be briefly discussed.

While design and certification application areas should be considered as two separate areas, for all intents and purposes, the design requirement is predominately driven by the certification requirements. Thus, for the purposes of this discussion, these two areas will be treated as a single requirement.

Regulators attempt to enforce and maintain safety standards through a set of essentially prescriptive rules that have evolved over time. In Europe they are know as Joint Aviation Requirements (JAR) [4] while in the USA the rules are known as the Federal Aviation Regulations (FAR) [3]. An example of one of the rules that has evolved over time relating to aircraft evacuation efficiency is the so-called "60-foot" rule. The rule appears in the JAR and FAR (i.e. 25.803 (f) (4)) [3], the 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." [3,4]

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'* [5]. Compliance with this rule is demonstrated by performing a full-scale evacuation demonstration. The demonstration is performed with a representative cross-section of the travelling public (age and gender distribution), in darkness and utilising only half of the normally available exits. 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 seconds if the aircraft is to pass the performance test. A complete video record is made of the event including behaviour within the cabin and at the exits. The video recordings of the evacuations are a valuable source of data on the performance level achieved during these types of certification evacuations. The certification performance test is only intended to provide a measure of the performance of the aircraft under an artificial benchmark evacuation scenario. It is not intended to predict the performance of the aircraft under a realistic accident scenario. However, it allows the performance of different aircraft to be compared under a set of identical – if somewhat artificial – scenario conditions.

There are several difficulties with the current 90 second trial. There is considerable threat of injury to trial participants. Between 1972 and 1991 a total of 378 volunteers (or 6% of participants) sustained injuries ranging from cuts and bruises to broken bones [6]. 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-second evacuation scenario. Volunteers are subject neither to trauma nor to the physical ramifications of a real emergency situation such as smoke, fire and debris, 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 minutes after the aircraft had ceased moving, while 15 years earlier in a UK certification trial, the entire load of passengers and crew evacuated the aircraft in 75 seconds [7,8]. In the certification trial, while passengers are keen to exit as quickly as possible, the behaviour exhibited is essentially co-operative, whereas in real accident situations the behaviour may become competitive. Even if complex issues of fire etc are excluded from consideration, relatively simple issues such as exit selection are far from realistic. Providing all exits on one side of the aircraft bears little or no resemblance to realistic accident scenarios.

On a practical level, as only a single evacuation trial is necessary for certification requirements, there can be 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.

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 $US2 million [6]. While the cost may be small in comparison to development costs, it remains a sizeable quantity.

A primary driver for the development of aircraft evacuation models is to augment or replace 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, GPSS) have been developed to address these needs. These models will be discussed in more detail later. However, at present it is worth noting that evacuation models designed to address 90-second certification applications have access to a plethora of data, in the form of video footage of previous 90-second certification trials, upon which behaviours within the model can be derived and key model parameters set.

Evacuation modelling for accident reconstruction is considerably more demanding than certification modelling. Some models have been developed in an attempt to simulate real emergency evacuation scenarios (e.g. airEXODUS, ARCEVAC, GOURARY, DEM, MACEY). An air accident as defined within FAR and JAR is:

> *"An occurrence associated with the operation of an aircraft that takes place between the time any person boards the aircraft with the intention of flight and all such persons have disembarked, where any person suffers death or serious injury, or the aircraft received substantial damage."* [9].

Modelling real emergency evacuation is far more complex than certification modelling for a number of reasons. Firstly, 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 [10], in another, the cabin may remain intact but passengers may be subjected to a mild threat of smoke [11]. The aircraft could be on its landing gear in one scenario [12] but may have partial failure in another [11]; the aircraft may be partially immersed in water as in the case of a runway overrun [13], etc. Thus the range of human behaviour that needs to be modelled is far more extensive than that found in the certification scenario.

Furthermore, reliable data on human behaviour and performance under these realistic accident scenarios is more difficult to obtain. There are fewer sources of accurate quantitative information on human performance in emergency evacuation situations. Unlike, 90-second certification trials there are no video recordings of the unfolding evacuation upon which behaviour 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 and data from contrived experimental trials.

6.3. Computer based evacuation models

The most significant developments in computer based evacuation modelling technology has occurred in the building industry. This has been the driving force for much of the development in evacuation modelling. This is somewhat ironic as one of the first computer based evacuation models to appear in the literature was an aircraft evacuation model, GPSS [47,48] in the 1970's. 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 modelling capabilities. As a result the area of aircraft evacuation modelling fell dormant for nearly 20 years.

In the interim, and completely independent of the earlier aircraft developments, the building industry developed an interest in evacuation modelling. 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 utilisation they also challenged the scope of the traditional prescriptive building regulations. Increasingly, engineers and regulatory officials were faced with 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.

In the building industry, research into quantifying and modelling human movement and behaviour has been underway for at least 30 years. This work has progressed down two routes, the first is concerned with the movement of people under normal non-emergency conditions. The second is concerned with the development of a capability to predict the movement of people under emergency conditions such as may result from the evacuation of a building subjected to a fire threat.

Some of the earliest work concerned with quantifying the movement of people under non-emergency conditions is that of Predtechenskii and Milinksii [49] and Fruin [50]. This research into movement capabilities of people in crowded areas and on stairs eventually lead to the development of movement models such as PEDROUTE/PAXPORT [52-54]. Evacuation research is somewhat more recent, one of the earliest published papers appeared in 1982 and concerns the modelling of emergency egress during fires [55].

In the following section of this document an attempt is made to describe the modelling methodologies available to simulate evacuation. This discussion is application independent and applies equally to building and aircraft evacuation models. Having established the principle methodologies available we go on to examine aviation evacuation models. A more detailed discussion of the modelling methodologies can be found in [57].

6.3.1. A review of the modelling methodologies used to simulate evacuation

Attempts to simulate evacuation essentially fall into two categories of model, those which only consider human movement and those which attempt to link movement with behaviour.

The first category of model concentrates solely on the carrying capacity of the structure and its various components. This type of model is often referred to as a "ball-bearing" model (also referred to as environmental determinism [58]) as individuals are treated as unthinking objects that automatically respond to external stimuli. In such a model, people are assumed to evacuate the structure, immediately ceasing any other activity. Furthermore, the direction and speed of egress is determined by physical considerations only (e.g. population densities, exit capacity, etc.). An extreme example of this type of model is one which ignores the population's individuality altogether and treats their egress en mass [59].

The second category of model takes into account not only the physical characteristics of the enclosure but treats the individual as an active agent taking into consideration his response to stimuli such as the various fire hazards and individual behaviour such as personal reaction times, exit preference etc. An example of this type of model is EXODUS [21-75].

A variety of different modelling methodologies are available by which to represent these different categories of evacuation model. Within the modelling methodologies adopted, there are also a number of ways in which to represent the enclosure, population and the behaviour of the population. The myriad approaches that are available led to the development of some 22 different building evacuation models and some 6 aircraft evacuation models. These models have been categorised [57] according to the underlying methodologies used to represent:

- Nature of model application,
- Enclosure representation,
- Population perspective, and
- Behavioural perspective.

Each of these key areas will now be discussed. In sections that describe both building and aircraft evacuation models, the aircraft evacuation models are highlighted in bold italics. It should be noted that the EXODUS is a suite of evacuation models with specific versions for aircraft, buildings and ships.

6.3.1.1. Nature of model application

Broadly speaking, models that simulate evacuation tackle this problem in three fundamentally different manners: that of optimisation, simulation, and risk assessment. The underlying principles associated with each of these approaches influences the models' capabilities.

Several of the models assume the occupants evacuate in as efficient a manner as possible, ignoring peripheral and non-evacuation activities. The evacuation paths taken are considered optima, as are the flow characteristics of people and exits. These tend to be models which cater for a large number of people or who treat the occupants as a homogenous ensemble, therefore not recognising individual behaviour. These models are generally termed **OPTIMISATION** models (e.g. EVACNET+ [81,82] and TAKAHASHI's MODEL [59]).

Alternatively, designers might attempt to represent the behaviour and movement observed in evacuations, not only to achieve accurate results, but to realistically represent the paths and decisions taken during an evacuation. These models are termed **SIMULATION** models (BGRAF [83], DONEGAN'S ENTROPY MODEL [84], EXITT [85,86], EGRESS [87,88], E-SCAPE [89], EVACSIM [90,91], EXIT89 [92,93], SIMULEX [94-96], MAGNETMODEL [51] PAXPORT [52-54], VEGAS [100,101], ***EXODUS [21-75], GPSS [47,48], ARCEVAC [97], GOURARY [98] and DEM [99]***). The behavioural sophistication employed by these models varies greatly, as does the accuracy of their results. These types of models may be used to predict and/or reconstruct realistic evacuation scenarios. They can also be used to determine layouts of configurations that are most conducive for rapid evacuation or be used to determine optimal evacuation procedures.

RISK ASSESSMENT models (CRISP [102,103], WAYOUT [104] and ***MACEY [105]***) attempt to identify hazards associated with evacuation resulting from a fire or related incident and attempt to quantify risk. By performing many repeated runs, statistically significant variations associated with changes to the compartment designs or fire protection measures, can be assessed.

Whichever approach is adopted, it is essential that the enclosure geometry, population and population behaviour be represented. Each of these aspects can be modelled using one of several approaches.

6.3.1.2. Enclosure representation

The method that a model utilises in representing the enclosure is an important characteristic of a model, as it is a key determinant of the level of detail that the model can ultimately provide. Two methods are usually used to represent the enclosure: fine and coarse networks. In each case, space is descretised into sub-regions, and each sub-region is connected to its neighbours. The resolution of this subdivision distinguishes the two approaches.

Using the **FINE NETWORK** approach (CRISP [102,103], BGRAF [83], EGRESS [87,88], SIMULEX [94-96], MAGNETMODEL [51], VEGAS [100,101], ***EXODUS [21-75], ARCEVAC [97], GOURARY [98], DEM [99] and MACEY [105])*** space is subdivided into a series of nodes or tiles. Each node/tile represents an area of the space that may typically be occupied by one person. The node/tile size is usually set to dimensions of the average human. Connectivity between the nodes/tiles is represented via arcs, which the simulated people traverse in moving between spatial nodes/tiles. Thus, with a fine network model people move from location to location within compartments. The location of people within each compartment is exactly known.

A large geometry may be made up of thousands of nodes and each compartment within the geometry, may be made up of many nodes. In this way, it is possible to accurately represent the geometry, and its internal obstacles, and accurately locate each individual at any time during the evacuation.

Coordinate based systems (SIMULEX [94-96] and ***DEM [99]***) are an extreme manifestation of the fine network paradigm. Within a coordinate based system the node size is reduced to a very small size and people can occupy a number of nodes.

In the **COARSE NETWORK** approach (DONEGAN'S ENTROPY MODEL [84], EXIT89 [92,93], EVACSIM [90,91], EVACNET+ [81,82], PAXPORT [52-54], TAKAHASHI's MODEL [59], E-SCAPE [89], ***GPSS [47,48],*** EXITT [85,86] and WAYOUT [104]) space is subdivided into compartments or large logically consistent regions. In buildings these may represent rooms, stairwells, etc, whereas in aircraft they may represent aisles, seat rows, exit passageways, and so forth. The connectivity between these compartments is represented via arcs. People move between compartments via the connecting arcs. Knowledge of peoples' location within compartments is not exactly known, however it may be approximated via queuing algorithms.

This approach presents difficulties when incorporating local movement and navigation including overtaking, the resolution of local conflicts, and obstacle avoidance. This is because the exact location of an individual is not represented, and therefore detailed calculations of individual movement, and the interaction between individuals cannot be made. This limitation should be kept in mind when examining the behavioural models.

For building applications, the main benefit of this approach is that it reduces the amount of computer processing, memory and ultimately the simulation time that is required. However, this approximation is not necessary for small problem domains, such as aircraft cabins, given the large processing power of modern desktop computers.

6.3.1.3. Population perspective

Another important feature of evacuation models is the method they employ in representing people within the enclosure. This aspect of evacuation models is referred to as the population perspective. Evacuation models are categorised as having either an INDIVIDAUL or GLOBAL population perspective.

Models that have an **INDIVIDUAL PERSPECTIVE** (BGRAF [83], E-SCAPE [89], EVACSIM [90,91], EGRESS [87,88], SIMULEX [94-96], MAGNETMODEL [51], VEGAS [100,101], ***EXODUS [21-75], GPSS [47,48], ARCEVAC [97], GOURARY [98], DEM [99], MACEY [105],*** CRISP [102,103], and EXITT [85,86]) represent each member of the population individually and track their progress throughout the simulation. Each member of the population can be assigned individual attributes, such as age, gender, movement rates, etc. Whilst these types of models treat each individual within the simulation as unique, they do not preclude the formation of groups.

Evacuation models that have a **GLOBAL PERSPECTIVE** (DONEGAN'S ENTROPY MODEL [84], EXIT89 [92,93], EVACNET+, [81,82] PAXPORT [52-54], TAKAHASHI's MODEL [59], WAYOUT [104]) do not recognise the individual, but delineate a population as an homogenous ensemble (or a grouping), without different identities. These models represent evacuation details not on the basis of which individual escaped, but on the numbers of occupants who escaped. This approach may be beneficial in both the management and the speed of the models, but lacks much of the detail available to the individual perspective.

Whilst employing a global perspective, it would be difficult to model the effects of events on individual occupants (the effect of toxic fire gases, for instance). Only a distributed, or average effect could be established throughout the population. This would give no indication, for example, of the survival rates of specific groups of individuals, such as the elderly or the disabled, but instead, only that of the proportion of the population that had been effected.

This problem would arise for a number of other evacuation factors including any individual attribute, communication, the response of the individual to cues, and the interaction of an individual or subgroup with the rest of the population. This deficiency may not be considered serious in simple, homogenous populations, but in more realistic situations, it would seriously hinder an accurate understanding of the behaviour of the population.

6.3.1.4. Behavioural perspective

To represent the decision-making process employed by the occupants, the model must incorporate an appropriate method for determining occupant behaviour. The behavioural perspective adopted is influenced by the population and geometry approaches taken, and as such is the most complex of all the defining aspects. Using current modelling techniques there are five commonly used approaches to represent behaviour within evacuation models; FUNCTIONAL ANALOGY BEHAVIOUR, IMPLICIT

BEHAVIOUR, RULE BASED BEHAVIOUR, ARTIFICIAL INTELLIGENCE based behaviour and NO BEHAVIOURAL COMPONENT.

FUNCTIONAL ANALOGY MODELS (MAGNETMODEL [51], TAKAHASHI's MODEL [59] and ***DEM [99])*** apply an equation, or set of equations, derived from a non-evacuation related discipline, to the entire population, which then completely governs the population's response. Although it is possible for the population to be defined individually in these models, all the individuals will be effected in the same way by this function, and therefore will react in a deterministic manner to its influences, undermining individual behaviour. The function used to describe the occupant behaviour is not necessarily derived from real-life occupant behaviour, but is instead taken from another field of study that is assumed to be analogous to human behaviour, (e.g. the functions which drive the Magnetic model were taken from Physics). Occupant movement and behaviour is then completely determined by this function, which may or may not have been previously calibrated with human movement.

Some evacuation models have NO BEHAVIOURAL RULES at all (EVACNET+ [81,82]). These models simply simulate the physical movement of the people. Thus, peoples' decisions are formed on the basis of physical influences, rather than through simulating more complex human decision processes.

IMPLICIT MODELS (EXIT89 [92,93], PAXPORT [52-54], SIMULEX [94-96] and WAYOUT [104]) do not represent the behaviour explicitly but make use of secondary data to represent their affects. These types of models are highly dependant upon the availability, reliability and validity of the data used.

Models which explicitly recognise the behavioural traits of individual occupants, usually make use of a RULE BASED system (BGRAF [83], EXITT [85,86], E-SCAPE [89], EVACSIM [90,91], ***EXODUS [21-75], GPSS [47,48], ARCEVAC [97], GOURARY [98], MACEY [105]*** and CRISP [102,103]). These models have a set of rules, or heuristics, that govern the behaviour of simulated people within the model. This allows for decisions to be taken by occupants, according to pre-defined sets of rules. These rules can be triggered in specific circumstances, and in such circumstances, have an effect. For instance, a rule may be:

If I am unable to enter the aisle and I perceive a high risk factor in waiting, and I have sufficient agility, I will attempt to jump over the seats to by-pass the aisle blockage.

A problem with this style of decision-making process is that in simplistic methods the same decisions are taken under the same circumstances, in a deterministic fashion. Deterministic models are open to criticism, as they do not represent natural variation inherent within a scenario. This has the disadvantage of denying the possibility of natural variations in outcomes through repetition. Most of the rule based models overcome this problem by introducing a stochastic component to the decision making process. This topic is discussed in more detail later (see Section 6.5).

Artificial intelligence based models (DONEGAN'S ENTROPY MODEL [84], EGRESS [87,88] and VEGAS [100,101]) utilise methods from artificial intelligence to mimic human intelligence in simulated people. Whilst this approach can yield realistic behaviour the level of user control is somewhat reduced.

Finally, the above categories are not mutually exclusive. Many evacuation models make use of a number of the above techniques in some form.

6.3.2. Building and Aircraft evacuation models

As already mentioned, evacuation modelling for the built environment is more highly developed than evacuation modelling in the aviation industry. As a result there are many more models available for simulating evacuation from the built environment than from aviation environments. It should be noted at this stage that building evacuation models cannot easily and reliably be used for aviation applications. This is due in part to the unique behaviour exhibited by passengers and crew in aircraft evacuations and key structural features that differentiate aircraft from buildings. For example, behaviours, such as seat jumping, and cabin crew re-direction and structural features such as exits with slides make it difficult to simply apply a building evacuation model to an aircraft evacuation situation.

Occasionally, building models have been used to simulate the evacuation of aircraft [106]. Not surprisingly the model predicts were poor. It is for these reasons that specialised aircraft evacuation models have been developed.

6.3.3. A review of aircraft evacuation models

Over the past 30 years only seven aviation evacuation models have been reported in the open literature. In chronological order they are:

1970 to 1980	General Purpose Simulation System (GPSS) developed by the FAA,
1987 to 1992	Gourary Associates (GA) model developed by Gourary Associates,
1990 to 1994	AIREVAC/ARCEVAC developed by Aviation Research Corporation
1994 to 1996	Macey's Risk Assessment Model developed by Cranfield University
1996 to 1996	The Oklahoma Object Orientated (OOO) model
1989 to now	EXODUS developed by the Fire Safety Engineering Group of the University of Greenwich
2001 to now	Robbin's Discrete Element Method (DEM) developed by Department of Mathematics at The University of Strathclyde

Of these, it appears that development of three models, namely, GPSS [47,48], GA [98] and ARCEVAC [97] has now been abandoned, whilst the OOO [107] model was a theoretical framework, never actually implemented. An earlier review of aircraft evacuation models was undertaken by Jeff Marcus of CAMI (Civil Aero-Medical Institute) in 1994 [108]. The review presented here brings this earlier review up to date.

6.3.3.1. General Features

As mentioned in Section 6.3.1.1. , models have previously been categorised as being developed for use as either risk assessment, optimisation and/or simulation tools [57]. All of the aircraft evacuation models to date have been ***SIMULATION*** models. A possible exception is the MACEY [105] model. While the model as a whole is a risk assessment model, at its heart is an aircraft evacuation model which is a simulation model. We will therefore consider this component of the MACEY model to be a simulation evacuation model.

In Section 1 it was also stated that there are essentially two types of aviation application, the simulation of the 90 second trial and the simulation of real accident scenarios. Three aircraft evacuation models have been developed primarily to simulate REAL EMERGENCY evacuations (ARCEVAC [97] and GOURARY [98]), one model has been developed to simulate 90-SECOND certification evacuations (GPSS [47,48]) and two models have been developed specifically to simulate both 90 second certification trials and real emergency evacuations (EXODUS [21-75], MACEY [105] and DEM [99]).

If the model is intended to simulate real accident scenarios it will need the capability to represent fire scenarios. This can be accomplished through the incorporation of a hazard sub-model. The hazard sub-model is intended to represent the spatial and temporal distribution of fire hazards such as smoke, heat and toxic gases. The method of representing fire hazards is in some part dependent upon the nature of the enclosure representation. Models that utilise a coarse network approach to represent space will be forced to simplify the representation of fire hazards. In such cases, the hazard distribution would be represented as uniform distribution within the defined spatial zone. Models utilising a fine spatial network to represent space can also represent the hazards as a uniform distribution over a predefined region of space (or zone) (e.g. GOURARY [98] and ARCEVAC [97]) or elect to represent the a unique hazard value at each node/tile location within the geometry (e.g. EXODUS [21-75] and MACEY [105]). Models such as EXODUS can utilise either approach.

Determining hazard values to use in such calculations is discussed in Section 6.5.3.3. . It is sufficient now to know that they can be obtained either via fire test experiments [109,110] and/or rough estimates, or via computer based fire simulation models such as Zone models [111,] or Computational Fire Dynamics (CFD) [115] models

Models that represent fire hazards should also have a representation of its affects on the simulated passengers. Human exposure to a thermo-toxic hazard would affect passenger's behaviour and their physiology. The behaviour model employed determines the behavioural response however; a toxicity model is required to represent the passengers' physiological response.

To some extent the approach used to represent the population determines the maximum sophistication of the toxicity model that can be employed. Models that have an individual population perspective could simulate the response of each unique individual to fire hazard exposure, with each individual having unique tolerance limits.

A model with a simplistic representation of toxicity (e.g. GOURARY [98]), typically assigns passengers with an arbitrary *endurance* or *stamina* attribute that represents the individuals threshold to thermo-toxic exposure. The attribute is decreased by cumulative exposure until either incapacitation and/or expiry occurs. Unfortunately, the arbitrary nature of this attribute makes reliable predictions of human response to fire hazards difficult.

By contrast some models (e.g. EXODUS [21-75] and MACEY [105]) make use of complex fractional effective dose models (i.e. FED models) to predict the physiological response of passengers to fire hazard exposure (see Section 6.5.3.3.3). Incapacitation/expiry is determined via an empirically determined cumulative fractional effect that is determined according to actual exposure during the simulation.

Other models may completely ignore the thermo-toxic affects of real emergency environments (e.g. ARCEVAC [97] and DEM [99]). However, its presence may affect the behaviour of passengers (ARCEVAC [97]).

Another major feature of aviation evacuation models is their ability to represent the interaction of passengers with cabin crew. Unlike in most building evacuation scenarios, the actions of cabin crew are highly influential on the evolving dynamics of the aircraft evacuation. As examples, cabin crewmembers prepare exits for use, redirect passengers and assist passengers at exits. These actions must be represented within the aircraft evacuation model in some way. Methods of representing cabin crew within aircraft evacuation models are categorised as being IMPLICIT, EXPLICIT, USER DRIVEN or NONE.

Some models completely ignore cabin crewmembers (e.g. MACEY [105]). Thus cabin crewmember tasks, such as exit preparation, is performed by passengers. Models with an IMPLICIT representation of cabin crew (e.g. GPSS [47,48] and DEM [99]), do not physically represent cabin crew within the simulation, although their actions are represented. For example, the affect of having an implicit assertive cabin crewmember adjacent to an exit may lead to a faster exit hesitations distribution being utilised. Likewise, crew could be represented through the assignment of relatively low times for exit preparation.

Models that have an EXPLICIT representation of cabin crew (e.g. ARCEVAC [97]), physically model the cabin crew as an individual within the simulation. The model determines events, such as the length of time required to prepare exits for use. Using exit preparation time as an example, the model would move the crewmember to the exit then the crewmember would open the exit and deploy the escape slide. Other actions such as crew redirection can also be represented explicitly. Some models are capable of both IMPLICIT and EXPLICIT representation of cabin crew (e.g. EXODUS [21-75]).

Finally, some models require user intervention in order to simulate the redirection of passengers (e.g. GOURARY [98]). These types of models require the user to monitor the unfolding evacuation and determine from the model output when redirection is required.

A key feature of aircraft evacuation models, and one that distinguishes them from building models, is the need to represent the behaviour of passengers when using aviation specific components, such as exits or escape slides. Some models use empirical data (GPSS [47,48] and EXODUS [21-75]) to specify realistic delays appropriate to the aircraft components, i.e. Type-I, Type-III exits etc. Such data is derived from analysis of experimental studies and 90-second certification trials. Through the use of this empirical data these models predict realistic flow rates through the exit.

Other models use more novel methods of representing behaviour at these components. Some models (GOURARY [98], ARCEVAC [97], MACEY [105] and DEM [99]) use a probability of exiting as a function of exit size and cabin crewmember proximity (GOURARY [98]), other models tend to assume an arbitrary cap on exit capability such as only allowing one passenger to occupy an escape slide at any one time (DEM [99]). Essentially, these approaches impose a flow rate upon the exit. The models parameters are then altered until something approaching the desired flow rates is generated.

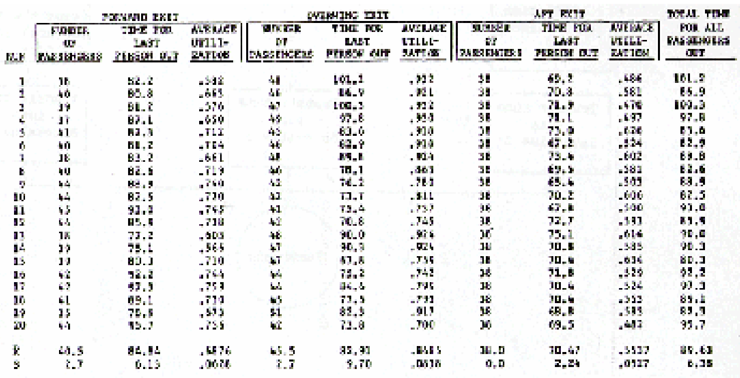
6.3.3.2. FAA GPSS model

The FAA model was developed in the 1970's and was intended to simulate 90-second certification scenarios. The model was designed to run on the massive mainframe computers of the day, the concept of desktop computers not being developed until the 1980's. The software was written using IBM's General Purpose Simulation System (GPSS) language.

Aircraft geometries were created within the GPSS programming language. The model did not have a user interface but was operated via the programming language itself. Alternative geometries and populations were created via reprogramming the model to represent the desired aircraft geometry.

Space within the model was represented using a coarse network interconnected with arcs. Thus, the aircraft was divided into components such as aisles, exit passageways, seat blocks, etc. GPSS identified the individual location of each of the passengers, so theoretically each passenger could be tracked throughout the simulation. However, passenger model parameters were assigned uniform values within the model, as the authors could not empirically define individual parameters and their likely affects.

The behaviour of passengers within the model was rule based. There were, for example specific rules that allowed passengers to redirect to shorter exit queues as well as rules governing the movement of passengers between aircraft components, such as seats and aisles. An assumption used in their redirection algorithm was that the passenger reached the alternative exit queue before a gap in the flow emerged. In addition to the behavioural rules, the model made use of empirically determined data in generating a random delay as passengers passed through an exit. The exit probability delay functions were calculated using data from CAMI (see Section 6.5.3.1.) for various different exit types. A further assumption of the model was that only three passengers could occupy each lane of an escape slide at any one time. A Type-A escape slide could therefore have a maximum passenger load of six passengers. Finally, exit



	FORWARD EXIT			OVERWING EXIT			AFT EXIT			TOTAL TIME
RUN	NUMBER OF PASSENGERS	TIME FOR LAST PERSON OUT	AVERAGE UTILI-ZATION	NUMBER OF PASSENGERS	TIME FOR LAST PERSON OUT	AVERAGE UTILI-ZATION	NUMBER OF PASSENGERS	TIME FOR LAST PERSON OUT	AVERAGE UTILI-ZATION	FOR ALL PASSENGERS OUT
1	38	52.2	.542	48	101.2	.922	38	65.2	.486	101.2
2	40	85.8	.665	46	86.9	.921	38	70.8	.581	85.9
3	39	81.2	.576	47	100.3	.922	38	78.9	.478	100.3
4	37	87.1	.650	49	97.8	.959	38	78.1	.497	97.8
5	41	83.3	.712	43	83.6	.910	38	73.9	.626	83.6
6	40	88.2	.764	46	82.9	.919	38	67.2	.524	82.9
7	38	83.2	.661	48	89.8	.904	38	75.4	.602	89.8
8	40	82.6	.719	46	78.1	.863	38	69.5	.583	82.6
9	44	88.9	.760	42	76.2	.783	38	65.4	.503	88.9
10	44	87.5	.720	42	73.7	.811	38	70.2	.606	87.5
11	43	93.8	.745	41	73.4	.757	38	67.8	.500	93.8
12	44	85.9	.718	42	70.8	.745	38	72.7	.593	85.9
13	38	77.2	.603	46	90.0	.924	38	75.1	.614	90.0
14	39	78.1	.565	47	90.3	.924	38	70.8	.585	90.3
15	39	80.3	.710	47	67.8	.759	38	70.6	.634	80.3
16	42	92.2	.744	44	78.2	.742	38	71.8	.529	92.2
17	42	93.3	.759	44	84.6	.795	38	70.6	.524	93.3
18	41	89.1	.719	45	77.5	.793	38	70.6	.552	89.1
19	35	75.8	.573	51	89.9	.917	38	68.8	.585	89.9
20	44	95.7	.755	42	71.8	.700	38	69.5	.483	95.7
$\bar{X}$	40.5	84.84	.6876	45.5	85.91	.8485	38.0	70.67	.5537	89.68
S	2.7	6.15	.0676	2.7	9.70	.0838	0.0	2.24	.0527	6.35

Figure 2: An example of the results from the GPSS model [47,48]

preparation times were assigned to individual exits. These were also determined from previous experimental trials at CAMI. A consequence of the exit delay probabilities was that the model was stochastic.

No hazard or toxicity model was required as the GPSS model was designed only to simulate 90-second certification trial evacuations. The model output was numerical. As output, the model calculated the times that passengers hesitated at the exits, the gap between passenger arrivals at the exit, the time spent on the slide for four gender/age groups. In addition the total evacuation time for the aircraft and the time of the last person out, continuous and non-continuous flow rates for each exit for each exit were output. An example of the results of the GPSS model output can be seen in Figure 2.

The GPSS model was validated using the four-certification trial cases shown in Table 1. It can be seen that the average total evacuation time of the model was only within 10% of the certification trial in one of the cases (L-1011 with redirection). The disparity in the remaining cases was attributed to variability in the performance of passengers and crew during the 90-second certification trial. It was thus concluded that more data was required from experimental trials in order to better represent motivation levels during emergency evacuations.

Table 1: GPSS validation history (reproduced from [108])

Type of Aircraft	Passenger Load	Certification Time (sec)	Average Simulated Time (sec)	Redirection
B747	527	66.2	84.0	Yes
L1011	356	101.1	93.5	No
L1011	356	82.0	54.9	Yes
L1011	411	89.7	79.6	Yes

6.3.3.3. The GA Model

Gourary Associates (GA) of the USA developed a model through part FAA and commercial funding during the late 1980's and early 1990's. The primary intention of the GA model was to simulate realistic emergency scenarios rather than the 90-second certification scenario. The GA model used a fine network method of representing space allowing one or more passengers to occupy each spatial node/tile. The population was represented as a collection of individual passengers, who were assigned individual attributes such as, *Endurance*, *Agility, Sex, Age* and *Wakeup time*, i.e. response time. The progress of each passenger was tracked throughout the evacuation.

The model was limited to 38 seat rows with up to six passengers within each seat row. The model allowed six exits. These exit could be positioned anywhere in the geometry. The exits could, for example, all be placed on the same side of the aircraft if desired. The model had a graphical user interface and ran in near real time. Edited geometries could be saved for later use.

Movement speeds were not empirically determined and attributed to each passenger as a parameter. Instead, each passenger had a probability of moving to an adjacent cell, based on the cells occupancy level, i.e. empty, occupied or full, the proximity of cabin crew and the type of cell being traversed. For example, the probability of a passenger moving between cells was higher in aisle nodes than in seat cells. Thus, different passenger speeds were modelled for specific terrain. In addition to this, the occupancy level of the targeted cell affected the probability of movement. For example, there was a higher probability of movement to unoccupied cells rather than those that were already occupied by a person. If a cell was full, i.e. containing two active people, then the probability of movement was impossible, i.e. zero.

Expired passengers were counted as occupying cells. This could lead to the model "jamming". An algorithm was included that enabled passengers to "bypass" cells that were occupied by expired passengers.

The probabilistic movement approach was also applied to passenger exiting. Once a passenger reached the exit they had a probability of exiting the aircraft. More effective exits would be modelled via increased probabilities. The proximity of cabin crewmember(s) at the exit increased the probability of exiting still further. Given the probabilistic nature of the movement sub-model, the GA model would have to be considered as stochastic in nature.

This model contained little further passenger behaviour from that already discussed. Indeed, the only notable other behaviour within the GA model, was passenger redirection.

Prior to running the model each passenger was assigned an exit. However, they could be diverted to other exits during the evacuation. Within GA this was accomplished without using computerised rules, but through user intervention via the keyboard whilst the simulation run. Firstly the user had to select an exit using the function keys F1-F6. This had the effect of placing a cabin crewmember at the exit. Having placed the crewmember at an exit the user pressed the arrow keys to divert passengers to the nearest exit in the selected direction. The drawback with this approach was that only one cabin crewmember could be modelled at any one time. A potential solution to this was provided via the ability to redirect every passenger in the simulation. This was accomplished by pressing <CONTROL+D> during the simulation.

Since GA was intended to simulate real emergency evacuations, hazard and toxicity models were required. Indeed, GA had a rudimentary representation of fire hazards and toxicity. Within the GA model, an environmental hostility value was required that decreased passengers *endurance* attribute until it had fully expired, at which point they died. The model allowed for two different hazard zones, with each having its own severity. However, the distribution of hazards throughout the aircraft cabin and their affect on passengers was completely arbitrary.

Indeed, the main failing of the GA model was that the parameters that it required were not empir ically specified [108]. The user was required to manually set all model parameters, such as exiting probability, passenger endurance and the toxicity of the environment. The arbitrary parameters would then be highly influential on the outcome of any simulations. In addition, whilst it is stated in its literature that validation was performed, its results were not published [98,108].

6.3.3.4. AIREVAC/ARCEVAC

In the late 1980's the South West Research Institute (SWRI) through Air Transport Association (ATA) funding began developing a model called AIREVAC. Later, in the early 1990's AIREVAC, became known as ARCEVAC and its development was taken over by Aviation Research Corporation of Canada as a commercial venture.

The ARCEVAC model was designed to simulate real emergency evacuation scenarios. ARCEVAC employed a fine network spatial representation, with space being descretised according to a user specific grid size. With a suitable small grid size the model functioned as a coordinate based scheme. As such passengers were assigned cross-sectional widths to represent the girth of their bodies.

Without rewriting the code, the model was limited to simulating the evacuations from the B727. At the time, the model ran considerably slower than real time. ARCEVAC had a user-friendly graphical user interface (see Figure 3*)* to allow the model to be configured. Simulation and geometry files could be saved for later use. The model was capable of outputting charts and data on the performance of the aircraft as a whole or individual exits (see Figure 4).

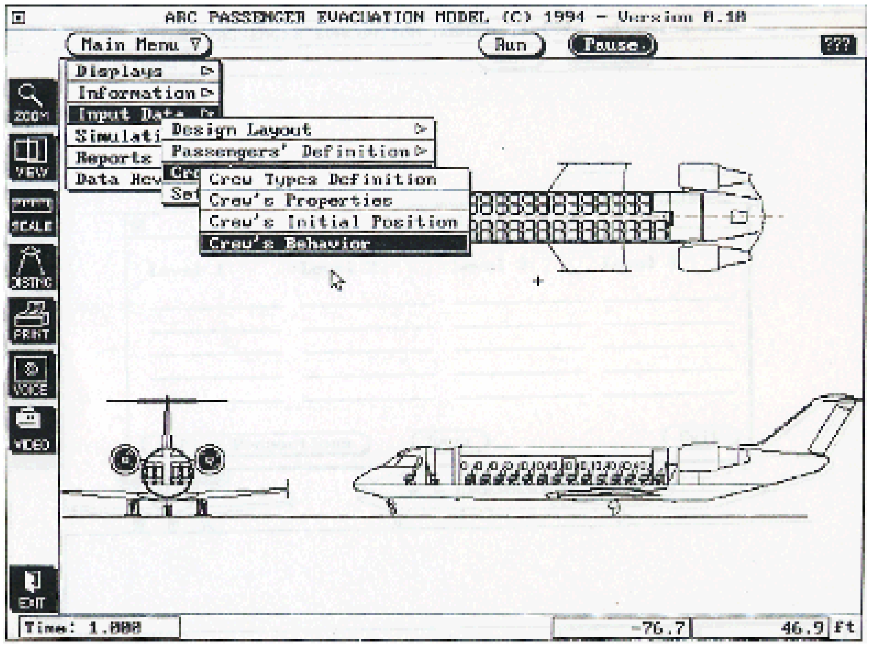


Figure 3: Graphic of screen output from the ARCEVAC model

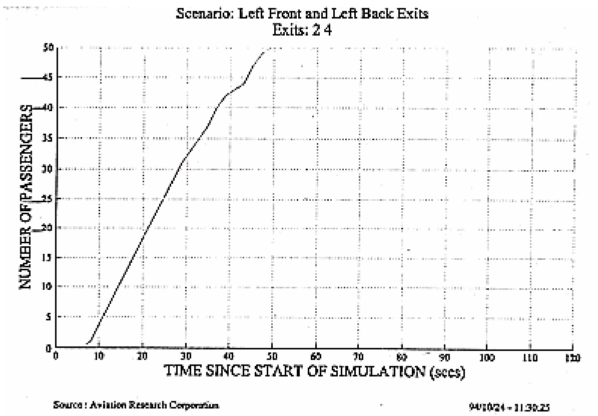


Figure 4: Example output from the ARCEVAC model

The population perspective of this model was individually based tracking each individual passenger throughout the evacuation. Indeed, passengers and crew within ARCEVAC contained numerous individual parameters, such as *Sex, Age, Constitution, Weight, Height, Cross Sectional Area, Agility, Selfishness* and *Group Selfishness*. Not only were passengers attributed with individual physical attributes, but they also have physiological and social attributes such as *state-of-mind* and *selfishness*.

To assist in defining populations within the model a randomiser was provided. The randomiser generated populations according to specified minimum and maximum values for different groups. Within these groups and for the purposes of representing group bonding peoples relationship with each other could be specified as being either: *business colleagues*, *friends* or *family members*.

ARCEVAC had a rule-base representation of passenger behaviour. The defining passenger parameters were used in conjunction with the behaviour rules to determine the response of each passenger to specific events during the evacuation. Indeed the behaviour within ARCEVAC was fairly sophisticated for its time. ARCEVAC contained the fundamental rules governing movement between nodes and exiting behaviour. Details of these aspects were not available in published literature.

In addition, ARCEVAC attempted to model group behaviour through user specified relationships and a group selfishness attribute. Also, ARCEVAC attempted to model the psychological state of mind of passengers during their evacuation. A numerical *state of mind* attribute represented the following states: *calm*, *alert*, *nervous*, *panicky* and *shock*. The *state-of-mind* modified both passenger movement and their response to specific stimuli.

Within the model, *Calm* passengers followed normal crew behaviour and were capable of changing directions to other exits without crossing seating. *Alert* passengers would choose the best evacuation route and may cross seating. *Alert* crewmembers gained a performance level. *Nervous* passengers would choose the best exit but would not redirect from their chosen exit without crew intervention. They were able to cross seating. *Nervous* crew would drop two levels of performance. *Panicky* passengers would choose any path to any exit so long as a threat is not present. They would not redirect themselves. *Panicky* crew would attempt to evacuate themselves. *Shocked* passengers would move randomly around the cabin space.

ARCEVAC had extensive capabilities with respect to simulating the actions of cabin crew. Cabin crew were modelled explicitly and are assigned specific "*missions*". *Missions* ranged from searching seats, stairs or aisles for immobilised passengers, to rescue/aid and general evacuation management. Assigning the mission of searching seats, stairs and aisles would make the cabin crewmember search these aircraft components for immobilised passengers. The aid mission would initiate an attempt at rescuing these passengers. The assist in evacuation mission would allow the cabin crewmember to redirect passengers to alternative exits or to assist in the flow of passengers through exits or monuments. Benefit to passengers from cabin crewmember missions was derived from a calmer *state of mind* attribute, increased *agility* attribute and more efficient exit choice.

Combinations of missions could be specified in order of priority. For example, the cabin crewmembers main priority could be to improve the flow rate of passengers through exits with the secondary mission of helping immobilised passengers.

Specific attributes, such as *valour* and *performance*, were assigned to cabin crew and influenced their ability to perform their tasks. The *valour* attribute was used in determining the point at which the cabin crewmember would abandon their mission in favour of their own survival. The performance level of the cabin crewmembers was specified through a series of probabilities and attribute modifiers. For example, the crewmembers' ability at assisting passengers during evacuation was determined via an *agility modifier* attribute. Probabilities were specified to represent the assertiveness of cabin crewmembers in issuing commands and the subservience of passengers to them. The final performance attribute was the *check interval*. This was used to represents the speed that the cabin crewmembers could perform their tasks, i.e. the frequency of their actions.

Since ARCEVAC was designed to simulate real emergency evacuations hazard and toxicity models were required. Whilst ARCEVAC contained a grid-based hazard model, it did not contain a toxicity model. Consequently the presence of hazards only affected the behaviour of passengers, for example increasing the passengers' *state-of-mind* attributes, rather than leading to incapacitation through thermo-toxic exposure. For example, explosions and or smoke would increase the state-of-mind of the passengers and crewmembers, i.e. it may move from being *Alert* to *Nervous*.

Like GA, ARCEVAC suffers from the arbitrary nature of its model parameters. This deficiency was even more acute given the vast number of parameters that were used in the model. The model contained far too many parameters all of which where completely arbitrary. Indeed, even the qualitative nature of most of the physiological variables were open to dispute.

ARCEVAC was validated against the evacuation of a Canadair Regional B727 Jet that underwent certification in 1993. The result of ARCEVAC was an evacuation time under 60 seconds. Due to its proprietary nature the results of the certification trial were not made public. However, during the validation exercise ARCEVAC generated graphs showing the number of passengers out as a function of time for individual exits as well as the aircraft as a whole. The validation exercise also considered different combinations of exit choice whilst maintaining an exit from each exit pair.

6.3.3.5. airEXODUS

The EXODUS software is developed by University of Greenwich Fire Safety Engineering Group (i.e. the authors of this report) with support from the UK CAA. EXODUS is a suite of software tools designed to simulate the evacuation of large numbers of individuals from complex structures. Development on EXODUS began in 1989. EXODUS was originally designed for use with aircraft, however, its modular format makes it ideally suited for adaptation to other types of environment. As a result its range of application has grown, as has the number of specific EXODUS products. The family of models consists of buildingEXODUS [61-63,73-75], maritimeEXODUS [64,65] and airEXODUS [21,67-29] for the built environment, marine/off-shore industries and aviation applications respectively. airEXODUS is designed for applications in the aviation industry including, aircraft design, compliance with 90 second certification requirements, crew training, development of crew procedures, resolution of operational issues and accident investigation.

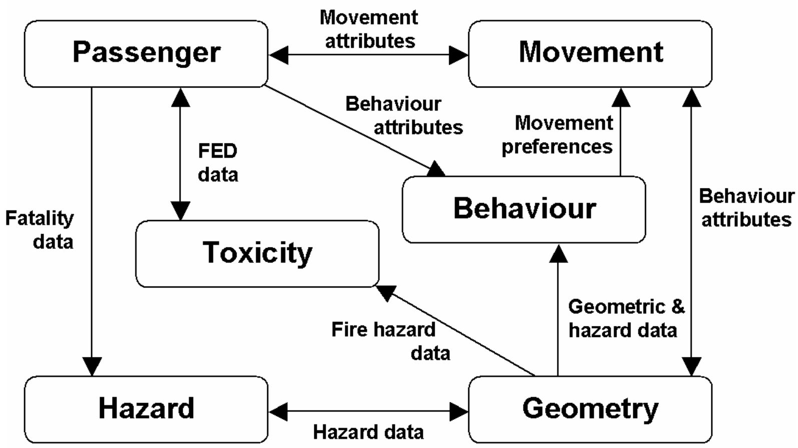


Figure 5: airEXODUS Submodel Interaction

EXODUS comprises five core interacting sub-models: the Occupant, Movement, Behaviour, Toxicity and Hazard sub-models (see Figure 5). The software describing these sub-models is rule-based, the progressive motion and behaviour of each individual being determined by a set of heuristics or rules. The spatial and temporal dimensions within EXODUS are spanned by a two-dimensional spatial grid and a simulation clock (SC). The spatial grid maps out the geometry of the structure, locating exits, internal compartments, obstacles, etc (see Figure 6). Geometries can involve multiple decks, connected by staircases. The structure layout can be specified using either a DXF file produced by a CAD package, or the interactive tools provided. The grid is made up of nodes and arcs with each node representing a small region of space and each arc representing the distance between each node. Individuals travel from node to node along the arcs.

The Population Sub-model allows the nature of the passenger population to be specified. The population can consist of a range of people with different movement abilities, reflecting age, gender and physical disabilities as well as different levels of knowledge of the ship layout, response times etc. airEXODUS assigns passengers with over 20 defining attributes, such as *Gender, Age, Weight, Height, Agility, Drive, Six different movement speeds* (for different types of motion and terrain), *Response Times, Patience* and *Social Genes.*

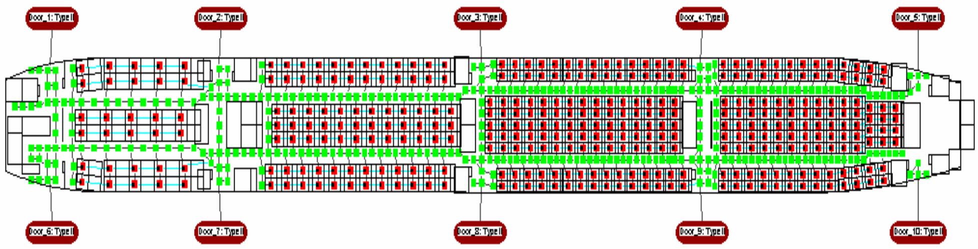


Figure 6: Cabin layout in airEXODUS. View depicted represents the interactive graphics component within airEXODUS. Aircraft depicted has five pairs of exits. The node structure showing seats, aisles and cross-aisles is clearly depicted.

On the basis of an individual's personal attributes, the Behaviour Sub-model determines the occupant's response to the current situation, and passes its decision on to the Movement Sub-model. The Behaviour Sub-model functions on two levels. These levels are known as GLOBAL and LOCAL behaviour. GLOBAL behaviour involves implementing an escape strategy that may lead an occupant to exit via their nearest serviceable exit or most familiar exit. The desired GLOBAL behaviour is set by the user, but may be modified or overridden through the dictates of LOCAL behaviour, which includes such considerations as determining the occupants initial response, conflict resolution, overtaking and the selection of possible detouring routes. In addition a number of localised decision-making processes are available to each individual according to the conditions in which they find themselves and the information available to them. This includes the ability to customise their egress route according to the levels of congestion around them, the environmental conditions and the social relationships within the population. Social relationships, group behaviour and hierarchical structures are modelled through the use of a "gene" concept [75], where group members are identified through the sharing of social "genes". Passengers are able to adapt their evacuation strategy according to a rational use of the information available to them e.g. they may wish to communicate information to other passengers, identified as a group member.

The Toxicity submodel determines the physiological impact of the environment upon the occupant. To determine the effect of the fire hazards on occupants, airEXODUS uses a Fractional Effective Dose (FED) toxicity model [116,117] (see Section 6.5.3.3.3 for more details). This model considers the toxic and physical hazards associated with elevated temperature, thermal radiation, HCN, CO, CO_2 and low O_2 and estimates the time to incapacitation. In addition to this behaviour, the passengers are able to respond to the environmental conditions by adjusting their behaviour. The thermal and toxic environment is determined by the Hazard submodel. airEXODUS does not predict these hazards but can accept experimental data or numerical data from other models including a direct software link to the CFAST fire zone model [112,113]. airEXODUS produces a range of output, both graphical and textual. Interactive two-dimensional animated graphics are generated as the software is running that allows the user to observe the evacuation as it takes place. The graphics are interactive allowing the user to interrogate occupants and events. In addition, a data output file is produced containing all the relevant information generated by the simulation, including a copy of the input data. To aid in the interpretation of results, a post-processor virtual-reality graphics environment known as vrEXODUS has been developed, providing an animated three-dimensional representation of the evacuation (see Figure 7).

Figure 7: vrEXODUS generated scene from an airEXODUS evacuation simulation

airEXODUS makes use of 90-second certification data [14] to specify certain model parameters. One of the most important parameters for representing aircraft style exits is the Passenger Exit Delay Time. This time represents 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 out-stretched hand first touches the exit. The latter time considers the amount of time taken to pass through the exit.

In general, the exit hesitation time is due in main to passengers either waiting at the exit for the path to clear and/or contemplating how to negotiate the exit. In either case, the exit negotiation stage does not usually start until there is space for it to commence. Furthermore, the process of passing through the exit and travelling from the exit to the ground are considered as separate events that can occur in parallel.

Within airEXODUS the exit delay time distribution is segmented into subintervals described by uniform distributions. The technique is dependent on the user having a good representation of the actual delay time distribution. In the current version of the software this data is extracted from past certification trials [14,15]. For example, consider main deck Type-A exits with assertive cabin crew. Data from 11 previous certification tests involving Type-A exits with assertive cabin crew was available. The data was derived from the following aircraft: A310 (255 passenger), A310 (280 passenger), B747, B747-300, B747-SR, B767-300, B767-346, B777-200 (420 passenger), B777-200 (440 passenger), DC10 and MD11 [14,15]. In total, passenger exit delay time data from 20 exits representing some 2078 passengers is used to define the passenger exit delay time distribution.

The outcome of aircraft evacuations is highly dependent upon the presence and behaviour of cabin crew. airEXODUS has the capability of representing cabin crewmembers implicitly, explicitly or via a combination of both methods. To explicitly simulate the action of the crew, a new feature of airEXODUS known as the Active Cabin Crew Management (ACCM) procedure is being developed. While in the standard version of airEXODUS crew initiated actions were achieved implicitly through the setting of model parameters, using the ACCM system, the procedures are explicitly modelled. Thus the cabin crewmember is modelled as are their actions and the passengers response to those actions.

Cabin management procedures are usually employed by cabin crew during certification trials [76, 77] and during real emergency evacuation situations [10, 11,78-80]. These procedures may involve crew instigated exit by-pass or other passenger re-direction strategies. In applying these techniques the crew are attempting to either achieve a more efficient use of exits thereby reducing the overall evacuation time, or direct passengers away from a potentially dangerous cabin section. When attempting to reduce

the overall evacuation time, crew are assessing the situation in their cabin zone and deciding when to redirect passengers onto another
cabin zone or nearby exit.

In reality, the decisions made by the crew will be based on the information that they have on conditions around their exit and what they may know about other exits. The knowledge that the crew has of cabin conditions can be restricted due to line of sight, congestion, visibility in smoke, noise, etc. Alternatively, it may be enhanced by technical means such as conventional communication systems or novel new devices such as crew head-set communication systems, door visual display systems, etc. A feature of the ACCM procedures within airEXODUS is that the decision making capability of the crew can be restricted according to the prevailing conditions and the equipment at their disposal. The crewmember can also be given a radius of effectiveness. This dictates the region over which the commands made by the crewmember will be effective.

During certification evacuations, passengers are more compliant and are thus more likely to follow a crew command to redirect to another exit while in real situations this may be somewhat more difficult to achieve as passengers are more likely to be concerned with their own self interest. Both these situations can be represented within airEXODUS using the ACCM procedures. The first mode of operation is akin to 90-second certification trials in which passengers are generally compliant to all crew commands. The second mode attempts to model real emergency evacuations in which passengers are less compliant. In airEXODUS, when modelling certification evacuations, passengers are made to be compliant and thus follow all instructions issued by cabin crew.

airEXODUS and the EXODUS software in general has undergone a significant amount of validation. airEXODUS has been used to simulate evacuation trials conducted at Cranfield University in their B737 cabin simulator [27,120]. In addition, a more challenging validation exercise was requested by the UK CAA, requiring airEXODUS to predict the performance of a modified Boeing B767 aircraft, (designated the B767-304ER), *prior to the actual test*, in order to establish the predictive capabilities of airEXODUS for 90 second certification trials. A confidential report [30] containing details of the model formulation and results of the simulations was produced by FSEG and distributed to the UK CAA and US FAA prior to the trial, and Boeing after the trial. A description of the results of the airEXODUS predictions may be found in [27].

In order to better assess the airEXODUS predictive capabilities, the UK CAA have sponsored systematic validation exercise involving past certification data. The certification exercise makes use of past wide and narrow body aircraft certification data [71]. In total some 6 different cases were examined using airEXODUS. In all cases airEXODUS successfully reproduced the trial results [29].

6.3.3.6. DEM

The DEM (Descrete Element Method) model was developed is the UK by the University of Strathclyde in 2000 [99]. The model is intended to simulate 90-second certification style evacuations and real emergency evacuations. The model has a graphical user interface that shows the position of each passenger during the simulation. The model has been demonstrated using the B737-300 aircraft (see Figure 8), although presumably other models could be specified.

The model uses a coordinate based fine network spatial representation and tracks the movement of each passenger during their evacuation. Additionally, each passenger has limited defining attributes, such *dominance*, *movement speed* and *size*. Thus, the population perspective of this model is individual based.

The movement model employed by DEM is a functional analogy based on differential equations that govern the motion of Newtonian soft sphere grains. A consequence of this approach is that passenger shape is circular. In addition, physical forces such as *friction*, *torque* and *inertia* are all variables within the Newtonian laws of motion and are thus model parameters. Another by-product of the functional analogy is that collisions between passengers result in them temporarily contracting and if the collision is side-on, then some amount of spin is imparted that causes passengers to rotate. Motion towards exits is achieved via artificial external forces that pull the soft sphere grains towards exits. The artificial attractive force that is exerted by the exits can be targetted at specific soft sphere grains within the model, thus different passengers can be made to use different exits. All of these parameters – which are a by-product of the functional analogy approach - are rather questionable when compared to actual human behaviour and movement.

There is no mention of exit preparation delays or passenger response times within published literature for this model [99]. It must therefore be assumed that the exits are always open and ready for use and that passengers respond at the same time. Exit flow rates are governed by the supply to the exits and a rule imposed by the model designers that only one passenger may occupy an escape slide at any one time. An additional delay was specified to represent that incurred by passengers negotiating Type-III exits. The delay was represented by the imposition of a uniform 2-second delay to passengers at the exit. Indeed, this delay exemplifies a major failing of this model. Namely, that the model parameter specification and assumptions are arbitrary.

Whilst, the movement model is a functional analogy, some movement rules exist in order to avoid blockages and to simulate passenger redirection. The *dominance* attribute is used to avoid blockages in contested areas such as aisles. The DEM model does not represent cabin crewmembers either explicitly or implicitly. However, passengers may redirect themselves to alternative exits if the *"queue is half the length of the queue that they are already in"* [99]. In addition, at the date of writing (February, 2002), none of the published literature relating to this model indicates that there is a representation of either hazards or their thermo-toxic effects.

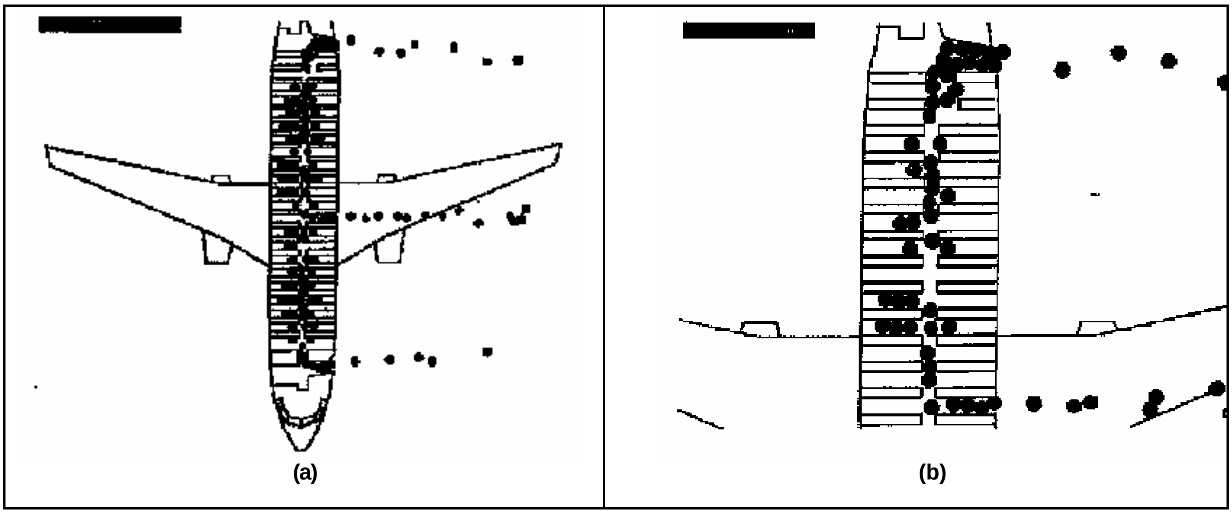


Figure 8: Screen shot from the DEM model

The model was validated against the evacuation of the B737-300. As the model is deterministic, only one result was generated (81 seconds) which the authors stated compares well with 75 seconds achieved during the 90-second certification trial. As a further example of the model, the B737-300 DEM model exit availability was configured as in the Manchester air crash [7]. The resultant evacuation time of 117 seconds was 44% higher than the certification case. The model did not attempt to simulate the affects of fire or the delays in preparing the over wing exit for use that occurred in the actual accident. These validation cases are rather meaningless when the completely arbitrary nature of the model parameters is considered. Any agreement with actual results should be considered fortuitous rather than by design.

6.3.3.7. Macey's risk assessment model

During the 1990's as part of a PhD thesis, Macey *et al* developed a risk assessment model at Cranfield University with support from the UK CAA. The model was intended to analyse real and certification evacuations.

The model was designed for risk assessment purposes and was intended to simulate the total set of evacuation scenarios. To facilitate this, the probabilities of specific scenarios occurring were determined from a comprehensive analysis of over 200 previous airliner accidents. Event trees were formulated from this analysis specifically for use within the risk assessment model. Probabilities such as the likelihood of the scenario involving impact, cabin burn through, internal and/or external fires were determined. In accidents involving fuselage breaks, a probability distribution of the break location was also determined. Additional probabilistic data was supplied regarding the likely cabin layout, weather conditions, phase of flight, airport distance, availability of emergency services, impact effects, fuselage split, fuel spills, jammed exits and impact injuries.

The risk assessment model comprised of fire, toxicity and evacuation sub-models. The fire scenarios were "empirically" determined from the supplied probabilities. The model would then randomly choose a scenario according to the supplied probabilities. For example, from the analysis of past accidents it was determined that 90% of the fire scenarios involved burn-through and external fire scenarios. Thus, it is quite likely that the model would choose to simulate a fire scenario that involved either burn-through and/or an external fire. Whilst recognising the need for an internal model of fires they were not represented within the risk assessment model. The likely location of the fire was determined from probabilities derived from analysis of 72 past accidents.

Having selected a scenario it was then modelled in 2-dimensions. The consequence of the 2-dimensional fire model is that common effects such as smoke/gas layering or stratification were not represented. The height of the fire was taken as being head height, i.e. 1.5 metres from the floor. The fire growth and smoke and toxic gases were modelled using differential equations. These simplifications are considered a significant weakness of the model as they cannot accurately represent fire development which is inherently three-dimensional.

A 2-dimensional airflow sub-model was used to simulate the spread of fire and smoke taking into account the scenario and aircraft configuration, i.e. the presence of fuselage ruptures and combinations of open exits. The thermo-toxic affects of the fire were modelled using *"standard"* FED models.

The evacuation sub-model was a fine network model with a graphical user interface capable of outputting the evacuation (see Figure 9). In total 80 different aircraft layouts were supplied with the model. It was stated that these include *"all major passenger aircraft types currently in service"*. Additional layouts could be generated using a syntax driven specification tool.

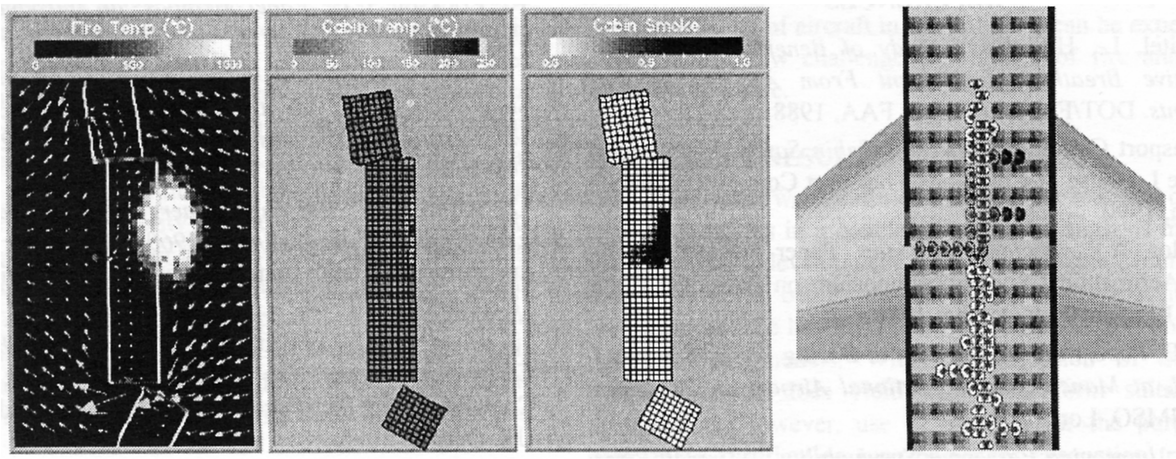


Figure 9: Screen shot of the output from Macey's model. Left is the airflow model, centre is the thermo-toxic model, and right is the evacuation model

It was recommended that the cell size within the model was set to 0.15 by 0.2m. Since passengers' dimensions are often larger than this, it was necessary for passengers to occupy more than one cell. Within the model each passenger could be tracked throughout the entire evacuation. In addition the passengers had *"expandable"* individual attributes such *reaction time*, *movement speed*, *narcosis* and *irritant levels*. The population perspective was therefore individually based.

The behavioural basis of this model was rule driven. The basic passenger behaviour was that they moved towards their nearest exit. The nearest exits could however; become less attractive should there be a large number of users or the exit inactive. Passengers were able to switch exits to adjacent active exits should their queues become smaller.

The published literature did not state that empirical data was used to determine the delay that passengers experienced in traversing exits. Instead exits were calibrated so that they generated flow rates that were equivalent to those generated during 90-second certification trials. Exit flow rates were not an output for the model but were imposed. It was recognised that these flow rates were not appropriate to real emergency scenarios in which cabin conditions and passenger motivation is very different.

Since cabin sections could rupture it may also have been necessary to supply data on the length of time required for passengers to traverse the ruptures. However, no data was supplied. Finally, a crash severity attribute was specified as part of the scenario definition. The crash severity value was used to degrade passenger movement rates through specific sections of the cabin.

This model had neither an explicit nor implicit representation of cabin crewmembers. Indeed they were not modelled at all. A consequence of this was that passengers were required to open the aircraft's exits.

The fire and toxicity sub-models were linked to the evacuation model so that individual thermo-toxic affects could be calculated for every passenger in the evacuation.

As mentioned previously the model was designed to simulate a range of empirically determined scenarios in order to ascertain a level of risk for a particular configuration. In order to validate the models, the designers contrived probabilities so that a scenario was selected that was equivalent to the 90-second certification trial. Using a certification trial configuration, four different aircraft were modelled.

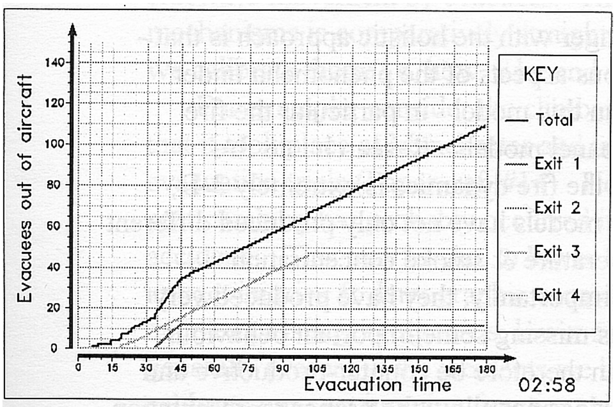


Figure 10: an example graph generated by Macey's model

Two of these were compared to the results of 90-second certification trials. In both cases the model predicated an evacuation time that was within 10% of the certification trial (see Table 2). In addition in both cases the results of the model were higher than that of the certification trial. The model designers stated that the over estimation by the model was due to passengers having to open the exits and exit overcrowding. The lack of cabin crewmember redirection led to sub-optimal evacuations that caused the overcrowding at some exits. In addition, from the validation results (see Table 2) it is apparent that only one time was presented for the validation results.

Table 2: The validation history of Macey's Risk Assessment Model (reproduced from [105])

Aircraft Type	Seats	Actual Time	Model Time
A320	179	79s	85.0s
A321	224	-	81.2s
B757	219	73.5s	77.8s
B737-800	189	-	91.8s

6.3.3.8. Oklahoma Object Orientated model (OOO)

In the mid 1990's Mary Court from Oklahoma University and Jeff Marcus from CAMI published a design specification for an Object Orientated evacuation model. Whilst the model itself was never actually developed, the design is described in this section.

The proposed model was for a simulation fine network model with an individual population perspective and rule based behaviour. The model was intended to be able to simulate both real emergency evacuations and 90-second certification trials. It was the designers wish that the model ran in real time (if possible), that the model generates output suitable for detailed analysis and animations for the purposes of presentations.

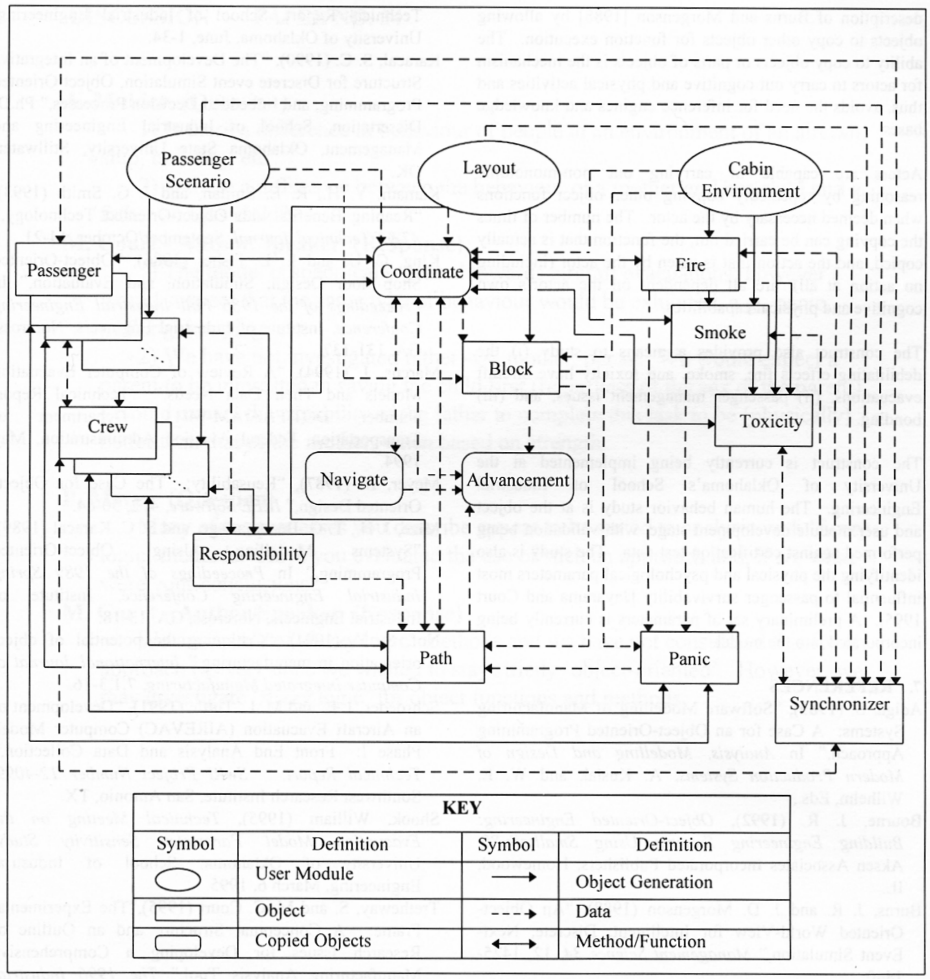


Figure 11: The proposed OOO model design

Required features were that the model was able to simulate group relationships, i.e. families and work colleagues, cabin crewmembers and associated passenger management issues, that the behaviour of passengers and crew adapted during the evacuation and to a dynamic thermo-toxic environment, that the thermo-toxic environment affected behaviour and also the physiology of the passengers and crew.

From these requirements an Object Oriented (OO) design was created (see Figure 11). The design contained three modules. The passenger scenario module allowed the user to build the passengers within the scenario. Within this module personal attributes such as, *age, sex, height, weight*, etc. *relationships* could be specified for passengers and cabin crewmembers. The layout module was used to construct the cabin geometry. Using this model seats, monuments and exits could be specified. In addition passengers could be assigned to specific exits within the model. The cabin environment module allowed the thermo-toxic environment within the cabin to be generated.

The OO model was comprised of 13 classes (objects or copied objects within Figure 11). The SYNCHRONIZER (sic) class was the controlling class that coordinated all of the other classes/objects within the simulation. Many instances of the PASSENGER and CREW classes were generated according to the desired number within the scenario. They would each have their own defining attributes and relationships with other passengers. The COORDINATE object distributed the aircraft geometry to other objects, i.e. to passengers, crew, fire, smoke and toxicity whilst sharing data with others: NAVIGATE, ADVANCEMENT, PATH and BLOCK. The BLOCK class contained information about obstacles such as seats, walls, other passengers and crew in addition to environmental obstacles such as smoke and fire. The NAVIAGTE class was responsible for choosing the headings for actors, i.e. passengers and/or crew. This was affected by their cognitive and physical abilities. The PATH class would assess available paths/routes that passengers and crew could take during an evacuation. This would be affect by the geometry, their location within the cabin, fire, smoke and toxicity and their cognitive abilities. The ADVANCEMENT object was responsible for moving passengers between locations within the simulation. Information regarding the FIRE, SMOKE and TOXICITY classes was not provided. Presumably, they would manage the growth of these hazards. Depending upon the type of scenario, some of the classes would not be required. For example, in a 90-second scenario the fire, smoke, toxicity and panic classes would not be required.

The RESPONSIBILITY class allowed information sharing between objects. For example, cabin crewmembers were given access to some of the attributes of passengers and greater knowledge of the cabin layout. Related passengers may be assigned responsibilities, such as parent and child relationships. Finally, the PANIC class would affect the actors' ability to reason, i.e. they may make poorer decisions if they were panicked.

The model design did not specify how the behaviour of passengers was affected when using exits or escape slides or how they would be modelled. Furthermore, no indication was given on how model parameters would be determined. Finally, as the model was never developed no validation was performed. As such the model's abilities are unknown.

6.4. A critical evaluation of aviation evacuation models

Having discussed evacuation models and their data, this section critically evaluates the aviation evacuation models. The key characteristics of the aircraft evacuation models are summarised in Table 3 and Table 4.

Table 3: Summary of Aviation Evacuation Model Methodologies

Model	Nature of application	Enclosure representation	Behavioural Perspective
GPSS	SIMULATION 90-SECONDS	COARSE	INDIVIDUAL & STOCHASTIC
GA	SIMULATION REAL EMERGENCIES	FINE	INDIVIDUAL & STOCHASTIC
ARCEVAC	SIMULATION BOTH	FINE	INDIVIDUAL & STOCHASTIC
EXODUS	SIMULATION BOTH	FINE	INDIVIDUAL & STOCHASTIC
DEM	SIMULATION BOTH	FINE	INDIVIDUAL & DETERMINISTIC
MACEY	RISK ASSESSMENT BOTH	FINE	INDIVIDUAL & DETERMINISTIC

Table 4: Summary of Aviation Evacuation Model Features, Validation History and Parameter Basis

Model	Hazard representation	Toxicity representation	Cabin crewmember procedures	Validation history	Parameter Assignment
GPSS	NONE	NONE	Implicit	4*90S of which 1 was unsuccessful	EMPIRICAL
GA	ZONE	SIMPLISTIC	Implicit	3*RE	ARBITRARY
ARCEVAC	ZONE/Arbitrary	NONE	Both	1 *90S	ARBITRARY
EXODUS	GRID/experimental or 3D model based	FED	Both	8*90S (1*Blind 90S), 2*EX	EMPIRICAL
DEM	NONE	NONE	None	1*RE	ARBITRARY
MACEY	GRID/2D model based	FED	None	2*90S+ / (4*90s)	ARBITRARY

+results of the certification trial was only known for two of the four validation exercises

6.4.1. Basis of Model Parameters

As mentioned previously, evacuation models are only as good as the data that is used in their formation. The methodology that a model uses in specifying key parameters is therefore of critical importance.

Some models, such as DEM, GA, ARCEVAC and MACEY use essentially ARBITRARY estimates to determine values for model parameters. For example, GA and ARCEVAC use an arbitrary probability of a passenger passing through an exit to determine the exit hesitation delay. Whereas, DEM specifies this delay indirectly through allowing only one passenger to descend each escape slide at any one time. MACEY's model is somewhat unusual in that empirical data is extensively used in determining the likely scenario (see Section 6.3.3.7.), however little empirical data is used in the evacuation sub-model itself.

Gaining confidence in models that have arbitrary parameters is difficult, as their results have no real world basis. For example, what does it mean in GA when a passenger dies having been exposed for 40 seconds to a 120 toxic hazard exposure?

GPSS and EXODUS make use of EMPERICAL data in specifying model parameters. In both models Exit Hesitation Delays are specified from analysis of the actual event. Within EXODUS numerous parameters are empirically determined, such as exit preparation time, passenger response time, passenger movement speeds, etc. As such, greater confidence can be gained in the results of the model as it is fundamentally based on empirical studies, i.e. reality.

6.4.2. Validation/Verification history

Confidence in any model is gained through its accuracy at reconstructing or predicting what happens in reality. Thus a convincing record of verification/validation is essential. Indeed, software validation should be considered as an on-going activity. For any complex simulation software, validation is not a "once and forget" task, but should be considered as an integral part of the life cycle of the software.

The verification/validation of evacuation software is no exception. Indeed, the lack of a large battery of convincing data for the verification of evacuation software has meant that a rigorous procedure needed to be established for the validation/verification of evacuation software. Such a procedure has been outlined in [124], and adopted by the building and maritime industries [32, 31]. This procedure can be readily adapted for use in the aviation industry and is outlined here.

There are at least four forms of validation/verification that evacuation models should undergo. These are,

(i) component verification,
(ii) functional verification,
(iii) qualitative verification and
(iv) quantitative verification.

(i) Component Verification.
Component verification involves checking that various components of the software perform as intended. This involves running the software through a battery of elementary test scenarios to ensure that the major subcomponents of the model are functioning correctly. For instance, this may involve checking that a person with an unimpeded travel rate of 1 m/s requires 10 seconds to travel 10 m or that an occupant with a fixed respiration rate travelling in a known atmosphere will acquire a particular FED in a given period.

(ii) Functional Verification.
Functional verification involves checking that the model possesses the ability to exhibit the range of capabilities required to perform the desired simulations. This requirement is task specific. To satisfy Functional Verification, the model developers must set out in a comprehensible manner, the complete

range of model capabilities, and inherent assumptions and give a guide to the correct usage of these capabilities. This information should be readily available in a technical manual that accompanies the software. Users of the software (or approval authorities) would then be in a position to determine whether the model is suitable for the proposed applications.

(iii) Qualitative Verification.
The third form of model verification concerns comparing the nature of predicted human behaviour with informed expectations. While this is only a qualitative form of validation, it is nevertheless important as it demonstrates that the behavioural capabilities built into the model are capable of producing realistic behaviours. The nature of the demonstration examples need to be relevant to the intended application and be of sufficient merit to satisfy the intended client or approval authority.

(iv) Quantitative Verification.
Quantitative verification involves comparing model predictions with reliable data generated from an evacuation demonstration. This must be viewed in light of the earlier comments concerning the integrity of the data, the suitability of the experiment and the repeatability of the experiment.

Which aspects of the numerical predictions are to be compared with experimental data must also be established. This is somewhat dependent on the nature of the intended application. It should be remembered that some evacuation models can produce a large variety of outputs, not simply the total evacuation time. Some models are capable of predicting exit selection, behaviour in smoke conditions, location of bottlenecks, exit flow rates, exit start times, exit finish times, exiting history etc. By simply comparing the total evacuation time it is possible to be mislead as to the fidelity of the prediction. However the level, nature and quality of the quantitative verification that can be achieved is dependent on the completeness and quality of the reported data.

The aim of quantitative verification is to demonstrate that the model is capable of reproducing measured behaviour. Hence it is necessary to specify suitable acceptance levels. This is however extremely difficult to do in the abstract as to a great extent it depends on the nature of the intended application. Some applications may require models capable of making predictions within 5% of measured values while others will be satisfied with results within 50% of measured values. The acceptance level must also take into consideration not only experimental errors and the completeness of the data set, but also whether data from a single or multiple experimental runs are available.

Finally, at least two types of quantitative verification may be performed. The first involves the use of historic data. In this case the user performing the verification has complete knowledge of the experimental results. The second type involves using the model to perform predictive simulations prior to having sight of the experimental results, a so-called “blind” prediction. Clearly, different types of questions and challenges could be posed by these two types of verification scenarios. Here, the nature and capability of the models in question must also be brought into consideration as what is required as initial input data by one model may be considered a predicted output parameter by another. Hence the definition of “blind” verification is complex and not necessarily universal. For example, one model may require flow rate data as an initial input while another model may predict flow rates. The level of data “blindness” is therefore dependent on the sophistication and capabilities of the model.

In practice, quantitative verification of aircraft evacuation models is accomplished by comparing model predictions with results of real world events, such as EXPERIMENTS (EX), 90-SECOND TRIAL (90S) or REAL EMERGENCY (RE) evacuation situations.

The most confidence can be gained through comparing models against the results of carefully controlled experiments that are repeated a number of times. The second most effective data source for validation is the 90-second certification trial. However, as mentioned previously they are not ideal as they generate only one data point on a hypothetical distribution of probable results (see Section 6.5.1). Even greater confidence can be gained through performing ‘blind’ simulations (B). In other words running the model before the results of the trial are known. Finally, real emergency evacuations are extremely difficult to use for quantitative verification as not only do they generate only one data point, but the precise conditions of the emergency are never known to the level required by the modeller to establish correct starting or environmental conditions and the actual evacuation times are seldom known to the degree of precision required.

As an example of the scope of quantitative validation possible using certification data consider the following example using airEXODUS. Recently, airEXODUS model predictions were compared with data from four wide body aircraft certification examples [71,29]. As airEXODUS is a stochastic model, it produces a potentially different result each time the model is run. For this verification exercise, the model was run 1000 times for each case. The distributions of results for the four cases are depicted in Figure 12 (solid lines). Also depicted are the certification trial results achieved for each aircraft configuration (vertical dashed lines). As can be seen, in each case the trial result falls within the relevant predicted distribution. The differences between the airEXODUS mean Total Evacuation Time (TET) and the evacuation time of the certification trials is shown in Table 5.

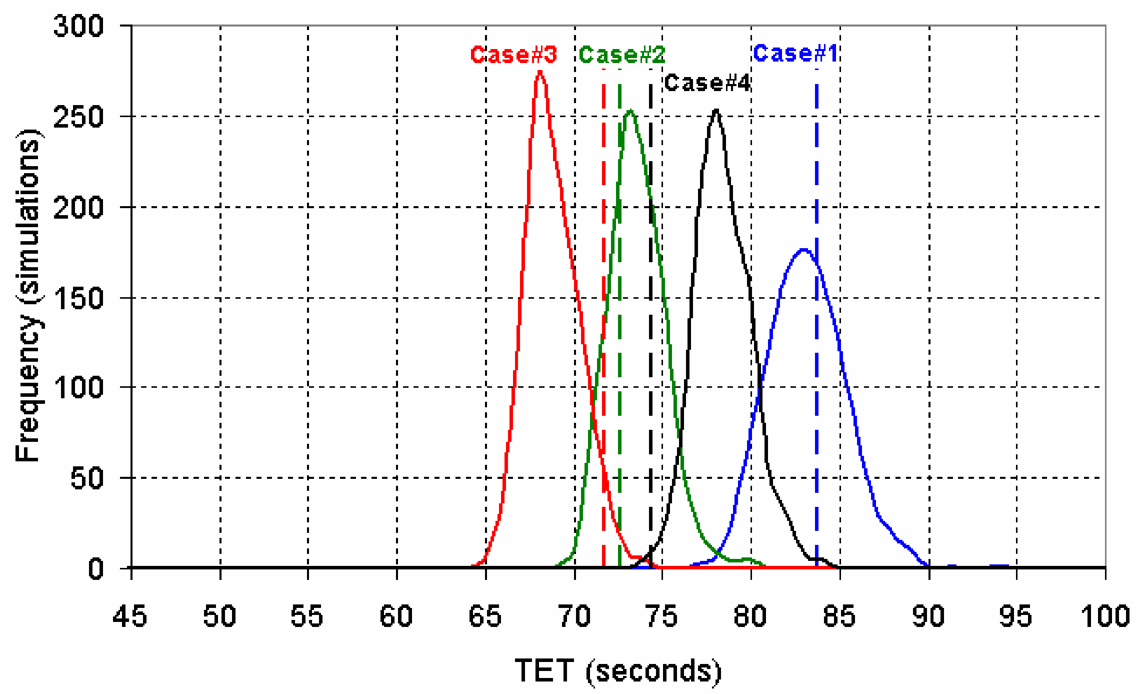


Figure 12: The frequency distributions of Total Evacuation Times (s) for the four wide body aircraft. (Continuous lines airEXODUS predictions, dashed line represents time achieved in trial).

The model predictions can be summarised as follows, airEXODUS is able to predict the results of the certification trials with reasonable accuracy, the mean absolute difference between the distribution means and the trial result being 2.8%. In all of the cases examined, the measured evacuation time of the certification trial is within the bounds of airEXODUS predictions. Furthermore, the general rank order of evacuation times achieved in the trials is also predicted by airEXODUS.

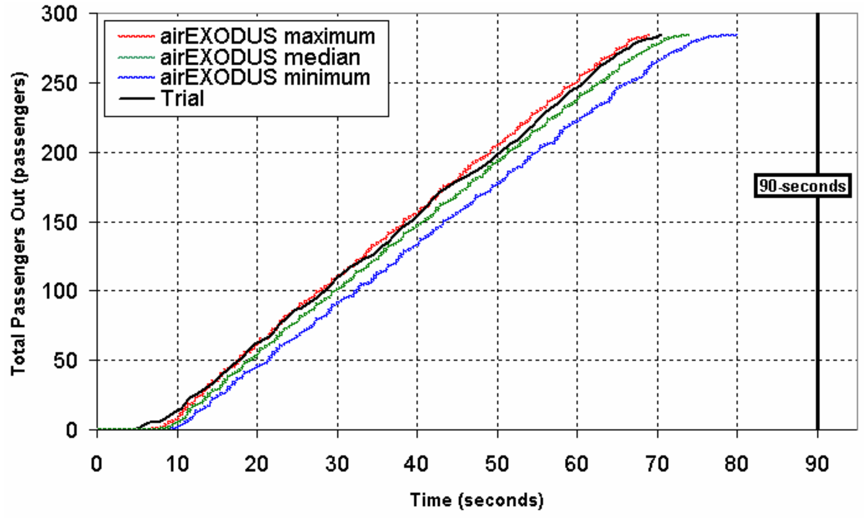


Figure 13: Cumulative exit times for CASE 2 trial result (Black) and predictive envelope created from airEXODUS simulations.

The above comparisons are based on essentially a single event, the time for the last passenger to exit the aircraft. A more meaningful comparison is based on the cumulative exit times for each passenger. For the certification trials this is determined from the video record of the actual trial. This produces a continuous curve representing the cumulative number of passengers to exit the aircraft during each second of the evacuation (see Figure 13). A similar curve is produced for each of the 1000 airEXODUS simulations. Rather than show each of the 1000 predicted curves, the predicted cumulative exit window is depicted in Figure 13 along with the median of the predicted curves. The window represents the maximum and minimum number of passengers to have exited the aircraft at each second. As such it represents the natural variation in the number of passengers that can be evacuated for this scenario at each second. Depicted in this figure are the relevant curves for Case 2. The other three cases produce essentially similar results.

Table 5: Trial and airEXODUS results and rank order for certification trial cases 1-4

Case / Aircraft	Trial Result (secs)	airEXODUS mean (secs)	Trial rank	airEXODUS rank
Case 1	83.7	82.7	4	4
Case 2	72.6	73.1	2	2
Case 3	71.7	68.3	1	1
Case 4	74.4	77.9	3	3

From Figure 13 it is clear that the airEXODUS predicted curves have a similar structure to the curve derived from the certification trial. This suggests that airEXODUS is predicting a similar chain of events to that which occurred during the certification trial. Furthermore, with the exception of the start up portion (approximately the first 10 seconds), the trial curve falls within the airEXODUS generated window throughout the trial. The start up differences are due to the exit ready time of the trial not corresponding precisely to that used in the simulation.

6.4.2.1. Verification history of surveyed aviation evacuation models

The GPSS software has been subjected to four quantitative validation exercises. In these cases four blind 90-second certification trial (4-B90S) evacuations were used. In three cases (L1011a, L1011b and L1011c) it predicted the result of the trials with reasonable accuracy. However, in the case of the B747 it performed poorly. This was attributed to variation in the performance level of passengers and crew during this trial.

The only verification of the GA model that is known concerns the qualitative verification using three real emergency evacuations (3-RE) the, DC-8 at Denver in 1961, B-727 Salt Lake City in 1965, and the DC-9 Denver 1976. These verifications are considered qualitative, as reliable times for the actual emergency evacuations cannot be established, nor precise starting conditions. Furthermore, the results of this exercise were not published.

Quantitative verification of the ARCEVAC model was performed using a single certification trial of Canadair Regional Jet (CL-65) after the trial had taken place (1-90S). Due to the proprietary nature of the actual certification trial data the model developers could not cite the total evacuation time for the trial. They merely state that their model generated an evacuation under 60 seconds.

The results from a single quantitative verification trial of the DEM have been published. This involved an evacuation analysis of the 90 second certification trial of a B737 aircraft (1-90S). In this case, DEM predicted a single evacuation time of **81** seconds, which was within 6 seconds of the time generated by the actual 90-second certification trial [122,99].

Quantitative verification of the MACEY model has been accomplished using four certification trials (4-90S) of which the results of two are known. In both of these cases the model predicted a single evacuation time that was within 10% of the actual time generated by the trial. Furthermore, in both cases the model over estimated the time generated by the certification trials.

Of all the aviation evacuation models, EXODUS appears to have the most extensive published verification history that incorporates all four validation components. Quantitative verification has been achieved using the results of **2** experiments (2-EX) [27], **5** wide-bodied 90-second certification trials [27,71,29] one of which was a blind analysis [27] and **2** narrow-bodied 90-second certification trials (8-90S, 1-B90S) [29]. All of these validation tests have shown the model to correlate well with reality.

Finally, it should be noted that it is extremely difficult to make any sense of validation performance when models use arbitrary data sets. As the data is arbitrary, it can be artificially changed from one simulation to another and one is left wondering 'is the level of agreement down to a fortuitous use of parameters or tuning of parameters for a particular simulation?'.

6.4.3. Discussion

Originally designed in the 1970's, GPSS is now very dated both in terms of platform (Large mainframe computers) and capabilities. It contains little human behaviour with the result that passengers simply behave like mindless ball bearings [123]. Whilst making use of empirically determined exit delay distributions, they were shown to be inadequate by its validation exercise. Finally, the model was only validated against four certification trials, of which one showed poor correlation.

DEM assumes passenger movement to be analogous to Newtonian soft spheres. As such passengers shape is assumed to be round. This model treats the movement of passengers much like ball bearings, an approach that is now considered dated [123]. In addition, some of the assumptions on which the model is based undermine its ability to reflect reality accurately. For example, one of the assumptions is that only one passenger may use an escape slide at any one time. This is simply not realistic, as more than one person can and do occupy slides at the same time. In addition the logical consequence of this approach is that for much of the simulation the length of the slide determines the flow rate through the exit. The rationale for this is unclear. Firstly, the relationship between slide length and flow rate has not been shown. In addition numerous passengers frequently occupy a slide at a time. This assumption alone undermines the results of the model. This casts serious doubts on the usefulness of the validation exercise presented in support of the model.

The GA model demonstrated many of the qualitative behavioural features of real emergency evacuations. In terms of qualitative features it included a more comprehensive representation of the behaviour than either GPSS or DEM. In addition the GA model had a rudimentary toxicity and hazard model. However, the main criticisms with the GA model are that their model parameters were not empirically determined and that their hazard and toxicity models were completely arbitrary. As such it is difficult to derive meaning from the results. Another failing was that cabin directed bypass was performed via the manual operation of the keyboard during a simulation. Finally, the model was only capable of simulating the evacuation of narrow-bodied aircraft. These failings were compounded by the lack of validation performed on the model.

ARCEVAC contained numerous complex behavioural features that distinguished itself from other evacuation models of the time. ARCEVAC, provided an explicit representation of cabin crewmembers that were capable of performing complex procedures (such as checking aisles or seats) whilst the simulation ran. In addition ARCEVAC offered a mechanism of representing the state of mind of simulated passengers, via a *state* attribute, and contained 'social attributes', such as *dominance*, *selfishness*, etc. Whilst containing numerous behavioural capabilities it may be criticised, as its behaviours were not based on empirical evidence from experiments or air accidents. In addition, the model was limited to simulating the B727 aircraft, although other aircraft may have been possible if the code was rewritten. Finally, the ARCEVAC model was only validated once and the results were unclear.

EXODUS contains numerous complex behavioural features. With respect to simulating 90-second certification trials, its model parameters are based on comprehensive research [14] relating to previous certification trials. It is arguable whether all human performance data generated from certification trials is strictly relevant to accident applications. The model attempts to use such data in addition to data derived from accident investigations and laboratory based experimental trials for accident related scenarios. EXODUS models cabin crewmembers both explicitly and implicitly, allowing them to perform many complex actions, such as opening exits and redirection. EXODUS has been successfully validated against numerous certification trials and experiments, two of which were performed blind. EXODUS is capable of simulating the evacuation of narrow-bodied (NB), wide-bodied (WB), double deck (DD) and blended wing bodied (BWB) aircraft. This model treats each person within the simulation as an individual allowing them to follow and adapt their individual evacuation strategies. Whilst, the behaviour within EXODUS is comparatively comprehensive, it does not cover the full range of behaviours that may be found in actual accidents. This is mainly due to the lack of reliable data upon which models can be formulated. Work is continuing on EXODUS model development. Work is focused on a range of activities including the study and development of behaviour exhibited in real accidents, the quantification of behaviour during real emergency evacuations and the further development of the models capabilities to simulate 90 second certification scenarios.

Like many other evacuation models, MACEY's risk assessment model suffers from arbitrary parameter assignment. Whilst a wealth of empirical data was used in setting the scenario, very little empirical data was used within the evacuation sub-model. As such, the performance of components such as exits were imposed on the model rather than generated by the model as results. In addition, whilst the model was capable of simulating evacuation via aircraft fuselage ruptures no data was employed in representing the delays that passengers were likely to experience in negotiating them. As the designers conceded the exit flow rates would not be appropriate in real emergency accidents. Furthermore the model completely ignored cabin crewmembers. Consequently, passengers prepared exits for use. During the validation exercise, this was cited as a possible reason for the model continually over estimating evacuation times. Finally, the Macey model makes use of two-dimensional fire and airflow sub-models. These are extremely simplistic and are incapable of reproducing important fire effects such as smoke layering.

6.5. Data for Evacuation Models

Associated with the development of computer based evacuation models is the need for comprehensive data collection/generation related to human performance under evacuation conditions. The nature of the particular type of scenario to be simulated will dictate the type of data required and the capabilities the model will require. Factual data regarding the evacuation process is essential to the development of computer evacuation models. Evacuation models have a high reliance on factual data regarding the evacuation process in order to:

(a) Identify the physical, physiological and psychological processes that contribute to, and influence the evacuation process and hence inform the formulation of appropriate models (examples of relevant processes include seat jumping, aisle swapping, family group coherence, movement in smoke, incapacitation due to inhalation of toxic products etc.)

(b) Quantify attributes/variables associated with the identified processes.

(c) Provide data for model validation purposes.

Three forms of data are useful in providing the required information. Accident reports containing interviews with accident survivors, video footage from 90 second certification trials and data generated from full-scale and component experimentation. Each of these data sources provides useful information for modelling.

Accident investigation reports that contain human factors analysis and survivor interview accounts are vital in providing information to identify the human element (i.e. item (a) above) that needs to be simulated if the model is to be used in performing simulations of realistic accident scenarios. Equally, data from 90 second certification trial videos can provide similar information suitable for models intending to simulate certification trials.

Once identified, the behaviours and occupant performance attributes must be quantified (i.e. item (b) above). For models intended to simulate real incidents a useful form of data is derived from full-scale and component tests. This is necessary as reliable quantitative data from real emergency evacuations simply does not exist - there are no cameras positioned to record proceedings. In these circumstances, the experiments must be contrived to replicate accident type situations without putting participants at risk of injury. The quantification of the identified attributes may involve collating probabilities of specific actions, such as seat jumping, measuring the time taken to perform specific actions, such as exit openings, passenger exit hesitation, etc. When undertaking experimentation, it is essential to ensure that a representative population is used for data collection. Often in performing evacuation experimentation specialist sub-populations such as students or military/police personnel or single gender groups are used. The results generated from such experiments are not likely to reflect the performance capabilities of the intended target population and as such are of questionable value.

For models intended to simulate 90 second certification trials, detailed analysis of video footage from trials can be used to quantify the identified attributes (i.e. item (b) above).

Finally, data is necessary to validate the predictions of evacuation simulations. Ultimately, the worth of a model is gauged against its ability to realistically and accurately reconstruct and/or predict the real world. Again, data from 90-second certification trials and contrived experimentation can be used to validate models.

6.5.1. Data from 90-second certification trial evacuations

By detailed study of video recordings from 90 second certification trials, both qualitative and quantitative data can be generated relating to passenger behaviour. From the analysis of videos of 90-second certification trials it is possible to establish various behavioural traits common to certification trials. For example, passengers spend an insignificant amount of time in releasing seat belts, very little aisle swapping occurs, passengers are very compliant to crew instructions, seat jumping is extremely rare, passengers hesitate at slide exits prior to committing to jump, etc. It is important to note that while these behaviours are extremely relevant to certification trials they may be completely irrelevant in real accident situations. In addition, it is possible to quantify passenger attributes identified in the 90 second trials. For example, the flow rates and movement velocities of passengers in aisles, the passenger exit hesitation time for various exits types, time to traverse slides, time to open an exit, etc. This type of data is essential if models are faithfully to reproduce the type of behaviour seen in certification trials.

It is however extremely difficult to obtain access to this type of data as the aircraft manufacturers that produce the data consider it to be valuable proprietary information that would provide advantage to their competitors. However, FSEG of the University of Greenwich with sponsorship of the UK Civil Aviation Authority and through strict confidentiality agreements with all the major manufacturers (i.e. Airbus Industries, Boeing Commercial Airplane, British Aerospace, and Douglas Aircraft Company Inc (McDonnell-Douglas (MDC) Corporation) has access to all the 90 second data video footage that exist. This information has been analysed by FSEG and forms an integral part of the airEXODUS model [14,15]. While the regulatory authorities have access to this data it is not generally available to other model developers.

In total some 30 evacuation trials of 24 aircraft have been analysed, that cover the period 1969 to 1996 and include commuter, single aisle, dual aisle and double deck aircraft. The data represents the evacuation of 68 Flight Crew, 194 Cabin Crew and 8865 passenger participants.

The data extracted concerns exiting behaviour of the passengers and crew on an aircraft by aircraft and an exit by exit basis. From the data the following information was collated: Cabin Crew Response Times, Exit Opening Times, Slide Inflation Times, Exit Ready Times, Passenger Exit Use, Passenger Exit Hesitation Times, Passenger Escape slide / Wing Use `Off Time’, Flow Rates, efficiency measures and Type-A Exit Lane Usage. This data has been presented in tabular form for each aircraft investigated.

Furthermore, the data provides a means to validate models designed to simulate 90 second certification trials. This is enabled by a thorough knowledge of; the starting conditions for each evacuation, the end times for each exit, the number of people to use each exit, the location of bottlenecks, flow rates through exits, etc.

Whilst these video records do provide much of the data required for the development and testing of models intended for the simulation of certification trials, the data is not perfect. Two main shortcomings are apparent.

Firstly, data generated for certification trials were not intended for computer model development. Thus, they are not carried out in the controlled experimental manner that would be most desirable for model development. Consequently, there is very little control over variables examined in the trials and modellers have to contend with “gaps” in the data. For instance, there may be insufficient data available covering all possible combinations of cabin crew assertiveness and exit type.

Secondly, for model validation purposes – as opposed to quantification of model variables – as only a single trial is produced for 90-second certification requirements we do not have an indication of the likely spread in experimental results for any given configuration.

The need to perform repeated experiments should come as no surprise as even under the most controlled experimental conditions, no evacuation exercise involving crowds of real people will produce identical results if the exercise is repeated - even if the same people are used [124]. For any structure/population/environment combination, the evacuation performance of the combination is likely to follow some form of distribution as indicated in Figure 14. A single observation of evacuation performance could produce an evacuation time that falls anywhere on the curve. Since the certification trial was run only once, it is impossible to determine the level of variation present within the experimental scenario.

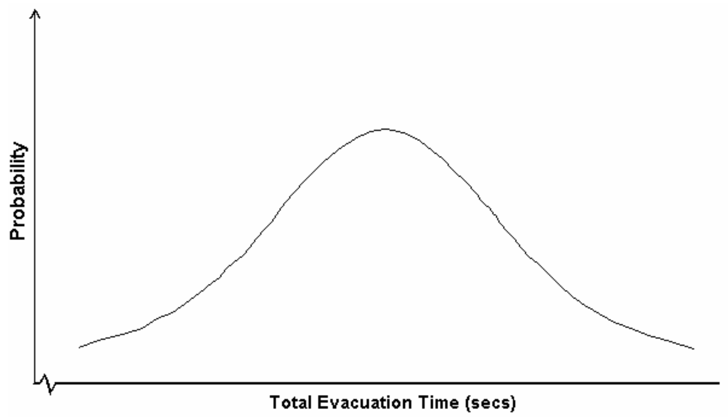


Figure 14: Hypothetical Distribution of the Probability of Specific Total Evacuation Times

Difficulties arise when comparing the result of a single certification trial against the results of an evacuation model that has been run many times and generated a distribution of results, much like Figure 14.

Ideally, the certification trial should be repeated several times. This shortcoming is not only a problem for modellers, it also highlights a significant deficiency in the certification process itself [6].

The data generated from this type of analysis is intended primarily for use in simulations of 90 second simulation trials. However in the absence of better information, some of this data may also prove useful for simulations of real accident scenarios. For instance while data relating to aisle swapping and seat belt release times generated from certification trials may not be suitable for simulating real incidents, the data related to passenger exit hesitation times and movement rates may be appropriate.

6.5.2. Data from aircraft accident/incident reports

Unlike certification evacuations, in real emergency evacuations passengers are subjected to very real psychological, physiological and physical threats that may engender competitive behaviour (as opposed to the co-operative behaviour seen in certification trials – see section 2). Consequently, the modelling of actual behaviour and events during real aircraft accidents is far more challenging than the simulation of certification trials. It also means that the collection of data describing and quantifying this behaviour is also much more challenging - unlike 90-second certification trials and experiments, in real aircraft accidents there are no cameras positioned to record proceedings!

Given the fact that the 90-second certification trial is not an accurate measure of evacuation performance during real emergency evacuations [6] (see section 2) it is necessary to identify potential sources of data describing and quantifying behaviour in real emergency evacuations.

A source of information concerning human behaviour in aircraft accidents is provided through aircraft accident human factors reports produced by organisations such as the NTSB of the USA and AAIB of the UK. These reports contain a wealth of information in the form of interviews with survivors (crew and passengers). The information is collected and documented to aid in the investigation of the accident. However in themselves, individual accident investigation reports do not provide a means to extract reliable generalities concerning actual human behaviour in a range of evacuation situations.

Without strong evidence to support the development of general behaviours we are in danger of relying on a combination of, intuition based on an incomplete knowledge of past accidents, recorded experiences from 90 second certification trials, full-scale experimentation and possibly worst of all, mythology. By mythology we mean the common practice of accepting a behaviour to be generally true, when there is little or no convincing evidence to support this belief.

As examples of commonly held myths in aviation safety consider the following. "During an evacuation passengers have a tendency to head for the exit through which they entered the aircraft, thus explaining bypass of otherwise perfectly serviceable exits". This is a commonly held myth that is a hangover from building evacuation research, where occupants are *believed* to favour familiar exits. While this is believed to be true in aviation evacuations there is little or no convincing evidence to support this belief. Evidence superficially supporting this type of behaviour may be found in any one single accident (e.g. Manchester), however this does not make this apparent behaviour a global truth. Furthermore if bypass does occur, there may be a rational explanation for this behaviour, rather than simply the desire to use a more familiar exit.

Needless to say, in developing evacuation models capable of simulating real accidents, it is vital to understand the phenomena that is to be modelled. One of the first systematic studies at piecing this information together was undertaken in 1970 by Snow et al in which they analysed four air accidents to highlight common factors that influence survival [127]. This paper concluded that configuration, procedures, the environment and passenger behaviour were vital in understanding survival. This work was the first attempt at building an empirical understanding of the dynamics of real emergency evacuations, and is an approach that is widely used today.

While several systematic studies [128] and databases [129] concerning aircraft accidents have been developed, these have concentrated on the details of the accident rather than on the nature of the resulting human behaviour. To date there have been two detailed studies into human behaviour over a range of accidents, one, an on-going study by FSEG of the UK known as the AASK database [130-35] and another by the NTSB of the USA covering a number of recent accidents and pre-cautionary evacuations [134].

The information available in these studies is based on air accident investigation reports and the passenger and crew testimonies that they contain. This data tends to take the form of anecdotal evidence, sometimes with third party corroboration. Using this data insight into the behaviour of passengers and crew during real emergency evacuations can be gained and appropriate behaviours and/or modifications to existing behaviours made within evacuation models. Thus, a model that is more realistic to real emergency evacuation can be developed.

While this type of data is unlikely to aid the quantitative analysis of parameters (see point (b) in section 4), or the validation process (see point (c) in section 4), the qualitative information is of considerable value in identifying the key processes influencing evacuation (see point (a) in section 4).

6.5.2.1. The AASK database

The AASK database has been developed by FSEG of the University of Greenwich with financial support from the UK CAA. This is an on-going project with work commencing in 1993. The AASK database is a repository of survivor accounts from aviation accidents. Its main purpose is to store observational and anecdotal data from the actual interviews of the occupants involved in aircraft accidents. With support from the UK CAA, the AASK concept has evolved into an on-line prototype system available over the internet to selected users. The current release of AASK is V3.0.

Security of the database is maintained at a number of different levels with passwords for the software and control of machine access. Currently only users authorised by the CAA are given internet access to AASK V3.0. Those interested in using AASK may register at the site http://fseg.gre.ac.uk/aask/index.html.

AASK V3.0 consists of five main components the,

- User Interface,
- Data Entry interface,
- Data Viewer,
- Data Query interface, and
- Seat Plan Viewer.

Data contained within AASK V3.0 consists of information derived from both passenger and cabin crew interviews, information concerning fatalities and basic accident details. The cabin crew component has become a significant aspect of the database providing insight into cabin conditions and passenger behaviour as seen from professionally trained cabin specialists. The fatalities component holds data for all fatalities documented in the accident reports while the Seat Plan Viewer graphically displays the starting locations of all the passengers – both survivors and fatalities - as well as the exits used by the survivors.

Data entered into the AASK database was extracted from the transcripts supplied by the Air Accident Investigation Branch in the UK and the National Transportation Safety Board in the US. The quality and quantity of the data was very variable ranging from short summary reports of the accidents to boxes of individual accounts from passengers, crew and investigators. Data imported into AASK V3.0 comprises information from accidents that occurred between 4/4/77 and 8/3/98. This consists of:

- 55 accidents,
- 1295 individual passenger records from survivors,
- 110 records referring to cabin crew interview transcripts, and
- 329 records of fatalities (passenger and crew).

AASK V3.0 can be used in three modes, standalone on a single computer, over a local area intranet and over the internet. The same query engine is used for all three modes of operation. The query engine developed for AASK has been designed so that users without a detailed understanding of the ACCESS database – on which AASK is based - can easily make use of the data. It should be stressed however that to run meaningful queries the user must understand the nature of the data held in the database. The AASK database can also be queried directly using ACCESS however, this can only be done locally.

The AASK database provides a versatile aid in the analysis of human experience in aircraft evacuations. While much data exists for input to the database, the data is limited in scope in that the qualitative aspects of the data far outweigh the quantitative. As such, conclusions drawn from the database must be treated with caution and with full knowledge of the implications of the questions posed and the nature of the data used to provide the responses.

AASK has been used as a development tool for the airEXODUS evacuation model. It is being used to highlight the type of behaviours that should be included within models aimed at simulating real accident scenarios. AASK is shedding light on what really happens during aircraft emergency evacuations and as such is helping to dispel some of the myths that pervade aviation safety. To this end some initial analysis of the data provided in AASK V3.0 was undertaken, this concentrated on seven main areas:

- Survival and reply rates,
- Age distribution,
- Seatbelt difficulty,
- Seat Climbing reasons,
- Direction and distance travelled,
- Exit usage, and
- Exit availability.

6.5.2.2. The NTSB Accident Survey

The NTSB has completed a recent data collection exercise from September 1997 to June 1999 involving 46 evacuations, 2,651 passengers and 18 different types of aircraft.

The study examined a range of evacuation aspects. Evacuees (passengers and crew) were surveyed in order to ascertain their views on the evacuations and to answer specific questions concerning the evacuation performance. The study investigated the following issues concerning exits and evacuation issues in general: access to the exits, emergency lighting, Type-III over wing exits, exit row passenger tasks, flight crewmember exit assignment, evacuation slides, exit height from the ground. In addition evacuation procedures were examined specifically those for planned evacuations, exit selection, slide commands, aircraft familiarisation, and guidance on when to evacuate. Finally the report examined communication issues between crewmembers, passengers and crewmembers.

This report contains some useful data for evacuation modellers. Firstly, information concerning the nature of probable types of evacuation scenario is presented. Data of this kind is essential in developing a holistic approach to certification, i.e. one that takes a performance-based approach considering the evacuation performance of the aircraft under representative scenarios. For example, of the emergency situations utilising escape slides, 37% of the cases experienced problems with at least one escape slide. In addition, the report states that in 3 of the 13 evacuations that utilised Type-III exits, passengers experienced difficulty. Furthermore in one of the three cases, an elderly passenger was unable to operate the exit at all.

Secondly, the report contains useful qualitative data on evacuations. For example, of those passengers that carried baggage onto the aircraft, nearly 50% of passengers reported attempting to evacuate with at least one item of their luggage. This is quite significant as some 66% of the interviewed cabin crew cited carry-on luggage as an obstruction and 37% of passengers thought that carryon luggage slowed their evacuation. During 90-second certification trials passengers have no carry on luggage although some luggage is distributed within the cabin to simulate accident debris. Thus, in 90-second certification trials these sorts of delays do not manifest.

6.5.2.3. The limitations of anecdotal evidence from air accidents reports

Whilst, anecdotal data from real aircraft accidents - be it from the AASK database or from passenger testimonies themselves - are useful for the identification of behaviours and to some extent their quantification, this type of data has limited scope for quantifying time-scales of events and for the validation of evacuation models in general.

Deriving definite time-scales of events during real emergency evacuations is difficult. Instead, temporal data takes the form of rough estimates from the testimonies of surviving participants, rescue workers and, depending upon the location of the crash, accounts from spectators with timing facilities such as airport towers or other flight crew as in the Manchester air crash [7].

As a consequence, vitally important pieces of data such as the length of time taken to open exits, unbuckle seat belts, etc is extremely difficult to obtain with certainty. Whilst it is extremely difficult to obtain accurate time-scales, it is not as difficult to gain an understanding of the likely occurrence of specific events, i.e. behaviours and events, through the frequency of their citation within testimonies and corroboration from others involved. However, in this context anecdotal evidence, in the form of personal testimonies, is only available from surviving passengers. Consequently, the behaviour of passengers that perished in the incident is limited to second hand observation from survivors. The data is therefore skewed towards the successful or survival behaviours.

As a result, full-scale and component experiments have been performed to better understand and quantify the performance of simulated real emergency scenarios.

6.5.3. Controlled evacuation experiments.

Due to the inherent limitations of certification trials and accident analysis, large-scale experiments and component tests offer an alternative source of data for model development. While a number of evacuation experiments have been carried out, to date, their primary purpose has been to address operational or regulatory issues. As their primary purpose was not to collect data to assist in the development of evacuation models, the data generated is often less than ideal for modelling purposes.

Nevertheless, this data can and is being used in the development of computer models. Depending on the nature of the experiment, this data can be used in the development of certification applications and for real accident applications. The data can also be used for all three components of model development identified in Section 4.

6.5.3.1. Large Scale Test Facilities

There are currently two major facilities capable of undertaking large scale or full-scale aircraft evacuation tests on a regular basis. These are located at the Civil Aero Medical Institute (CAMI) in the USA and Cranfield University in the UK.

CAMI lead the world in developing a reusable large scale test facility for evacuation analysis. The CAMI cabin simulator – developed in the 1960's - consists of a C124 fuselage section, 12 feet wide and 77 feet long, mounted on hydraulically controlled platforms so that various pitch and roll conditions can be simulated [136,137]. This test facility has been extensively utilised in the last 30 years *"answering questions concerning seating density, exit size and location, passenger flow rates through exits, and flight attendant behaviour"* [137].

This test facility is in the process of being superseded by CAMI's B747 wide body simulator (WBS) [138]. The main component of the facility is a retired B747 aircraft that will be used to enhance the study of evacuation problems encountered by larger aircraft with higher door sill heights (16 feet) and multiple aisles. The aircraft was decommissioned and purchased by the FAA in 1997 and the facility has undergone a major refit to allow the installation of control and recording equipment, the rapid alteration of interior configuration making it possible to be used to simulate multiple interior layouts and the development of a zoned smoke system which allows the interior to be smoke filled in 30-45 seconds.

Cranfield University currently has two active cabin simulators. The first is a B737 capable of simulating NB aircraft evacuations and the second, the Very Large Evacuation Simulator (VLES) funded by the UK CAA, is of flexible modular design and is capable of simulating WB, BWB, DD and MB evacuations [139]. The VLES opened on the 12th of July 2001 and is 36 feet wide (11 metres), 82 feet long (25 metres) and 32.8 feet (10 metres) high and is the first of its kind. In addition Cranfield had previously used a Trident Three aircraft cabin section to simulate narrow-bodied aircraft evacuations. The Trident Three evacuation simulator has now been decommissioned following the construction of the B737 test simulator.

These facilities have been used to perform numerous experiments to better understand human performance in evacuation situations. Some trials have been performed under non-competitive behaviour and so are similar in nature to the certification trial while other trials have been performed under competitive behaviour – a technique pioneered by Cranfield University – in an attempt to simulate the conditions of real evacuation situations. A brief summary of these experiments is outlined in this section.

6.5.3.1.1. Early CAMI research

There has been much research carried out using the CAMI cabin simulator. Since the Manchester air disaster of 1985, this facility has investigated topics such as effects of exit size, passenger abilities, platforms and exit approach configurations of Type-III exits on evacuation performance [140,142-151]. These trials have included techniques to simulate competitive behaviour pioneered at Cranfield (see Section 6.5.3.1.2). Before discussing these more recent trials - that make use of the variations of the Cranfield methodology - the early work of CAMI will be discussed.

(a) Early attempts at simulating emergency conditions
In 1966, Garner and Blethrow of the FAA undertook the first evacuation exercise under simulated 'emergency' conditions [152]. The cabin section that was utilised was an actual Lockheed Constellation L-1649 fuselage that had recently crashed. The aircraft had crashed on a hill and had split into three pieces. Following the crash the wreckage was restored to *"a practical and safe specimen"* [152] for use in evacuation experiments.

The experiment that was conducted made use of emergency lighting, dense white non-toxic smoke, outside flashing strobe lights at the rear of the aircraft and prior to the evacuation some simulated engine noise. The evacuation scenario also involved cabin crew, simulated injured passengers that needed rescue and ropes at over wing exits. The aircraft also had an uneven orientation. To a passenger moving forward the pitch of the front section was six degrees downwards and the mid-section and aft section were 20 degrees and thirty-two degrees upwards respectively. For safety reasons, only half of the middle and all of the aft sections were used in the experiment.

This experiment was of qualitative value in revealing the myriad of human behaviour that may occur in real evacuation situations.

(b) The effects of aircraft attitude
Using their test facility, CAMI, in 1978 analysed the impact of landing gear failure, upon evacuation performance [136]. This was achieved using the hydraulic capability of the CAMI facility to achieve various combinations of pitch and roll. The analysis was performed in order to ease concern over the performance of B747 style staircases during emergency evacuation. In total CAMI performed 210 trials, with subjects evacuating through spiral, straight-segmented staircases, passageways with seats on one side and without seats on both sides, both with and without simulated smoke, via light obscuring goggles.

During these experiments a different subject population, typically between 23-26 (depending upon attendance), was obtained each of the seven trial days. Each population performed 30 trials on each of the days. Each sub-population was subjected to a different series of scenarios on each day.

The trials were conducted under non-competitive conditions. Thus, while the behavioural regime is similar to a certification trial, the actual scenario investigated i.e. uneven floor, is more akin to real accident situations.

Their findings provide useful information with respect to the qualitative performance of passengers during these trials. However, in their experiments volunteers were required to traverse the experimental apparatus in both directions, i.e. up and down the stairs and forward and aft of the passageway. Unfortunately, in the published report [136], flow rates are presented for the combination of both movement directions. As such the data is of little use to evacuation modellers, as information cannot be extracted for motion in a single direction.

This information is of vital importance to the simulation of real accident scenarios and it is hoped that these experiments will be repeated and data useful for model development generated.

(c) Evacuation performance of disabled passengers
The FAR 28.803 emergency demonstration does not require the inclusion of passengers with movement disabilities. As such, no information regarding the evacuation of disabled passengers is available from 90-second certification trials. While some information is available on the performance of disabled passengers in accident reports, this information provides no quantitative data on movement rates.

In 1977, CAMI performed a series of trial evacuations using various different categories of disabled passengers. In total 153 subjects were used of which 129 had some form of disability. Disabilities included quadriplegics, blindness, partially sighted, cerebral palsy, elderly, deafness, mental deficiency, leg casts, obesity, multiple sclerosis, polio, arthritis, birth defects, paraplegic and via anthropomorphic dummies the non-ambulant. Useful quantitative data was generated concerning the extended response times of the disabled passengers, their slower movement speeds through aisles and seat rows and large exit hesitation delays. In addition, qualitative trends such as the requirement for cabin crew and or carer assistance during the evacuation and the propensity for 'sub-queues' [149,21] to form behind slow moving passengers were revealed and fatigue effects [149].

This data is of great importance to modellers attempting to simulate real evacuation situations.

6.5.3.1.2. Techniques for simulating competitive evacuation

Following the Manchester air disaster of 1985 and as part of a UK CAA funded research programme, Prof Helen Muir and others from Cranfield University pioneered a new technique to simulate 'competitive behaviour' of the type reported in emergency evacuations [120,153,155]. The technique involved giving £5 bonus payments to the first 50% (later increased to 75% in some experiments) of passengers to evacuate a Trident aircraft fuselage used as a full-scale cabin simulator. Muir later concluded that the technique was successful, stating that,

> *"The experimental programmes had successfully demonstrated that it was possible to develop new techniques to simulate the behaviour which can occur in aircraft emergencies involving life threatening situations…"*[159].

Using these techniques Muir went on to investigate the effects of bulkhead widths [153- 155,159], seating configuration [153-157,159] and cabin crew motivation [120,158,159] adjacent to exits. Results of this work indicated that, contrary to the prevailing theories of the time, the flow rate of passengers through constricted areas of the cabin was lower when the passengers behaved competitively, i.e. similar to real emergency, than when they behaved in an orderly manner, as in 90-second certification trials. This hypothesis was also found to be true in the presence of non-toxic theatrical smoke. From the modelling perspective this data serves as a useful indication of the likely performance during real emergency evacuations.

In addition, Muir also found that the presence and motivation of assertive cabin crew tended to increase the flow rate of passengers through floor level aircraft exits [120,158,159]. The Cranfield analysis was restricted to Type-I exits as this was the only floor level exit with crew support. This result is similar to the FSEG finding concerning passenger exit hesitation times based on the analysis of 90-second certification data for Type-I and Type-A exits [14,15].

Research still needs to be undertaken to compare passenger exit hesitation times generated from competitive experimental trials and 90 second certification trials. This is of importance as it may be possible to use certification data concerning exit hesitation times for real accident applications.

6.5.3.1.3. Experiments involving Type-III exit performance

Subsequent to the Manchester air disaster of 1985, numerous experiments have been conducted both at CAMI and at Cranfield University during the period 1989-2000 concerning Type-III exits. Some of the relevant findings are briefly summarised in chronological order below.

Initially in 1989, Rasmussen *et al* based at CAMI attempted to determine the effects of seating configuration adjacent to Type-III exits on the exit hatch removal and egress [140]. Of the configurations examined it was concluded that the dual 6" passageway was significantly faster than the single 6" ($p<0.005$) and 10" ($p<0.01$) passageway configurations. Another finding of this work was that exit hatch removal and disposal was not greatly affected by passageway configurations. From an evacuation modelling perspective these experiments provide some useful quantitative and qualitative information on exit preparations and likely exit flow rates against which evacuation models could be validated. However, the data was not presented in a form useful for evacuation modellers. If video footage of these trials were made available, exit hesitation delays could be extracted as could passenger movement rates and movement behaviour appropriate for the exit configuration.

McLean *et al* followed this in 1989 with an investigation of the effects of wearing smoke hoods on evacuations through type-III and Type-IV exits in smoke and clear air [141]. This study found that evacuation through the Type-III exit was faster than through the Type-IV exit ($p<0.005$). It was found that wearing smoke hoods increased the egress time through both types of exits ($p<0.05$). Furthermore, other factors such as size of the exit and smoke hood and passenger learning influenced individual evacuation times. In its current form, this work provides useful qualitative information and some quantitative information, in the form of a performance decrement, on passenger evacuation through these types of exits. Here again, video footage of these evacuations would assist model developers in assessing exit hesitation curves for evacuations in the presence of non-toxic smoke, both with and without smoke hoods.

In 1989, Muir et al first utilised the monetary payment technique (see Section 6.5.3.1.2) and investigated the effects of passenger motivation on egress through different bulkhead apertures and different passageway configurations leading to Type-III exits [153]. This research demonstrated that high motivation, induced by financial rewards (see Section 6.5.3.1.2), led to significant ($p<0.01$) differences in performance to that observed under 'normal' experimental motivation levels. This study indicated that findings from experiments using 'normal' motivation levels were likely to be different from those using 'high' motivation levels. It was also found that human factors effects, such as age, gender, evacuation strategy planning were highly influential on the experimental results. In its current from this work has provided useful qualitative data during 'high' motivation conditions. In addition some quantitative information was generated, that could indicate suitable performance decrements that could be applied to simulate 'high' motivation/competitive conditions.

In 1990, Muir *et al* examined low passenger motivation in theatrical smoke conditions [154]. This work was useful in that it further revealed passenger behaviour under theatrical smoke conditions. This work indicated no significant differences between the Type-III passageway arrangements in smoke conditions (optical density of 0.5 per foot). However, significant differences ($p<0.01$) were noted in the non-competitive trials with and without smoke. From a modelling perspective it provides useful qualitative information on Type-III component performance levels under smoke conditions. It is for example, noteworthy that the configurational impact adjacent to the Type-III exit is less significant in the presence of smoke. Qualitatively, some data exists to validate models of non-competitive smoke evacuations.

Continuing this work, in 1992 Muir analysed the impact of 'high' motivation when evacuating through bulkhead passageways and Type-III exits in smoke with different exit passageway widths [155]. This analysis further revealed that evacuation performance was significantly linked to passageway configurations. In addition, gender was found to significantly ($p<0.05$) effect egress time. However, other human factors such as height, weight and age did not appear to contribute to egress times. In its published form, some of this qualitative data is of use for evacuation modelling in that it provides insight into human behaviour that may need to be represented in evacuation models.

For example, in the 13" and 18" passageway configurations, it was suggested that these configurations might have been *perceived* by the participants as affording more space than actually existed. As a result, multiple passengers attempted to access the passageway concurrently. This led, on occasions to passengers vying for access to the passageway. From a qualitative perspective, this type of insight into the behaviour of passengers around these type of exit configurations is essential if the correct behavioural response is to be modelled. In addition, some quantitative information was generated regarding the affect of age on egress times. In particular it was shown that the older the participant the longer the egress time through certain passageway configurations. If sufficient data of this type were available to model developers a relationship of age and exit capability could be developed.

In 1992, McLean *et al* examined specific dual and triple seating configurations adjacent to single and dual Type-III exits focusing on hatch removal and rates of egress under 'normal' experimental motivation conditions [144]. Again this study revealed significant differences between egress times associated with different exit passageway configurations. This provoked interest in specific passageway arrangements that were explored in more detail in later experiments. Additional information was generated regarding exit hatch removal and disposal times. Evacuation models could use this data to set exit preparation times, i.e. hatch operation time and disposal time, and to better understand the likely effects of various passageway configurations.

Fennell *et al* investigated Type-III exit configuration in 1993 under 'normal' experimental motivation conditions [156]. This concerned the effects of exit hatch weight and seat configuration on Type-III exit operation and resulting evacuation times. Through the use of anthropomorphic dummies, they also simulated the impact of dead passengers situated immediately adjacent to these exits on evacuation times. They found some differences in exit hatch removal and disposal at specific passageway widths. In addition exit plug weight, passenger gender and passageway configuration were all found to have significant effects ($p<0.001$) on exit opening times. This resulted in numerous findings regarding exit hatch operation and disposal according to gender, age and hatch weight. Indeed in some experiments the weight of the hatch was too great for the operator and the experiments were abandoned. The presence of the anthropomorphic dummy (simulating an incapacitated/dead passenger) revealed useful qualitative data on passenger behaviour. In some cases passengers attempted to move the dummy whereas in other cases they did not. Additional delays in exit operation were incurred on account of the dummies awkwardness and it being located in the out board seat. In its published form, this research has generated useful data for evacuation models on likely human behaviours and some quantitative data on exit opening times.

In 1995, McLean *et al* published the first of two investigations on evacuation through Type-III exits under 'high' motivation conditions [142]. This study examined seat placement effects on evacuations through the Type-III exits. This studies primary aim was to provide more definitive answers to the questions raised in previous studies. Indeed the results of this study supported much of the findings of previous work. The effects of passageway widths were again shown to exert significant influences on evacuation performance. The second part of the study examined the effect that individual passenger differences / human factors had upon the experiments [143]. It was found that height did not have a significant impact on egress time but that age, weight, waist size and gender did. Further findings were presented describing effects from a combination of human physical factors. From an evacuation modelling perspective this research is important as it provides qualitative information into the relationship between human physical factors and exiting capabilities. If sufficient data were collected it may provide the basis for establishing the quantitative relationship between these factors and exit capabilities.

In 1996 Muir *et al*, published additional results from experiments on the 3”, 13”, 18”, 25”, 34” and 6” OBR (Out Board seat Removed) exit passageways leading to Type-III exits under ‘normal’ and ‘high’ motivation conditions [157]. Again this study found that the Type-III exit passageway width had a significant effect on evacuation efficiency. Learning effects were also noted to influence trial results, highlighting potential problems in comparisons with dissimilar pervious experimental designs. This experiment generated similar qualitative data to previous studies in terms of exit preparation times, the behaviour of passengers using specific passageway configurations and exit flow rates. In addition, some quantitative data concerning exit flow rates for Type-III exits was generated that could be used to calibrate model exit flow rates. It may also be possible to extract from these studies raw data relating to exit hesitation time distributions.

Finally, in 1999 McLean *et al*, presented results of experiments into the effects of passenger densities (either 30 or 50 passengers) through the 13” Type-III exit passageway [145] with and without cabin crew. For the trials with cabin crew, three different seating locations were investigated. Mclean noted that cabin crew location resulted in insignificant differences in the average egress times. However, the time for the fifth to thirtieth passenger to evacuate through the Type-III exit showed a significant ($p<0.001$) hyper-additive increase in the high-density case and a significant ($p<0.002$) decrease when cabin crew were present. Furthermore, the high-density configuration without cabin crew was by far the slowest case examined. This research has highlighted numerous qualitative factors that could be factored into evacuation models, such as the improved exit flow rates resulting from the presence of cabin crew. However, to be of value quantitative data relating to the impact of crew on exit flow rates should be derived from this experiment. Unfortunately, results from this research are not available in open literature.

These studies represent a huge investment of resource and effort that produced much data on the behaviour of passengers at Type-III exits. Numerous factors were each investigated such as: passageway width, seat encroachment on the Type-III exit aperture, hatch weight, passenger instructions on hatch operation, the method of hatch disposal, the age, weight, height and girth of passengers, the presence of cabin crew, the density of the passenger distribution within the cabin section, etc. Whilst generating much useful data for regulations and the resolution of operational matters, the published results are not always in a form that is of maximum use to evacuation model developers. In order to maximise the benefit for evacuation model development, the video footage from these trials should be made available for further analysis.

It is suggested that future trials should include the involvement of evacuation model specialists to ensure that maximum benefit is derived from such trials and that the data is presented in such a way so as to be of use to model developers. Furthermore, while much work has been done and a considerable amount of data has been collected, before definitive relationships are established for use in computer models it must be established whether or not this data is consistent.

In a recent analysis of this research [145], McLean was forced to conclude that conclusive results from these experiments are limited. As McLean stated, the experiments listed above have generally resulted in,

> *“Data that are largely confounded by individual subject variability and the effects of practice… [and] incomplete designs have often been compounded further by comparisons of the data thusly obtained with other data acquired using similar methodologies, which have, unfortunately, also generally suffered from the same types of deficiencies.”*

In addition to McLean’s critique, a recent study by the NTSB concluded that the experiments performed by CAMI that involved Type-III exits contained “*…a number of significant design flaws…that bring* *into question the applicability of the research to an actual emergency evacuation situation."* [134]. For example, within the CAMI studies that were performed in 1995, each subject performed some 30 evacuations. The NTSB were concerned that significant learning would have occurred over the course of these trials that severely limits the usefulness of these particular studies.

While McLean's confidence in the results of these experiments is low, we have little alternative but to make the best of this data until his reservations are corroborated and more suitable data is made available. Until then, this data is useful in that they have highlighted numerous qualitative trends that evacuation models should include and the quantification of various important human behaviours.

Indeed in a bid to answer some of the questions raised by these studies CAMI have recently completed the most extensive series of aviation evacuation experiments to date [147,148]. This involved the experimental phase of a new evacuation study of the Type-III exits. This study represents the largest study of these exit types. The experimental phase involved 2544 volunteers split into groups of 55 with each group performing 4 evacuations each, thus producing a total of 10000 exit crossings and 48 naive evacuations.

The purpose of this study was primarily to investigate passageway configuration (6" OBR dual, 20", 13", 10"), hatch location (discarded inside or outside of the exit), subject group density and subject group location. Half of the evacuations used the 'high' motivation technique and half used 'normal' experimental motivation. As each subject performed four evacuations these experiments will be able to analyse the impact of learning. Similar to the CAMI experiments performed in 1995 and 1999, cabin crew marshalled passengers towards the exits from the forward and aft extremities of the cabin.

The results of this study are not yet published however they should provide more qualitative and quantitative data for evacuation models.

The results of the research at CAMI and Cranfield University are of interest to evacuation modellers as they ***identify*** (see point (a) in section 4) and ***quantify*** (see point (b) in section 4) numerous relevant factors that influence evacuation. Whilst useful in their own rights, the information is limited as model developers must make use of the data that is published in the format that is published. While addressing important factors, this information may not be in a form suitable for model developers. Ideally, the video records of the experiments should be made available to model developers or model developers should be included in the team designing and analysing experimental results.

6.5.3.1.4. Experiments involving Type-I exit performance

Analysis of factors affecting exit performance has not been limited to Type-III exits. Indeed, both Cranfield and CAMI have performed research using Type-I exit types.

As part of the aforementioned Type-III studies, in 1989 Muir et al published the results of experiments into cabin configuration adjacent at exits using the Trident cabin simulator at Cranfield University (Section 6.5.3.1.) [153]. These experiments involved 2262 volunteers in groups of 60 taking part in over 134 evacuations of which 80 were through Type-I exits and 54 through Type-III over wing exits. The results of this work indicated that high motivation and low bulkhead aisle widths adjacent to exits were detrimental to evacuation efficiency. This was closely followed by two more studies from Cranfield using the same equipment. The first was in 1990 and examined the effect that theatrical smoke had upon performance under 'normal' experimental motivation conditions [154]. This followed in 1992 by the results of using 'high' motivation techniques [155]. From a modelling perspective, this research has provided quantitative data on the flow rates of passengers through aisles and bulkheads. This data could be used for the validation of model predictions for these aircraft components under 'high' motivation, 'normal' experimental motivation both with and without non-toxic smoke.

In 1996, Muir *et al* published a report detailing the importance of the number of cabin crew and performance at Type-I exits using the B737 cabin simulator (see Section 6.5.3.1.) [158]. In this series of experiments, a total of 1307 volunteers participated in 4 trials in groups of 60. Evacuations, using one active door and two active doors were carried out under 'normal' and high motivation experimental conditions. This research has provided useful qualitative information on influential factors that determine the performance of floor level exits. In addition, this research has provided useful data on the flow rates of exits against which model predictions can be validated.

In 1995 [150] and 1999 [151], McLean *et al* published the results of a research study investigating the affects of using platforms in place of escape slides during 90-second certification trials. This research was prompted primarily by concern over the validity of recent use of platforms during a 90-second certification trial, e.g. the MD-11 in 1992 [161,162]. Trials of this aircraft were permitted to use slides due to safety concerns following the paralysis of a volunteer during the original certification of the MD-11 in 1991. Whilst the use of platforms had previously been permitted at exits that are not required by FAR to have escape slides, such as over-wing exits on the B737-300, B737-400 and DC-9-80 [14,8,163,164]**,** the use of platforms in place of escape slides was unknown. This research was not just of interest to 90-second certification demonstrations, but also to research in general as previous studies performed at Cranfield had utilised platforms in place of escape slides [153-155,158].

The first study involved a total of 239 adults in groups of 59-60 performing 4 trials each under 'normal' and high motivation experimental conditions and in clear air and smoke. This research concluded that the *"platform allowed much faster evacuations than the inflatable slide"* and that *"doorsill-height platforms do not model escape slides very well"* [150].

The second study investigated the impact the exit size and egress means had on evacuation performance. This study involved a total of 174 volunteers divided into five groups of between 34-36 with each performing six evacuations. The experimental trials involved combinations of 'normal' and 'high' motivation in smoke or clear air onto either platforms or escape slides. The conclusions of this study were that *"…evacuation result obtained with one type of egress means should not be casually generalized [sic] to any other"* [151]. In addition the report stated, *"…evacuations of a specific aircraft should use that aircraft's actual evacuation means to obtain the highest fidelity possible."* [151].

6.5.3.2. Evacuation component testing by manufacturers

In addition to experiments performed at the CAMI/Cranfield facilities, manufacturers frequently test new components of aircraft, such as slides, exit configurations, signage designs, etc. Whilst numerous tests are performed throughout the world the data that they generate is difficult to obtain, as typically it is commercially sensitive and proprietary. However, this data if made available, could be of great importance to model developers. If the tests are done under appropriate conditions, the data they generate could be useful for both 90-second certification trial scenarios and real accident analysis. A further discussion of these tests and the role they can have in modelling for certification can be found in Section 6.5.1.

6.5.3.3. Thermo-toxic environments

Present in many real emergencies is a thermal and toxic hazard that is capable of hindering evacuation and/or causing loss of life. As such, evacuation models that attempt to simulate real emergency evacuations require a representation of both the affects that they have upon passenger behaviour and the possible loss of consciousness and ultimately life. The FAA has been investigating the effects of pooled fires on aircraft cabins and its toxicological impact upon passengers for many years. Their work and its appropriateness for the purposes of evacuation modelling is summarised in this section.

Firstly, it is necessary to define the principle type of fires that are likely in an emergency aircraft evacuation. Fires may take the form of internal fires, possibly originating from damaged or defective aircraft systems, or an external pooled kerosene fire. The majority of research by the FAA has been focused on the external pooled kerosene scenario

6.5.3.3.1. The FAA C133 full-size fire test facility

The FAA fire C133 test facility subjected a mock aircraft cabin to a pooled kerosene fire. The pooled fire originated from an external tray measuring 10 feet by 8 feet which contained 50 US Gallons of kerosene fuel and was positioned at the sill height of a Type-A sized exit opening. The size of the opening was supposed to be representative of a rupture in the cabin fuselage, thus passenger seating was situated directly adjacent to the Type-A sized opening.

The size of the tray was determined through tests of various tray sizes in order to reproduce the radiant flux of an "infinitely" large pooled kerosene fire [110]. The data for an "infinitely" large pooled fire was obtained through subjecting a real DC-7 aircraft [**165**] to an external pool fire of 30 feet in diameter through a similar sized opening. The resulting radiant flux when measured at the centre line of the cabin fuselage during the DC-7 test was only marginally higher (20%) than the radiant heat flux from the C133 fire test model.

The result of their experiments was that their test aircraft cabin section consistently flashed over at approximately 2¼ minutes. This finding was explicitly stated by the FAA technical report:

> *"Uncontrolled post-crash fires in an intact fuselage will produce flashover condition, which will be followed by a loss in survivability throughout the cabin."* [110]

In a bid to ascertain the validity of the C133 test model's findings, Trimble [166] reviewed 10 aircraft accidents with fires, for the occurrences of flashover, smoke and/or gas induced debilitation/collapse before completing egress and he also examined the time-scale of the evacuations. The cases Trimble investigated are summarised below:

- United Airlines DC-8 at Denver on 11.7.1961
- United Airlines Boeing 727 at Salt Lake City on 11.11.1965
- Varig Boeing 707 near Paris Orly on 11.7.1973
- Saudi Arabian Airlines L1011 at Riyadh on 19.8.1980
- Spantax DC-10 at Malaga on 13.9.1980
- Air Canada DC-9 at Cincinnati on 2.6.1983
- Pacific Western Airlines Beoing 737 at Calgary on 22.3.1984
- British Airtours Boeing 737 at Manchester 22.8.1985
- Delta Airlines Boeing 727 at Dallas on 31.8.1988
- US Air Boeing 737 at Los Angeles on 31.8.1988

With respect to flashover, Trimble found that in two of the cases (6 and 8) flashover was completely discounted by their air accident investigations. The remaining 8 cases investigated had no mention of flashover although smaller flash-fires were mentioned in some air accident reports. His analysis of gas induced debilitation collapse revealed that for the majority of passengers incapacitation occurred as a result toxic gas inhalation. Additionally, Trimble found that an average evacuation time-scale from 9 accidents was 3 minutes and 50 seconds.

Trimble's conclusions were that, whilst the FAA C133 test model certainly does represent an aircraft fire scenario, the test model should not be assumed as the general pattern for real aircraft pooled fire scenarios [166]. Indeed, Trimble argues that the testimonies of passengers and the pathological evidence from real aircraft accidents indicates that toxic gases are the principle source of incapacitation not excessive exposure to thermal radiation, as indicated by the C133 test model. As such, Trimble questions the validity of extrapolating from the test model to real aircraft fires. As Trimble stated during his Thesis:

> *"The C133 fire test model results from the FAA technical centre, that there is no significant threat to occupants from combustion smoke and associated toxic/irritant gases before flashover occurs in an aircraft cabin. Such a view does not accord with the testimonies of many survivors from previous fire related accidents, nor the associated toxicology, and it is considered that there is sufficient discrepancies between the results form this particular fire test model and real accident experience to indicate that the apparent findings from this fire model and the above premise have been relied upon to an unwarranted degree."* [166, pp110]

From an evacuation modelling perspective the results of these tests provide some useful data on a possible thermo-toxic scenario during a real emergency evacuation. In addition these experiments have been useful in highlighting and quantifying the types of gases that are released from the pyrolysis of an aircraft cabin and its furnishings. Using these data, evacuation models can be configured to represent the experimental fire. However, the data generated from these test fires cannot be assumed to be the only or most representative fire scenario for aircraft accidents. Indeed, according to the work of Trimble, the toxic data generated in these test fires is unrepresentative of the most challenging aircraft fires that occur.

6.5.3.3.2. Computer based methods of modelling fire

In addition to using data from fire tests, computer fire models can be used to generate the fire atmosphere that passengers are subjected to. Computer models to simulate fire are generally categorised as being either Zone [111] or Computational Field Dynamics (CFD) [115] based. Zone models, also known as volume models, solve conservation equations for relatively large control volumes or zones. They generate an average heat, gas and smoke concentration for both upper and lower layers in each zone. The output for each zone is an average, it is therefore impossible to determine gas species concentrations within individual areas of a compartment, i.e. the spread of smoke and/or gas species from one side of a compartment to another, or the location of the flame plume within a compartment. As a consequence heat, gas species and smoke concentration data generated by a zone model for an aircraft fire should be considered to be a rough approximation. Primarily, this is due to the fact that the specific location of smoke, heat and gas concentrations within aircraft compartments are of crucial importance to the outcome of the accident, i.e. the pattern of behaviour and fatalities. As such a more detailed representation of fire within computer models is required. This is provided through the CFD approach.

CFD based models subdivide each compartment or zone into thousands of small three-dimensional cells. The physical properties, i.e. gas, heat and smoke concentrations are then calculated for each cell. As finer meshes are employed within CFD models, they can more accurately predict velocity and temperature fields. However, whilst generating more detailed results the approach is computationally expensive. With respect to simulating fire spread through an aircraft cabin, the size of the mesh elements is of importance, as it would affect the results of the model. A smaller mesh could better represent the geometric features, i.e. seats, overhead bins, etc. However, as the mesh size is decreased so the computational expense of running the model is increased. Thus a balance is usually found.

CFD computer models have the benefit of providing individual thermo-toxic data for many different locations within the aircraft cabin. By contrast, in experiments measurement is taken at only a few stations. Thus, CFD based models have the potential of providing more detailed information for evacuation models.

With both types of models, initial and boundary conditions are required. In this respect, previous experiments have proven useful. The FAA C133 test model for example has generated much information on the likely fire intensity from a pooled fire. In addition, a comprehensive history of validation within the aircraft cabin application domain is necessary to in order to gain confidence in the results of the model.

To summarise, CFD models are best able to generate suitable data for evacuation models. However, the answer that the models will generate is dependant upon the parameters that are provided and the computational resources that are available. As with any model, confidence has to be gained through extensive successful validation within the proposed problem domain.

6.5.3.3.3. Human tolerance to thermal and toxic hazards

Much research has been carried out to ascertain human tolerances to thermal and toxic hazards. This research has primarily been performed using rats, mice and monkeys as human surrogates [167-176]. The toxic gases that required investigations have been determined through the pyrolysis of aircraft cabins and furnishings as well as through the pathological analysis of accident victims [166,109,110,127]. Thus, human tolerance experiments have analysed tolerance to specific toxic products and toxic combinations [167-176].

The concept of Fractional Effective Dose (FED) has been utilised to model the time taken to incapacitation from various different toxic threats, such as Heat, Radiation, Hydrogen Cyanide (HCN), Hydrogen Fluoride (HF), Hydrogen Chloride (HCl), Carbon Dioxide (CO_2) and Carbon Monoxide (CO). The FED is numerical and is therefore ideally suited to computer models. The FED model has been described numerous times previously [116,117], and so will not be described in detail here. Suffice to say that the FED assumes the effects of its components to be additive and is reliant upon having a good quality data when specifying its parameters. Originally the FED model was only able to indicate the time to incapacitation from asphyxiant gases.

The effects of asphyxiant gases are that, in sufficient quantities they affect ones ability to breath and to remain conscious. As Purser states they *"affect the nervous and cardiovascular systems, causing confusion followed by loss of consciousness, followed ultimately by death from asphyxiation"* [117]. Common asphyxiant fire gases include CO, HCN, CO_2 and (low) O_2 [117]. A common exposure profile is that *"There is little effect initially, but when a critical threshold dose level is reached severe effects occur suddenly. These consist of a brief period of intoxication (similar to severe alcohol intoxication), followed by a collapse into unconsciousness."* [117].

Later, Purser expanded the FED model to include the effects of irritants [117]. Irritants are highly irritant and potentially depilating gases, such as HCl, HF, Sulphur Dioxide (SO_2), Nitrous Oxides (NO_x) and Acrolein (HCHO), that are nearly always present in aircraft fires [166,117]. In sufficient quantities these irritant gases can cause severe discomfort and agitation, such that passengers ability to escape is annihilated to *"a degree of incapacitation approximately equivalent at the point of collapse resulting from exposure to asphyxiant gas"* [117]. Even in small quantities irritant gases can cause *"Painful stimulation of the eyes, nose, throat and lungs"* [117]. However, Purser recognises that quantifying their effects for any one individual is difficult as *"Effects lie on a continuum from mild eye irritation to severe eye and respiratory tract pains"* [117].

The net result of this research is an empirically based mathematical model of human tolerances to toxic and thermal assault. The FED model not only models time to incapacitation but also time to irritation. Furthermore, being numerical, the model is ideally suited to integration into computer evacuation models. However, like any model, it is only as good as the data upon which it is based.

6.5.3.3.4. Human behaviour in smoke

In recent years, human behaviour experiments in smoke have been limited to non-irritant toxic theatrical smoke [159, 155]. Experiments in aircraft have been conducted both at Cranfield [154,155] and CAMI [140,141]. However, some years ago, experiments were performed using irritant smoke and human volunteers [177,109] in non-aircraft enclosures [177].

The primary impact of smoke is that particulate in the atmosphere obscures the amount of light that is transmitted, thus leading to a decreases in visibility. During an emergency evacuation this has the effect of limiting passenger visibility creating disorientation. In addition, passenger movement is also effected. Passengers may decide to crawl so as to avoid contact the upper hot and dark smoke layer. In very dense smoke, passenger vision is completely annihilated and positional awareness is limited to tactile information.

The FAA conducted some tests into the effects of smoke on cabin visibility [109,178,179]. In these experiments passengers were required to read letters signs through various concentrations of smoke. The effects of cabin and sign luminescence, and letter spacing were examined using white [178] and black smoke [179]. Passengers were not subjected directly to the smoke in these experiments. However, in earlier experiments this had been shown that the ability to read signs was reduced in irritant smoke conditions when compared against non-irritant conditions. This was attributed to discomfort and eye lacrymation. Similar affects have been reported in real aircraft accidents [7]

Jin subjected volunteers to irritant and non-irritant smoke whilst performing a complex action and walking through a corridor [177]. In this work, Jin showed that human performance both in terms of movement ability and performing their task were reduced in irritant smoke.

The results of this research are that it is possible for computer models to have some representation of human behaviour in smoke environments. However, the work of Jin was performed in a corridor not an aircraft cabin. Consequently it is not of direct relevance to behaviour in aircraft, as it is likely that a different range of behaviours would be exhibited when moving through smoke within an aircraft cabin. As such more research is needed in order to better understand the behaviour during smoke environments. Ideally, video footage of subsequent trials involving smoke would be made publicly available for the benefit of evacuation modellers. Furthermore, the work that has been done in aircraft enclosures [154,155] have not controlled or quantified the concentration of smoke the passengers have been subjected to. It is thus not possible to determine the impact of smoke concentration on human performance in these experiments. Thus, it would be desirable to conduct a range of experiments within aircraft environments in which the smoke concentration was controlled.

6.6. A critical evaluation of aviation evacuation model data

It is apparent from this review that a large quantity of data is available for use in evacuation models. In this section we attempt to identify areas that require further data.

6.6.1. Current Data Requirements

As has already been described (see section 2), the nature of the intended simulation, i.e. certification or accident simulation, determines the quantity and quality of data required to perform the simulation. While there is a large amount of data available from certification trials and controlled experiments there are still gaps in these data sets that need to be addressed.

One of the most significant components of evacuation models concerns the manner in which the model represents the exiting process. To simulate this accurately requires data, either from certification trials or from experiments. The trial data best represents the conditions found in certification trials while experimental data has the potential to represent conditions found in real emergency evacuations through the use of the competitive evacuation experimental protocols. From the study of video footage of these trials or experiments it is possible to extract passenger exit hesitation time distributions and exit flow rates that can be used by the model developers to define the passenger performance at the various exits.

In considering the data required for the simulation of certification trials, a considerable amount of exit hesitation time data has been extracted from certification trial video footage [14,15]. This data has been collected by FSEG and is based on data provided by the aircraft manufacturers. While more raw data may exist, it has not been made available to FSEG for analysis. As a result, some exit-type/crew-assertiveness combinations either lack sufficient data or have no data at all (see Table 6).

Table 6: Frequency of exit hesitation data from 90-second certification trials [14,15]

	Number of evaluations per Exit Hesitation Delay / Assertiveness category (exits)			
Exit Type	**Combined assertiveness**	**Assertive**	**In-between**	**Unassertive**
Type-A	35	20	12	3
Canted Type-A	7	7 (general assertiveness category)		
Upper Deck Type-A	1	1	No data	No data
Type-B	No Data	No Data	No Data	No Data
Type-B (Dimensions)	7	5	2	No Data
Type-C	No Data	No Data	No Data	No Data
Type-C (Dimensions)	7	5	2	No Data
Type-I (Dimensions)	3	1	2	No Data
Type-I (Combined)	17	11	6	No Data
Type-III	12	12 (general assertiveness category)		

It is apparent from Table 6 that data for the upper deck Type-A exit is scarce, as data only exists for one evacuation in which the crewmember behaved in an assertive manner. No data at all exists for Type-A upper deck exits with in-between assertion level and unassertive cabin crewmembers.

In amendment 25-88 [16], the FAA and JAA introduced two new types of exit. They were the Type-C and Type-B. The classification of these exits was based not only on exit dimensions but also on requirements for exit passageway widths, cabin crewmember jump seat placement, the provision of assist spaces, escape slide capacity and total exit preparation times. At present, no data exists on exits classified as Type-B or Type-C at the time of certification. However, in order to better represent the variation in performance of various sizes of Type-I exits, the Type-I exit data has been categorised according to the dimensions of the exit, i.e. of Type-I, Type-C or Type-B dimensions.

Other exit type/assertiveness categories are also not represented within the FSEG database. Namely, any data for Type-C or Type-B exits as defined by amendment 25-88 [16]. Those exits of Type-B dimensions, Type-C dimensions and Type-I dimensions all with unassertive cabin crewmembers. Also, data for floor level exits without slides is lacking from the database.

Furthermore, some exit types would benefit from additional data to better define the exit hesitation time distributions. These include: Type-B dimensions, Type-C dimensions and Type-I dimensions all with in-between assertion level cabin crew (2 evacuations only per category) and the Type-I dimensions exit with assertive cabin crew (1 evacuation only).

Certainly, data can and should be made available to the research community and extracted from future certification trials to help fill the data shortfall however, there are unlikely to be sufficient certification trials to completely satisfy this requirement. Targeted manufacturer component testing (see section 6.5.3.2.) offers a possible way to plug the data gap. However, to be valid, this testing must be done under strict certification conditions.

Other data that would be useful for certification analysis includes, passenger flow rates in aisles for different seating configurations, slide times, flow rates from specific passageway and cross aisle configurations, flow rates from evacuations in which cabin crewmember impede flow through the exit.

For accident analysis, there is a wide array of data that requires a systematic collection strategy. The collection of this data differs from that of certification data as the experiments can be undertaken using competitive behaviour protocols that attempt to simulate accident conditions. It must be emphasised that such data should be collected for both wide and narrow body aircraft configurations. This data includes, passenger exit hesitation times for different exit and crew assertiveness combinations, exit flow rate data, passenger aisle movement rates for different cabin orientations, passenger movement rates on staircases for different cabin orientations, passenger aisle/staircase movement rates in smoke for different cabin orientations, impact of cabin luggage on evacuation efficiency, frequency of aisle swapping, passenger instigated redirection to alternative exits, etc. In addition, for accident analysis, passenger cultural differences may be an important factor and so should be examined both in accident analysis, such as through the AASK data base (see section 6.5.2) and in controlled experiments.

Furthermore, it would be a valuable exercise to compare passenger exit hesitation time data collected from certification trials with the equivalent data collected from competitive evacuation trials. Some have assumed that this data may be significantly different however, until a detailed systematic analysis is undertaken this will not be known for certain. It is the belief of the authors that there are unlikely to be significant differences in this data, especially for situations involving assertive crew. If this were shown to be true, this would be a tremendous advantage, as it would justify the use of certification data in accident analysis.

Existing data from experimental studies performed by CAMI and Cranfield may help to bridge some of the data gap. Unfortunately, the data that has been published in the literature is not presented in an appropriate form for integration into evacuation models. Typically, published literature summarises qualitative features, perhaps providing an overall measure of performance such as a flow rate or an average time for a specific action. Data in this form is not usually sufficient to satisfy the requirements of model developers. For example, data in the form of distributions of measured quantities would be more valuable. Where appropriate, this data should be re-analysed and presented in a form that will satisfy the model developers. Ideally, in future, when new experiments are undertaken the needs of the model developers should be considered in order to gain the maximum benefit from the experiment.

Cabin crew play a vital role in managing the evacuation process. As such, their behaviour and influence should be included within evacuation models. Analysis of video recordings from 90-second certification trials and transcripts of interviews with cabin crew following accidents has provided insight into this interaction and allowed complex models to be developed. However, more information is required to improve these models, in particular in real accident situations. Analysis of evidence from accidents involving dense irritant smoke suggests that the effectiveness of cabin crew at redirecting is severely reduced in real emergency evacuations [10]. Currently, research at FSEG using the AASK database is attempting to determine the significance of the qualitative differences in cabin crew effectiveness between real emergency evacuations and 90-second certification trials [19,20]. While this is useful, quantitative data is required. This can only be achieved through controlled full-scale experimentation. Such a study could provide useful data for both evacuation models and safety regulators.

Numerous studies have shown that exit hesitation time data is dependent on passenger physical characteristics of age, gender and size. If sufficient data were collected it would be possible to specify the exit hesitation time distribution not as simply a probability distribution but as a probability distribution dependent on these physical attributes. This would require considerably more data then currently exits and a concerted effort between the various experimental facilities to co-operate in the generation of such data.

Finally, with the exception of anecdotal data from accident investigations, very little data is available concerning passenger/crew performance in evacuation situations involving ditching or situations involving cabin ruptures. Experimental data relating to these type of incidents could be collected and used in evacuation models.

6.6.2. Future Data Requirements for VLTA and BWB aircraft

Very Large Transport Aircraft (VLTA) pose considerable challenges to designers, operators and certification authorities. VLTA designs currently being considered are capable of carrying 800+ passengers with interiors consisting of two aisles and two full-length passenger decks. Other more radical concepts consist of a Blended Wing Body (BWB) design, involving one or two decks with possibly four or more aisles. The drive for increased efficiency, passenger capacity and aircraft size is balanced by the need to maintain, and if possible, improve current safety standards. One of the highest safety priorities for aircraft designers and regulators alike concerns the evacuation efficiency of aircraft design. Questions concerning seating arrangement, nature and design of recreational space, the number, design and location of internal staircases, the number, location and type of exits, the number of cabin crew required and the nature of the cabin crew emergency procedures are just some of the issues that need to be addressed. Computer models offer a means of addressing these issues but only if the data requirements of these models can be meet.

The massive increase in passenger capacity and aircraft size being suggested also challenge some of our preconceptions in equipment design and crew emergency procedures. For instance, in order to efficiently complete an evacuation, will it be necessary to extend emergency procedures to the marshalling of those passengers evacuated to the ground? Imagine a situation with 800 passengers on the ground, possibly on one side of the aircraft. What impact will they have on fire fighting and rescue operations? Who should take responsibility for the grounded passengers? Should evacuation procedures be developed that allow passengers to travel between decks before exiting the aircraft? How will crew communicate effectively to control such an evacuation on a single deck and between decks? Will the proximity of multiple emergency slides have a detrimental effect on evacuation efficiency and safety? Can exits be safely spaced further apart than the current arbitrary 60 foot limit [21] What impact will this have on evacuation times and survivability?

If BWB aircraft become a reality, should designs incorporate continuous solid cabin partitions along the length of the aircraft? Should these cabins have cross aisles linking each cabin section? Will it be sufficient to simply have exits in the forward and aft sections of the aircraft? Can the largest exits currently available cope with passenger flow arising from four or five main aisles? Do we need to consider new concepts in exit design, perhaps introducing three or four lane exits? How efficient can a three or four lane exit be in evacuating passengers? Should the main aisles be made wider to accommodate more passengers? How much time is actually required for safe egress from a BWB aircraft? Does the 90-seconds concept have any relevance to VLTA and BWB aircraft?

While there are currently no VLTA flying, the A380 has been labelled a VLTA by some. The A380, while physically the largest passenger aircraft currently planned does not represent a massive increase in passenger capacity, at least for its standard configuration. The standard passenger seating capacity of the A380 is reported to be 550 passengers in a three class configuration [22] however, significantly greater seating capacity options are possible, with 822 passengers being suggested for the single class configuration [23]. This is compared with the B747-400 that carries 416 in a three class configuration with a reported maximum of 660 for the single class configuration [23]. Another feature of the A380 is that it has two passenger decks positioned one on top of the other. This in itself is not unusual or novel as the B747 has flown with an upper deck for many years. While it may be debated whether the new Airbus A380 should be classified as a VLTA, the number of passengers that are seated on the upper deck make the A380 different to existing aircraft.

With the upper deck comes the need to evacuate passengers using the upper deck exits and slides. A feature of upper deck exits is that the exit slides are much longer than those of more ‘standard’ exits. For example, on the B747 the upper deck sill height is **7.8** metres and on the A380 it is set to be **8.1** metres above the ground [23]. One assumption concerning the use of high sill height exits is that passengers would hesitate longer at the upper deck exit before they jumped onto the slide compared to lower height main deck exits. While there is very little data concerning the use of upper deck slides under certification evacuation conditions, what data that is available suggests that this is not the case, and that passenger exit hesitation delays while slightly longer are similar to those of more standard exits [14,24]. Clearly, more research in the form of component testing is required to generate the required data (see section 2.1).

In addition to higher sill heights, longer exit slides and large numbers of passengers located on upper decks, VLTA double deck aircraft can possess one or more staircases. Again, in itself this is not a new concept as the B747 has flown for many years with a staircase connecting the two decks. While evacuation procedures for VLTA may not require the use of the staircase(s) in order to pass an evacuation certification trial, it is desirable that staircase design be appropriate for evacuation situations. Emergency evacuation scenarios may develop where it is necessary or desirable to evacuate all or some passengers down the stairs and out the main deck exits rather than out the upper deck exits. While less likely, accident situations may also develop where it is necessary to move some passengers to the upper deck and out the upper exits. While this may not be a problem for existing aircraft, the sheer number of passengers located on the upper deck of VLTA configurations makes this an issue worth investigating.

Currently, the CFR 25 aviation regulations are silent on the issue of staircase design [3,4]. This omission could lead to the development of sub-optimal conditions during an evacuation should the staircase be needed as a means of escape. As an example, the height of a stair riser and the depth of a stair tread are known to be important factors in determining the ease of use and efficiency of staircase design. Additionally, the requirement for handrails that separate a wide staircase into lanes has long been recognised as essential in building and marine regulations [25,26]. It is recognised that central handrails enable passengers to use the entire width of the staircase during an emergency evacuation as opposed to 'hugging' the walls close to the outer handrails. Handrails are mandatory in building codes as they provide support to occupants and serve as guides for people whose vision may be impaired due to smoke and/or lighting failure [26]. In addition, within building codes it is recognised that to be effective the handrails must be within reach of staircase users [26]. Therefore building codes mandate that handrails must be within 30 inches of the "natural path of travel" [26]. Onboard marine vessels the requirement for handrails is of even more importance as marine vessels are subject to dynamic and static changes in pitch and roll. Similar situations could develop on aircraft that have crashed and have gear failure.

As previously mentioned (see Sections 6.5.3.1.1 and 2.1) aircraft staircase design has been studied in previous research undertaken by the FAA Civil Aerospace Medical Institute (CAMI) in 1978. The staircases that were investigated were very narrow having an effective width of 20 inches. As such the passengers evacuated in single file and used the handrails extensively. Unfortunately, the staircase width used in these experiments is simply not relevant for staircases that are expected to accommodate two or more passengers simultaneously. While there are no specific rules addressing staircases in the CFR, special conditions were specified for the certification of the B747. These conditions do not specify staircase design constraints but state objectives that should be meet by good staircase design, e.g. stairs must be safe, must work in adverse attitude conditions etc.

6.7. The use of Evacuation Models for Certification Applications

Before computer models can reliably be used for certification applications they must undergo a range of validation demonstrations. While 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.

The success of at least some aircraft evacuation models (see section 6.4.2) in predicting the outcome of previous 90-second certification trials are compelling arguments of the suitability of these models for evacuation certification applications - at least for derivative aircraft. For aircraft involving truly 'new' features 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 does 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.

However, it is not sufficient to simply replace full-scale testing of aircraft with a combination of computer modelling and component testing. While this may make testing the aircraft a safer and more efficient process, can we also make the aircraft itself safer by design? If we are to rise to this challenge it is essential that we begin to question some of our current preconceptions concerning certification.

Evacuation models have the capability of examining many different types of evacuation scenario. 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? The selection of suitable evacuation scenarios could be guided through analysis of past accident data [34]. For example, the analysis of past accidents can suggest which exit combination is most likely to occur. This could be used to assist in selecting the number and location of exits to assess in the certification trial.

Furthermore, unlike full-scale testing, evacuation models allow 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 should be tested by computer simulation.

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? For a particular scenario should the requirement stipulate that ***every*** simulation be sub-90 seconds? Or should the distribution mean or the 95 percentile result be sub-90 seconds? In the hypothetical example provided (see Figure 15), 950 of the 1000 simulations (i.e. 95%) produced an evacuation time less than 90 seconds. Should this aircraft configuration be deemed to pass or fail the certification criteria?

An interesting example of this dilemma was shown during the recent airEXODUS validation exercise [29]. In this example, one of aircraft achieved an actual certification performance of 83.7 seconds with a mean airEXODUS predicted evacuation time of 82.7 seconds. While 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, the airEXODUS analysis [29] suggests that of the 1000 simulations, three or 0.3% are predicted to marginally fail the certification requirement. If the mean rule (i.e. 50% less than 90 seconds) 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.

Any aircraft configuration will produce a range of evacuation times over a number of tests, some of which may well be over the 90 seconds. Under the current 'make or break' single test regime, a single performance result is selected from this '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 second 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 could be repeated. It has been argued by some that to achieve parity with the current certification process, 100% of the generated simulations should produce times less than 90 seconds to pass. Clearly, this would not achieve parity with the current certification process.

For those who which 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 modelling analysis. As part of this methodology it would still be necessary to first generate the evacuation time distribution using many repeat simulations. This would generate the probability space of possible evacuation times for the aircraft configuration under the selected certification scenario. From this probability distribution a single evacuation time would be selected at random and deemed to be the certification performance of the aircraft. This in essence is equivalent to the current practice of performing only a single trial for certification. 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 modelling 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 re-define 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 endeavouring to produce a more meaningful measure of aircraft evacuation performance.

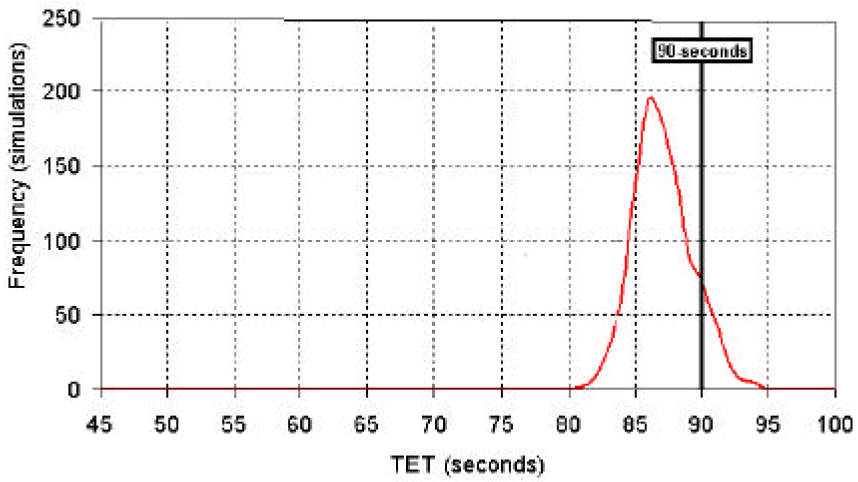


Figure 15: Numerically generated evacuation time distribution (frequency Vs evacuation time) for a particular scenario for a hypothetical aircraft configuration.

This raises the question, does the "magic number" 90 seconds have any actual meaning under these circumstances? 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 pre-defined acceptable amount of time. In the U.K. for public buildings this turns out to be the "magic number" 2.5 minutes. 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 while the RSET may be the time required for the occupants to vacate the structure. Put simply, the ASET must be greater than the RSET. 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 evacuation and fire models are being used to assist in the determination of both the ASET and the RSET. 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 half way 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 second "magic number" used in the aviation industry while the RSET can be determined by computer simulation [31]. 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 are prescribed in a similar way to the current 90 second certification trial. The ship design must pass all four benchmark scenarios in order 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 should be considered for aviation.

Other disciplines such as the building and maritime industries accept computer based simulations as part of the certification process. As indicated in section 6.4.2, 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 [31]. This documentation is intended to demonstrate the credibility and appropriateness of the approach adopted and furthermore allow easy verification and reproduction of the submitted results. These requirements include the specification of:

- the variables used in the model to describe the dynamics, e.g. walking speed of each person;
- the functional relation between the parameters and the variables;
- the type of update used within the model;
- 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;
- 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 should require a similar level of documentation.

6.8. Conclusions

While some 30 evacuation models have been developed for the building industry, to date, there have only been seven models proposed for the aviation industry. It should be noted that building evacuation models cannot easily and reliably be used for aviation applications. This is due in part to the unique behaviour exhibited by passengers and crew in aircraft evacuations and key structural features that differentiate aircraft from buildings. Of these seven models, one is believed to have not gone beyond the concept stage and another was developed in the early 70's and is no longer in use. Of the remaining five models, development work appears to have stopped on the Gourary and Arcevac models with the current status of Macey's and Robbin's model being uncertain as they formed part of university students research dissertations. Of these models, only airEXODUS appears to be currently still receiving development attention. Furthermore, of these five models, only airEXODUS appears to make use of fundamental human performance data to characterise the capabilities of passengers. In addition, while all the models have undergone some form of validation/verification, the airEXODUS model has the most thorough battery of validation evidence and it is also in line with validation protocols suggested in other industries.

It has been suggested in this report that evacuation models offer a possible alternative to the current practice of performing a single live evacuation demonstration. While 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. In order 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 certification simulation, much data already exists and has been analysed while much more data is available and yet to be analysed. However, more data is required to and a concerted effort must be undertaken to collect the required data.

The success of at least some aircraft evacuation models in predicting the outcome of previous 90-second certification trials are compelling arguments of the suitability of these models for evacuation certification applications - at least for derivative aircraft. For aircraft involving truly 'new' features it is expected that evacuation models in conjunction with component testing of the new feature will be necessary. For the next generation of VLA, one of the areas requiring this form of collaboration concerns passenger exit hesitation times (or exit flow rates) at upper deck exits.

Furthermore, the challenge facing all the stake holders involved in aircraft certification i.e. regulators, approval authorities, accident investigators, manufacturers, airlines, unions, and ultimately the travelling public, is to develop a better understanding of the modelling technology being developed and with that understanding specify relevant design 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 stake holders have a good appreciation of the current certification process and its limitations.

Finally, computer based aircraft evacuation models – together with reliable data - have the potential to be used for aircraft certification and provide manufacturers, operators and regulators a means of assessing novel designs, procedures and accident scenarios associated with VLT and BWB aircraft.

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7. APPENDIX B

EXECUTIVE SUMMARY

Very Large Transport Aircraft (VLTA) pose considerable challenges to designers, operators and certification authorities. Questions concerning seating arrangement, nature and design of recreational space, the number, design and location of internal staircases, the number of cabin crew required and the nature of the cabin crew emergency procedures are just some of the issues that need to be addressed. In this report we investigate issues associated with staircase design and cabin crew procedures using the airEXODUS evacuation model. A hypothetical VLTA identified as the UOGXXX, involving two decks and a passenger load of 580 passengers with a single main staircase is defined within the airEXODUS model.
Four basic evacuation scenarios are examined namely:

- Scenario 1: All exits on BOTH decks
- Scenario 2: 90-second exit configuration
- Scenario 3a: ONLY lower deck exits
- Scenario 3b: Crew rotate passengers
- Scenario 3c: Crew redirect passengers
- Scenario 3d: Scenarios involving additional stair lanes
- Scenario 3e: Scenarios involving stair location
- Scenario 4: Limited passenger movement between decks

While airEXODUS has the ability to represent "extreme" passenger behaviour of the type reported in actual aviation accidents, such as seat jumping, this type of behaviour is not included in these simulations. All the cases considered here are run under certification type evacuation conditions involving:

(i) Assertive cabin crew located at each Type-A exit,

(ii) Orderly passenger behaviour of the type found in certification evacuations,

(iii) Each exit being made ready in a representative time derived from past relevant certification tests.

All of the modelled scenarios that are presented within this report are simulated under 90-second certification trial conditions and are thus representative of controlled physical experiments involving real passengers. Passenger performance and behaviour on stairs is based on data gathered from the marine and building environments. This assumes that the staircase design is similar to that found in buildings. A new feature of airEXODUS known as the Active Cabin Crew Management (ACCM) procedure is employed during some of the simulations described in this report to simulate crew management of the evacuation process.

7.1. Introduction

Very Large Transport Aircraft (VLTA) pose considerable challenges to designers, operators and certification authorities. VLTA designs currently being considered are capable of carrying 800+ passengers with interiors consisting of two aisles and two full-length passenger decks. The drive for increased efficiency, passenger capacity and aircraft size is balanced by the need to maintain, and if possible, improve current safety standards. One of the highest safety priorities for aircraft designers and regulators alike concerns the evacuation efficiency of aircraft design. Questions concerning seating arrangement, nature and design of recreational space, the number, design and location of internal staircases, the number, location and type of exits, the number of cabin crew required and the nature of the cabin crew emergency procedures are just some of the issues that need to be addressed.

The massive increase in passenger capacity and aircraft size being suggested also challenge some of our preconceptions in equipment design and crew emergency procedures. For instance, in order to efficiently complete an evacuation, will it be necessary to extend emergency procedures to the marshalling of those passengers evacuated to the ground? Imagine a situation with 800 passengers on the ground, possibly on one side of the aircraft. What impact will they have on fire fighting and rescue operations? Who should take responsibility for the grounded passengers? Should evacuation procedures be developed that allow passengers to travel between decks before exiting the aircraft? How will crew communicate effectively to control such an evacuation on a single deck and between decks? Will the proximity of multiple emergency slides have a detrimental effect on evacuation efficiency and safety? Can exits be safely spaced further apart than the current arbitrary 60 foot limit [1]? What impact will this have on evacuation times and survivability?

Quite apart from questions of emergency evacuation, issues concerning the appropriateness of VLTA designs in allowing the rapid and efficient movement of passengers during boarding and disembarkation are an additional essential design consideration. Furthermore, these requirements may potentially conflict with the requirements for emergency egress. Ultimately, the practical limits on passenger capacity are not based on technological constraints concerned with aircraft aerodynamics but on the ability to evacuate the entire complement of passengers within agreed safety limits.

While there are currently no VLTA flying, the A380 has been labelled a VLTA by some. The A380, while physically the largest passenger aircraft currently planned does not represent a massive increase in passenger capacity, at least for its standard configuration. The standard passenger seating capacity of the A380 is reported to be 550 passengers in a three class configuration [22] however, significantly greater seating capacity options are possible, with 822 passengers being suggested for the single class configuration [23]. This is compared with the B747-400 that carries 416 in a three class configuration with a reported maximum of 660 for the single class configuration [23]. Another feature of the A380 is that it has two passenger decks positioned one on top of the other. This in itself is not unusual or novel as the B747 has flown with an upper deck for many years. While it may be debated whether the new Airbus A380 should be classified as a VLTA, the number of passengers that are seated on the upper deck make the A380 different to existing aircraft.

With the upper deck comes the need to evacuate passengers using the upper deck exits and slides. A feature of upper deck exits is that the exit slides are much longer than those of more ‘standard’ exits. For example, on the B747 the upper deck sill height is **7.8** metres and on the A380 it is set to be **7.9** metres above the ground [195]. One assumption concerning the use of high sill height exits is that passengers would hesitate longer at the upper deck exit before they jumped onto the slide compared to lower height main deck exits. While there is very little data concerning the use of upper deck slides under certification evacuation conditions, what data that is available suggests that this is not the case, and that passenger exit hesitation delays while slightly longer are similar to those of more standard exits [24,187]. Clearly, more research in the form of component testing is required to generate the required data.

In addition to higher sill heights, longer exit slides and large numbers of passengers located on upper decks, VLTA double deck aircraft can possess one or more staircases. Again, in itself this is not a new concept as the B747 has flown for many years with a staircase connecting the two decks. While evacuation procedures for VLTA may not require the use of the staircase(s) in order to pass an evacuation certification trial, it is desirable that staircase design be appropriate for evacuation situations. Emergency evacuation scenarios may develop where it is necessary or desirable to evacuate all or some passengers down the stairs and out the main deck exits rather than out the upper deck exits. While less likely, accident situations may also develop where it is necessary to move some passengers to the upper deck and out the upper exits. While this may not be a problem for existing aircraft, the sheer number of passengers located on the upper deck of VLTA configurations makes this an issue worth investigating.

Currently, the CFR 25 aviation regulations are silent on the issue of staircase design [198]. This omission could lead to the development of sub-optimal conditions during an evacuation should the staircase be needed as a means of escape. As an example, the height of a stair riser and the depth of a stair treed are known to be important factors in determining the ease of use and efficiency of staircase design. Additionally, the requirement for handrails that separate a wide staircase into lanes has long been recognised as essential in building and marine regulations [25,26]. It is recognised that central handrails enable passengers to use the entire width of the staircase during an emergency evacuation as opposed to 'hugging' the walls close to the outer handrails. Handrails are mandatory in building codes as they provide support to occupants and serve as guides for people whose vision may be impaired due to smoke and/or lighting failure [26]. In addition, within building codes it is recognised that to be effective the handrails must be within reach of staircase users [26]. Therefore building codes mandate that handrails must be within 30 inches of the "natural path of travel" [26]. Onboard marine vessels the requirement for handrails is of even more importance as marine vessels are subject to dynamic and static changes in pitch and roll. Similar situations could develop on aircraft that have crashed and have gear failure.

Aircraft staircase design has been studied in previous research undertaken by the FAA Civil Aerospace Medical Institute (CAMI) in 1978. This involved a series of trials to determine the movement rate of passengers through spiral and straight staircases with and without handrails under various pitch and roll conditions [201]. The staircases that were investigated were very narrow having an effective width of 20 inches. As such the passengers evacuated in single file and used the handrails extensively. Unfortunately, the staircase width used in these experiments is simply not relevant for staircases that are expected to accommodate two or more passengers simultaneously. While there are no specific rules addressing staircases in the CFR, special conditions were specified for the certification of the B747. These conditions do not specify staircase design constraints but state objectives that should be meet by good staircase design, e.g. stairs must be safe, must work in adverse attitude conditions etc.

Computer based aircraft evacuation models – together with reliable data - have the potential to address all of these issues and provide manufacturers, operators and regulators a means of assessing novel designs, procedures and accident scenarios associated with VLTA. In a previous publication, the authors demonstrated how aircraft evacuation models could be used to investigate the rationale behind existing prescriptive rules associated with exit separation, the so-called 60-foot rule [21]. In this paper we will demonstrate how computer based evacuation models can be used to investigate issues associated with VLTA configuration and crew procedures.

7.2. The airEXODUS Model

7.2.1. EXODUS Overview

EXODUS is 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. Today, the family of models consists of buildingEXODUS **[**61**,**62**,**63,64**]**, maritimeEXODUS [65,66] and airEXODUS [21,67,27,28,70,64,71] for the built, maritime and aviation environments respectively.

airEXODUS is designed for applications in the aviation industry including, aircraft design, compliance with 90-second certification requirements, crew training, development of crew procedures, resolution of operational issues and accident investigation. The airEXODUS model and its validation has been described previously [21,67,27,28,70,64,71] and so only the components relevant to this study will be briefly described here.

The EXODUS software takes into consideration people-people, people-fire and people-structure interactions. It comprises five core interacting sub-models: the **Passenger, Movement, Behaviour, Toxicity and Hazard** sub-models (see Figure 16). The software describing these sub-models is rule-based, the progressive motion and behaviour 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. Each of these components will be briefly described in turn.

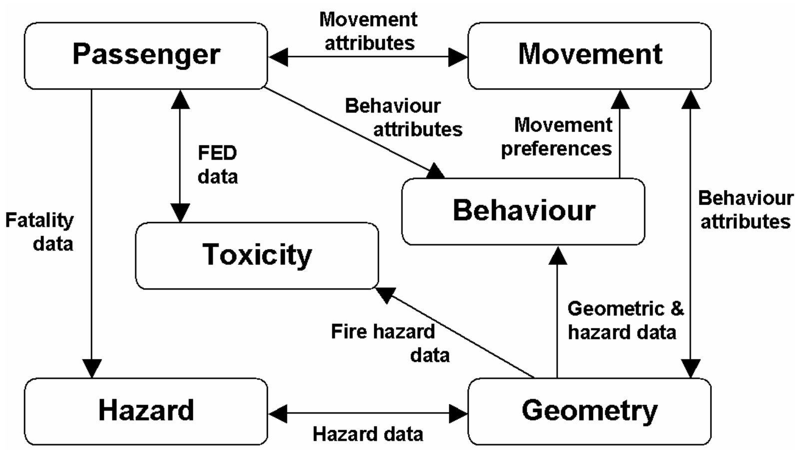

Figure 16: EXODUS Submodel Interacton

7.2.1.1. The GEOMETRY representation

The **GEOMETRY** of the enclosure 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 0.5m intervals. The nodes are then linked by a system of arcs. Each node represents a region of space typically occupied by a single passenger.

7.2.1.2. The MOVEMENT submodel

The **MOVEMENT SUBMODEL** controls the physical movement of individual passengers from their current position to the most suitable neighbouring location, or supervises the waiting period if one does not exist. The movement may involve such behaviour as overtaking, side stepping, or other evasive actions.

7.2.1.3. The PASSENGER submodel

The **PASSENGER SUBMODEL** describes an individual as a collection of defining attributes and variables such as name, gender, age, maximum unhindered fast walking speed, maximum unhindered walking speed, response time, agility, etc. Of particular interest for this report is the speed of passengers on stairs. This has been defined according to the age and gender of the passenger and whether the passenger is ascending or descending the stairs. The data is based on human performance data derived from building studies [190]. As for the aisle speeds, this is defined as the maximum unhindered stair speeds, which can be affected by congestion etc. Each passenger can be defined as a unique individual with their own set of defining parameters. Cabin crewmembers require additional attributes such as, range of effectiveness of vocal commands, assertiveness at using voice 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 while others are dynamic, changing as a result of inputs from the other submodels. Passengers with disabilities may be represented by limiting these attributes.

7.2.1.4. The HAZARD submodel

The **HAZARD SUBMODEL** controls the atmospheric and physical environment. It distributes pre-determined fire hazards such as heat, radiation, smoke and toxic fire gases throughout the atmosphere and controls the opening and closing times of exits.

7.2.1.5. The TOXICITY submodel

The **TOXICITY SUBMODEL** determines the effects on an individual exposed to toxic products distributed by the hazard submodel. These effects are communicated to the behaviour submodel which, in turn, feeds through to the movement of the individual.

7.2.1.6. The BEHAVIOUR submodel

The **BEHAVIOUR 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 behaviour submodel functions on two levels, global and local. The local behaviour determines an individual's response to the local situation e.g. jump over seats, wait in queue, etc while the global behaviour represents the overall strategy employed by the individual. This may include such behaviour as, exit via the nearest serviceable exit, exit via most familiar exit or exit via their allocated exit. In the most recent research version of the software, cabin crewmembers can be identified and their behaviour specified to represent crew procedures. In this version, cabin crewmembers may perform specified duties during an evacuation such as opening exits, halting passenger flow, redirecting passengers to specific exits, continuous cabin flow monitoring with appropriate redirection, etc.

7.2.2. Passenger Behaviour

While airEXODUS has the ability to represent "extreme" passenger behaviour of the type reported in actual aviation accidents [213, 214], such as seat jumping, this type of behaviour is not included in these simulations. All the cases considered here are run under certification type evacuation conditions involving:

(iv) Assertive cabin crew located at each Type-A exit,
(v) Orderly passenger behaviour of the type found in certification evacuations,
(vi) Each exit being made ready in a representative time derived from past relevant certification tests.

All of the modelled scenarios that are presented within this paper were simulated under 90-second certification trial conditions and are thus representative of controlled physical experiments involving real passengers. Passenger performance and behaviour on stairs is based on data gathered from the marine and building environments (see section 7.3). This assumes that the staircase design is similar to that found in buildings.

7.2.3. Cabin Crew Behaviour

Previous research suggests that there is a relationship between the assertiveness of cabin crew members at exits and the achieved exit flow rates [24,187,215]. To reflect this passenger Exit Delay Time distributions have been determined to represent the varied levels of cabin crewmember assertiveness and their impact upon the flow rates through exits. The 'assertive' passenger Exit Delay Time distribution is used exclusively for this study.

A new feature of airEXODUS known as the Active Cabin Crew Management (ACCM) procedure is employed during some of the simulations described in this paper. While in the standard version of airEXODUS crew initiated actions were achieved implicitly through the setting of model parameters, using the ACCM system, the procedures are explicitly modelled. Thus the cabin crewmember is modelled as are their actions and the passengers response to those actions.

Cabin management procedures are usually employed by cabin crew during certification trials [216,217] and during real emergency evacuation situations [218,78,220,221,222]. These procedures may involve crew instigated exit by-pass or other passenger re-direction strategies. In applying these techniques the crew are attempting to either achieve a more efficient use of exits thereby reducing the overall evacuation time, or direct passengers away from a potentially dangerous cabin section. When attempting to reduce the overall evacuation time, crew are assessing the situation in their cabin zone and deciding when to redirect passengers onto another cabin zone or nearby exit.

In reality, the decisions made by the crew will be based on the information that they have on conditions around their exit and what they may know about other exits. The knowledge that the crew has of cabin conditions can be restricted due to line of sight, congestion, visibility in smoke, noise, etc. Alternatively, it may be enhanced by technical means such as conventional communication systems or novel new devices such as crew head-set communication systems, door visual display systems, etc. A feature of the ACCM procedures within airEXODUS is that the decision making capability of the crew can be restricted according to the prevailing conditions and the equipment at their disposal. The crewmember can also be given a radius of effectiveness. This dictates the region over which the commands made by the crewmember will be effective.

During certification evacuations, passengers are more compliant and are thus more likely to follow a crew command to redirect to another exit while in real situations this may be somewhat more difficult to achieve as passengers are more likely to be concerned with their own self interest. Both these situations can be represented within airEXODUS using the ACCM procedures. The first mode of operation is akin to 90-second certification trials in which passengers are generally compliant to all crew commands. The second mode attempts to model real emergency evacuations in which passengers are less compliant. In airEXODUS, when modelling certification evacuations, passengers are made to be compliant and thus follow all instructions issued by cabin crew.

In the simulations described in this paper, cabin crewmembers have been given complete information sets with respect to events within the aircraft cabin. As a consequence the procedures that are employed within these simulations should be considered as optimal or ideal.

7.2.4. Certification Data used in airEXODUS

airEXODUS makes use of 90-second certification data [24] to specify certain model parameters [24]. In the work presented here, the most important parameter is the passenger Exit Delay Time. This time represents 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 out-stretched 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 [21,24,224].

For the purposes of this study, data corresponding to main deck Type-A exits with assertive cabin crew is used for the main deck. Data for upper deck exits of the type likely to be employed on VLTA is scarce. At present airEXODUS makes use of 90-second certification trial data from the upper deck of a B747 [223].

Another key parameter in airEXODUS is the Exit Ready Time. This attribute represents the time required by a crewmember or passenger to render the exit escape system ready for use. The Exit Ready Time attribute was uniformly set at **14** seconds for every case considered within this report. Thus the total exit preparation time for each of the exits was set at **14** seconds. The exit preparation time used in this paper is considered conservative but not atypical of the exit preparation times required for Type-A exits.

7.3. VLTA configuration Issues examined using airEXODUS

Here we demonstrate how evacuation models may be used to examine configuration issues associated with VLTA. Several scenarios will be considered, namely the use of all exits on both decks, the use of half the normally available exits as in a certification demonstration trial and the use of all the exits on the main deck. The last case will require the upper deck passengers to make use of the main staircase during the evacuation.

7.3.1. VLTA Test Aircraft Configuration

To demonstrate the use of airEXODUS a hypothetical VLTA was designed by the authors. The aircraft – designated the UOGXXX - has two decks and a capacity of 580 passengers in a three-class configuration. The upper deck seats 236 passengers in first and business class while the lower deck seats 344 passengers in first and economy class (see Figure 17).

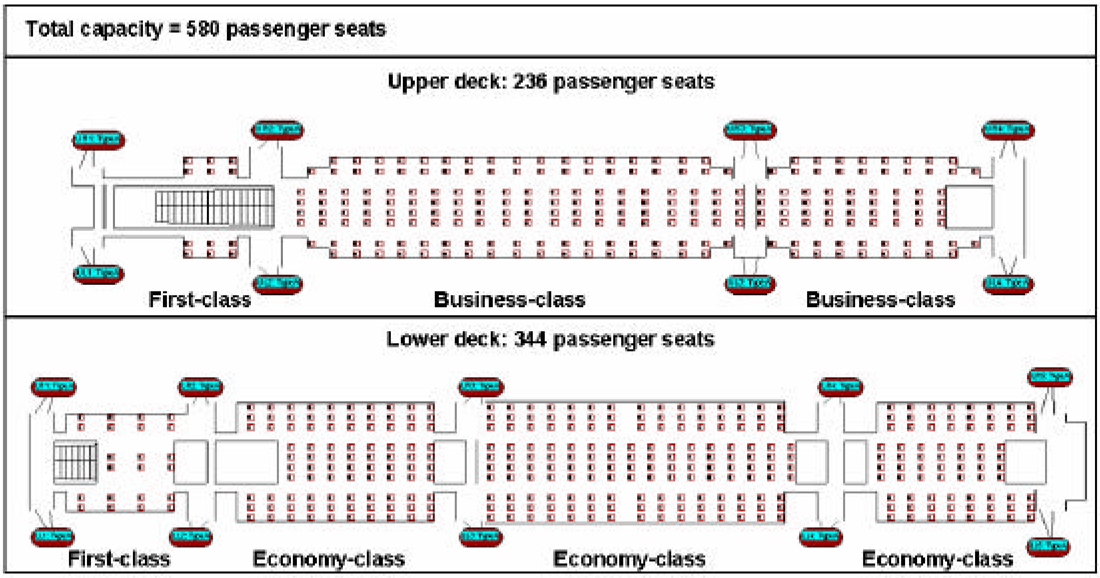

Figure 17: A schematic of the UOGXXX VLTA

The UOGXXX has nine pairs of Type A exits, four on the upper deck and five on the lower deck. This is in excess of the six exit pairs that would be required to simply cater for the number of passengers [198]. The larger number of exits result from other regulations within CFR 25 that dictate that exits are required at each end of the cabin section and that the distance between any exit pair was not in excess of 60ft. Furthermore, the authors wished to avoid overwing upper deck exits and mixing different exit types. A schematic of the aircraft design is shown as Figure 17 .
A staircase was positioned towards the front of the aircraft so as to assist in the expeditious boarding and disembarking of passengers. Other considerations included the desire not to split a class, maintaining a three class layout and causing minimal disruption to the first class passengers. The staircase was sufficiently wide to accommodate two passengers side by side separated by a central handrail. The staircase has dimensions typical of that found in buildings. Within airEXODUS, the behaviour of the passengers on the staircase is based on that found in buildings, where the speed of passengers is dependent on the age and gender of the passenger and whether they are travelling up or down the stair.

7.3.2. Population Specification

The population complies with FAR requirements for certification testing [225]. Passengers defined in airEXODUS are created using the 90-second Population function available in the software. This function generates the required numbers of passengers according to the specified mix (in terms of age and gender) as set out in FAR [191].

Table 7: Core attribute ranges for the 90-second populations used in airEXODUS simulations

Group	Attribute	Min	Max
Males 18-50	Drive	10.0	15.00
	Walk (m/s)	0.5	0.60
	Fast Walk (m/s)	1.0	1.2
	Stair Up (m/s)	0.63	0.63
	Stair Down (m/s)	0.86	0.86
	Response Time (s)	0.0	5.0
Males 50-60	Drive	6.0	12.0
	Walk (m/s)	0.35	0.55
	Fast Walk (m/s)	0.70	1.10
	Stair Up (m/s)	0.51	0.51

	Stair Down (m/s)	0.67	0.67
	Response Time (s)	4.00	7.00
Females 18-50	Drive	5.00	13.00
	Walk (m/s)	0.45	0.60
	Fast Walk (m/s)	0.90	1.20
	Stair Up (m/s)	0.59	0.59
	Stair Down (m/s)	0.67	0.67
	Response Time (s)	0.00	6.00
Females 50-60	Drive	5.00	8.00
	Walk (m/s)	0.25	0.45
	Fast Walk (m/s)	0.50	0.90
	Stair Up (m/s)	0.49	0.49
	Stair Down (m/s)	0.60	0.60
	Response Time (s)	5.00	8.00

Table 8: Core passenger attribute ranges used in simulations presented in this report

Attribute	Min	Max	Mean
Drive	1.19	14.99	9.82
Walk (m/s)	0.26	0.60	0.49
Fast Walk (m/s)	0.52	1.20	0.99
Stair Up (m/s)	0.49	0.63	0.57
Stair Down (m/s)	0.60	0.86	0.73
Response Time (s)	0.02	8.00	3.93

In airEXODUS, simply specifying the age and gender of each passenger is not sufficient. Each person has 21 defining attributes, each of which must be assigned a value. The population tools in airEXODUS allow a range for each attribute to be specified, so that when a person is created, each attribute is assigned a random value between the limits set. The 90-second Population consists of four population groups: Males aged 18-50, Males aged 50-60, Females aged 18-50 and Females aged 50-60. The core parameters for these groups are distributed as indicated in Table 7. In addition to those parameters shown in Table 4, the Patience attribute was set at a very large value for all the simulations in order to model a compliant (non-competitive) population. Passengers when attributed with infinite patience will always wait patiently in queues whilst moving religiously towards there nearest exit. Listed in Table 8 is the range of core attributes generated for the passenger populations.

7.3.3. Relevant airEXODUS parameters

Several airEXODUS parameters will be presented within this study. These are; Personal Elapsed Time (PET), Total Evacuation Time (TET), Cumulative Wait Time (CWT), Exit Flow Rates, Distance and OPS (see [21,61,27] for details).
The TET is a measure of the evacuation time for the aircraft. It is measured from the start of the evacuation to when the last passenger exits the aircraft. A single TET is determined for each evacuation simulation. Perhaps of more interest to an individual passenger is the PET. The PET is a measure of an individual's evacuation time. It is measured from the start of the evacuation to when the passenger has exited the aircraft. A PET is determined for each passenger in the evacuation simulation. The Response Time is the time a passenger takes to respond to the call to evacuate, release their seat restraint and stand. A Distance is calculated for each passenger. The Distance parameter records the total distance that each passenger had to travel during the evacuation.
The CWT measures the total amount of time a passenger has spent in congestion. This is measured after the passenger has completed their Response Time, i.e. unbuckled seat belts and stood up, to when the passenger has exited the aircraft. This can include time spent in the seat row attempting to get into the aisle, time spent stationary in the aisle and time spent queuing at the exit. A CWT is determined for each passenger in the evacuation simulation.

The exit flow rate measure gives an indication of the performance of exits during an evacuation. It can be calculated for each exit by dividing the number of passengers that used the exit by the duration of the flow. An exit flow rate represents an *average* flow rate for the entire duration of passenger flow.
As a measure of optimal performance FSEG have developed a statistic known as the OPS or Optimal Performance Statistic. The OPS measure has been described in detail in previous papers [61,27]. The OPS can be calculated for each evacuation, providing a measure of the degree of performance. The OPS is defined as follows:

$$OPS = \frac{\sum_{i=1}^{n} TET - EET_i}{(n-1) * TET}$$

Equation 1

n = number of exits used in the evacuation,
$\boldsymbol{EET_n}$ = Exit Evacuation Time (time last pax out) of Exit ***n*** (seconds),
TET = Total Evacuation Time (seconds) i.e. max[***EET***].

While it is unlikely that an aircraft will achieve an OPS = 0, near optimal performance will be marked by very low values of OPS. Selecting an acceptable value for OPS is somewhat arbitrary. For the purposes of this report we will consider OPS values of 0.1 or less as being optimal.
The Off-Time (for Type-A exits) is the time required for the passenger to reach the ground once they have mounted the slide. Like the passenger Exit Delay Time, this is derived from certification data. However, in the present study, this is ignored. Thus the evacuation times represent the time out of the aircraft, not the on-ground times. If on-ground times are desired, a suitable slide time can be added to the TET.

7.3.4. Defining airEXODUS scenarios

All of the modelled scenarios that are presented within this paper were simulated under 90-second certification trial conditions and are thus representative of controlled physical experiments involving real passengers. Whilst airEXODUS has the capability of modelling more extreme behaviours of the type witnessed in real emergency evacuations they will not be activated in these scenarios. In addition, in all the cases examined the "off-times" have not been included. To find the on-ground time it is necessary to add an appropriate slide time.
The scenarios considered in this section examine different combinations of exit availability and the impact that they have upon total evacuation time, exit flow rates and travel distances. In addition the type of cabin crewmember communication and procedures necessary to ensure an optimal evacuation are examined.
In total four main scenarios are considered. Scenario 1 investigates a precautionary evacuation in which all of the exits on the aircraft are available for use during the evacuation. This scenario provides an indication of the best possible evacuation time for the proposed aircraft design.
Scenario 2 investigates the standard 90-seconds scenario, in which only one side of the aircraft's exits are available for evacuation. This case provides an indication of how the UOGXXX will perform in a standard 90-second certification trial.
Scenario 3 represents a variation of the precautionary evacuation in which all passengers use the main deck exits. Thus passengers and crew from the upper deck are required to descend the staircase that joins the two decks. Two variations of this scenario, 3b and 3c are also investigated in which cabin crew attempt to optimise the evacuation. Scenario 3d investigates the impact that widening the main staircase has on the performance of the evacuation, while scenario 3e considers moving the location of the staircase. The final scenario investigates the repercussions of sending some passengers from the lower deck to the upper deck.

Table 9: Summary of exit availability in each of the four scenarios

	Type-A exit pair availability								
	Upper 1	Upper 2	**Upper 3**	**Upper 4**	**Lower 1**	**Lower 2**	**Lower 3**	**Lower 4**	**Lower 5**
Scenario 1	Left + Right	Left + Right	Left + Right	Left + Right	Left + Right	Left + Right	Left + Right	Left + Right	Left + Right
Scenario 2	Right Only	Right Only	Right Only	Right Only	Right Only	Right Only	Right Only	Right Only	Right Only
Scenario 3a	None	None	None	None	Left + Right	Left + Right	Left + Right	Left + Right	Left + Right
Scenario 3b	As 3a with intelligent ACCM at the base of the stairs								
Scenario 3c	As 3a with crew alternating redirection at base of the stairs								
Scenario 3d	As 3b and 3c with increased stair width								
Scenario 3e	As 3d with relocation of stair case								
Scenario 4a	None	None	Left + Right	Left + Right	None	None	None	Left + Right	Left + Right
Scenario 4b	As 4a with partial movement between decks controlled by ACCM on the lower deck								

Finally, airEXODUS is stochastic in nature. This means that every time a simulation is repeated a slightly different evacuation time will result, as the individual passengers and crewmembers are unlikely to exactly repeat their actions. In addition, as the passenger Exit Delay Time is randomly attributed according to the specified distribution, passengers will not necessarily incur the same Exit Delay Time on exiting the aircraft in subsequent simulations. For this reason, it is necessary to repeat a simulation numerous times in order to generate a distribution of results (see Figure 18). Each simulation case detailed in this paper has been run 1000 times by airEXODUS to capture stochastic variations.

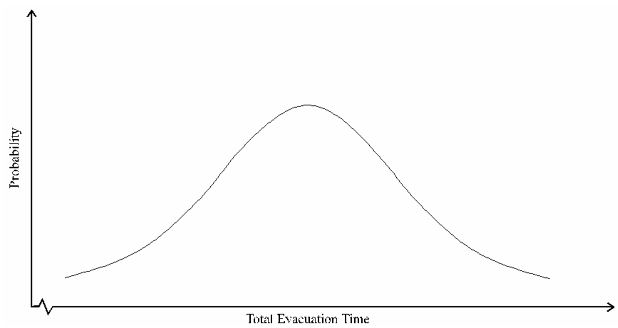

Figure 18: Hypothetical distribution of the total evacuation time for a given structure/population/environment combination

7.3.5. Scenario 1: Precautionary evacuation using all available exits

Scenario 1 simulated a precautionary evacuation in which all of the exits were available. These simulations generated an average total evacuation time of **46.8** [44.5-56.9] seconds, with an average personal evacuation time of **25.0** seconds (see Table 10). In all of the simulations evacuation is achieved in a relatively short amount period of time (see Figure 19). Furthermore, all of the simulations that were generated by the model produce evacuation times that are well within the FAR requirement (i.e. 90 seconds).

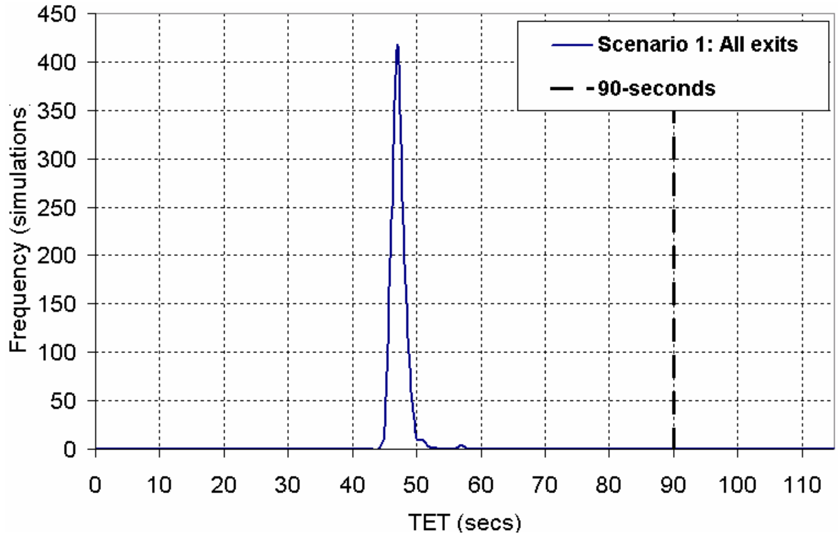

Figure 19: airEXODUS generated frequency distribution of TETs for Scenario 1

Whilst the final outcome of the evacuation is important, another measure of evacuation is provided by cumulative exit performance. This is a measure of the total number of passengers to exit the aircraft in each second of the evacuation.

In airEXODUS the personal evacuation time (PET) of each passenger is recorded. From this the cumulative number of passengers who have exited the aircraft in each second of the evacuation can be determined. This process can be repeated for each of the repeat simulations. For the series of simulations a simulation envelope can be defined by taking the minimum and maximum number of passengers who have exited the aircraft in each second. For the simulations considered here, each case was repeated 1000 times. The simulation envelope for each scenario represents the minimum and maximum from 1000 simulations. Thus, each of the 1000 repeat simulations will produce a curve that falls within the envelope. In addition, the median of the 1000 airEXODUS simulations is plotted at every second of the simulation.

As can be seen in Figure 20 , initially there is a period during which no passengers evacuate whilst the doors are readied for use. This is typically followed by a short period during which the passenger flow is established. This is marked by the rapid initial increase in gradient at around 14 seconds. Very quickly the exits are at near maximum flow capacity, indicate in Figure 20 by a near constant positive gradient. This state persists for the majority of the evacuation. Near the end of the evacuation, when the supply of passengers to exits begins to diminish the gradient begins tail off. The flow terminates when there are no more passengers to evacuate. It is apparent that the majority of passengers evacuate the aircraft in a very short period of time.

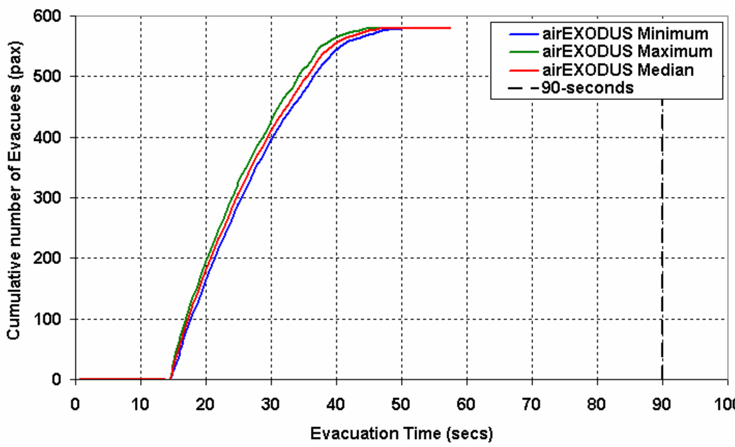

Figure 20: Cumulative number of evacuees as a function of time for scenario one

Further examination of the data reveals that, on average, a passenger wastes some 46% of their personal evacuation time in congestion. It is apparent that when all of the exits are available the UOGXXX can easily meet the 90-second evacuation requirement. This should come as no surprise, as the number of exits that are installed on the aircraft are well in excess of those required for the population size (see CFR 25 [198]). The high OPS values indicate that the exit flows did not finish together. This suggests that it is possible to improve the evacuation times still further if a better passenger exit usage could be achieved. In particular the forward exits were under utilised. One way of achieving a better exit utilisation is to have a better passenger distribution between the exits. Another possible solution (at least for the certification case) would be to introduce an active cabin management system that would allow cabin crew to by-pass passengers to the under utilised exits.

Table 10: Summary of results for Scenario 1 (precautionary evacuation using all exits)

All Decks					Upper deck			Lower deck		
TET (secs)	CWT (secs)	Dist (m)	PET (secs)	OPS	TET (secs)	Evacuees (pax)	OPS	TET (secs)	Evacuees (pax)	OPS
46.8 [44.5-56.9]	11.6 [11.3-12.0]	7.2 [7.1-7.3]	25.0 [24.6-25.5]	0.23 [0.18-0.37]	44.6 [41.3-49.1]	236 [236]	0.24 [0.16-0.33]	46.7 [43.9-56.9]	344 [344]	0.22 [0.17-0.37]

We also note that on average, the upper deck finishes **2.1** seconds ahead of the lower deck. It should be recalled that these times do not include the slide times. While not reported here in detail, it is also interesting to note that the generated exit flow rates of practically all the Type-A exits were below the average performance for Type-A exits under certification conditions [24]. The lower deck exits were 19% slower while the upper deck exits were 20% slower than expected. This lower than expected exit performance results from the relatively poor passenger supply to the exits which in turn is a result of having both exits in an exit pair operating.

In this scenario the achieved flow rates of the Type-A exits were constrained by the flow rates of the main and cross-aisles that supplied the exits. The cross-aisles were scarcely utilised in this scenario hence the supply of passengers to each exit was reduced. In the case of forward or aft exits and for some mid-section exits (depending on the nature of the cabin splits) passenger flow to the exit was limited as it was fed from a single main aisle (see Figure 6a).

In contrast, in certification evacuation scenarios, only a single exit from an exit pair is available. In these cases both main aisles effectively feed the exit (see Figure 6b), as passengers from the far main aisle make use of the cross aisle to access the exit.

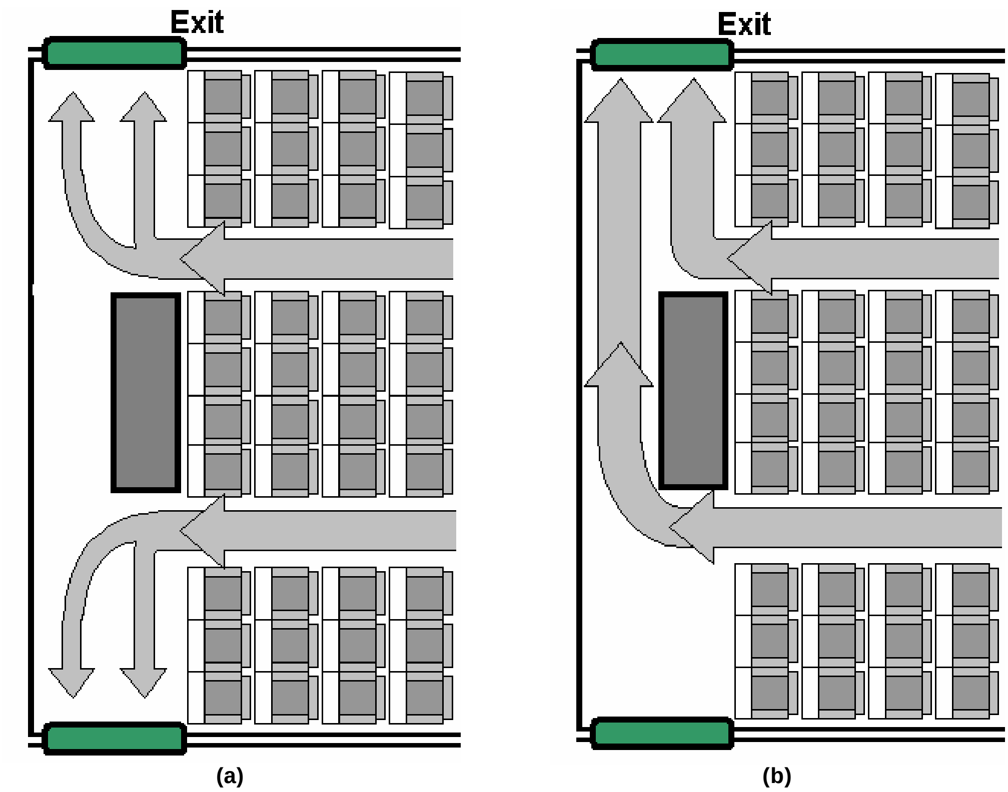

Figure 21: Hypothetical flow pattern at an end of section exit when (a) both exits from exit pairs are available and (b) one exit from and exit pair is available

In contrast, in certification evacuation scenarios, only a single exit from an exit pair is available. In these cases both main aisles effectively feed the exit (see Figure 21b), as passengers from the far main aisle make use of the cross aisle to access the exit.
In a balanced evacuation system, the supply of passengers to the exit should be broadly equivalent to the flow rate capability of the exits. In an ideal situation we should find that:

Discharge (capacity) ˜ Supply (capacity) **Equation 2**

If an inequality exists between the supply or the discharge capacities either a bottleneck will develop (discharge < supply) or the exit will be under utilised (discharge > supply). In the case of Scenario 1, the supply capacity, i.e. the aisle, was less than the exit discharge capacity resulting in the poor exit flow rates achieved.

7.3.6. Scenario 2: Certification evacuation scenario

Scenario 2 investigated the evacuation of the UOGXXX under simulated 90-second certification trial conditions. Scenario 2 generated an average total evacuation time of **66.6** seconds and an average personal evacuation time of **34.3** seconds (see Table 11). All of the simulations that were generated were under the 90-second certification trial testing requirement (see Figure 22).

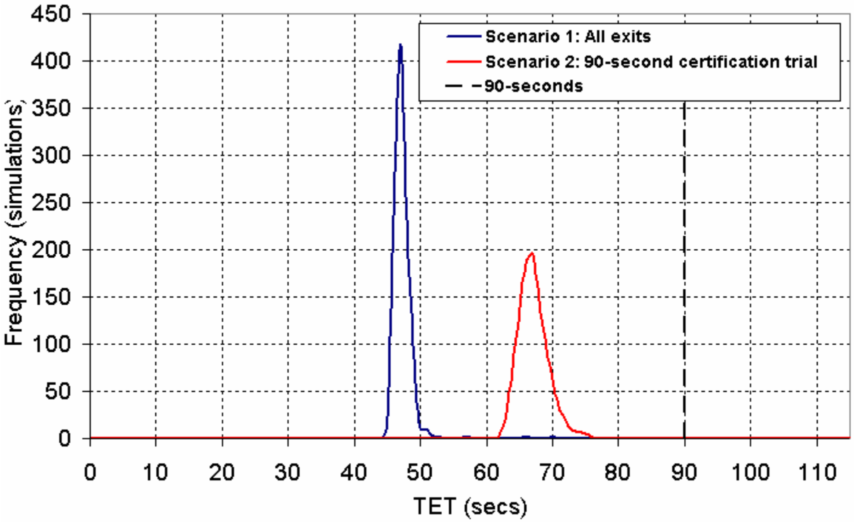

Figure 22: airEXODUS generated TET frequency distribution for scenarios 1 and 2

A similar evacuation evolution is generated in this scenario to that of the previous scenario. Again, there is initially a period of inactivity as the exits are prepared. The exits are prepared at 14 seconds and the flow of passengers through the exits begins, indicated by the positive gradient. Towards the end of the evacuation the supply of passengers to the exits begins to decrease, reflected by the lower gradient.

All the simulations generated total evacuation times were below 90 seconds. Figure 22 shows the frequency distribution of total evacuation times generated by airEXODUS in scenario 2. It can be seen that the frequency distribution curve falls below 90-seconds. Furthermore, the distribution is broader than for Scenario 1 suggesting a greater degree of variability can be found in Scenario 2 compared to Scenario 1.

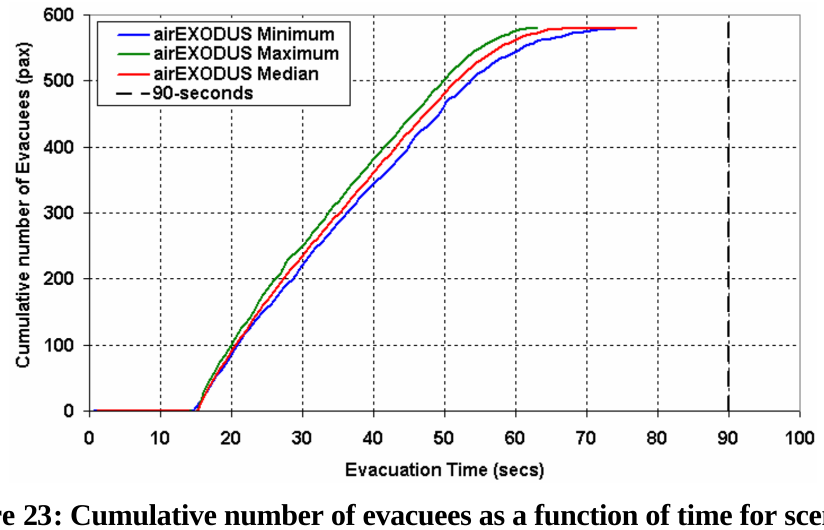

Figure 23: Cumulative number of evacuees as a function of time for scenario two

Further examination of the data reveals that, on average, a passenger wastes some 57% of their personal evacuation time in congestion. As is to be expected, evacuation times have increased significantly relative to Scenario 1, but it is worth noting that the times have not doubled. These results, while ignoring the "slide times" suggest that the aircraft design could easily meet the requirements of the 90-second certification trial.

Table 11: Summary of the results of airEXODUS in Scenario 2 (certification evacuation scenario)

All Decks					Upper deck			Lower deck		
TET (secs)	CWT (secs)	Dist (m)	PET (secs)	OPS	TET (secs)	Evacuees (pax)	OPS	TET (secs)	Evacuees (pax)	OPS
66.6 [61.4-75.9]	19.5 [18.6-21.1]	8.4 [8.3-8.5]	34.3 [33.3-36.0]	0.25 [0.19-0.34]	64.1 [59.2-72.7]	236 [236]	0.22 [0.14-0.32]	66.1 [59.8-75.9]	344 [344]	0.32 [0.26-0.42]

As with the previous case, the OPS for these simulations are quite large. This indicates that evacuation while achieving sub 90-seconds is inefficient. Overall evacuation times could be improved as suggested in the previous example.
Examination of the pattern of exit finishing times indicates that the forward exits finish some **33** seconds before the remaining exits. This resulted from the relatively low number of passengers located in the first-class cabin section. As such the forward exits were idle for much of the evacuation.

7.3.7. Scenario 3a: Precautionary evacuation using lower deck exits

This scenario is similar to a precautionary evacuation in which only the lower deck exits are utilised. Here we are primarily interested in examining the performance of the staircase and its contribution to evacuation performance. In this scenario upper deck passengers are forced to descend the staircase to reach lower deck exits. In doing so, passengers have access to **10** Type-A exits (i.e. more than half the normally available exits) all of which are located on the lower deck. The staircase connecting the two decks is positioned so that it empties onto the lower deck in the vicinity of the R1 and L1 exits.
When passengers are forced to use the internal staircase to access the exits on the lower deck, the evacuation time increases dramatically to an average of **149** [143.7-158.6] seconds (see Table 12). In this scenario, all of the airEXODUS simulations are well in excess of the 90-second certification trial testing requirement (see Figure 24).
Furthermore, in this scenario while passengers have access to more than half the normally available exits, they are forced to travel a considerably longer distance (on average 13.9m (see Table 12) compared with 8.4m in Scenario 2 (see Table 11)) to reach the exits and they must also traverse the staircase. The longer evacuation times may be due to the longer travel distances, the congestion on the stairs, the resulting access that the upper deck passengers have to the lower deck exits due to the location of the stairs, etc. Indeed, the longer evacuation times could be a function of all these factors. However, it should be noted that in an earlier publication the authors demonstrated that under certification conditions, simply travelling a longer distance does not necessarily incur a longer evacuation time [21].

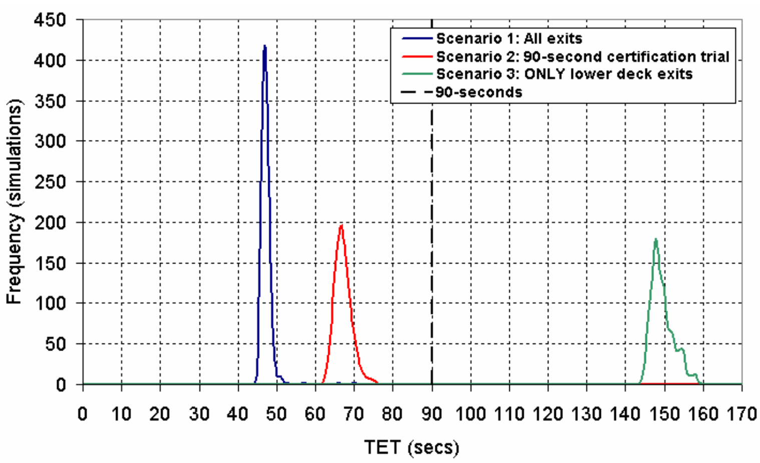

Figure 24: airEXODUS generated TET frequency distribution for scenarios 1, 2 and 3a

In this scenario all the passengers coming down the staircase from the upper deck make use of the front two exits (R1 and L1). However, examination of the exit flow rates for the R1 and L1 exits on the lower deck reveal very poor flow rates were achieved. This suggests that the flow capacity of the exits was not the cause of the poor performance and that a bottleneck may exist somewhere else in the evacuation system.

Insight into the dynamics of this scenario was gained through examining the real time animation output from airEXODUS. Figure 25 depicts a frame from this animation at **48** seconds. This suggests that after **48** seconds the only passengers remaining on the aircraft are upper deck passengers. In addition, the graphics indicate that these passengers were forced to queue in the aisles of the upper deck whilst waiting to descend the staircase. Closer examination of Figure 25 reveals that the cross-aisle area at the foot of the staircase was sparsely populated (the dashed circle in Figure 25) in contrast to the densely populated reservoir at the top of the staircase (the solid circle in Figure 25). Furthermore, Figure 25 reveals that the staircase – represented by the vertical columns to the left of the diagram - were full of passengers. This leads to the conclusion that the staircase itself was contributing to the bottleneck, forcing passengers to queue on the upper deck.

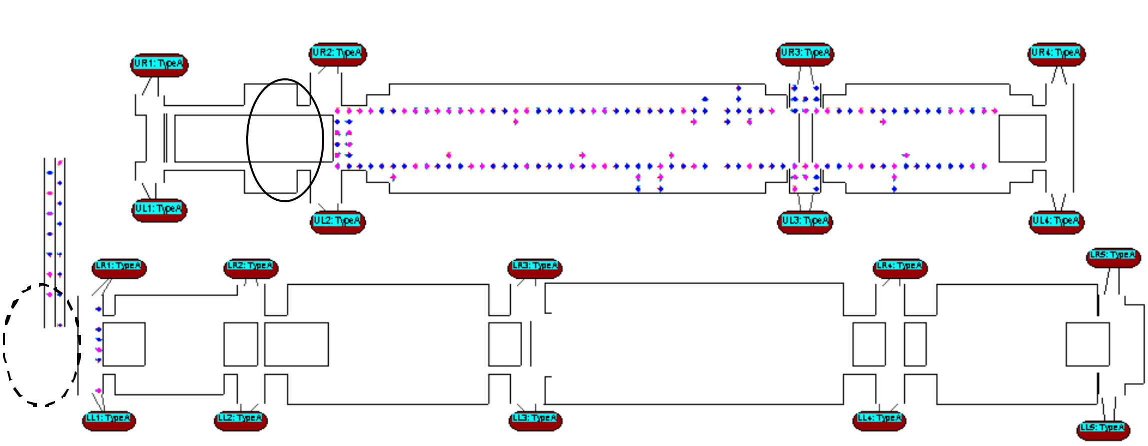

Figure 25: Graphic output from airEXODUS showing congestion at the top of the stairs 48 seconds after the start of the evacuation

Recall from Section 7.3.5 (Equation 2) that in a balanced escape system the discharge capacity (the exits) must be broadly equivalent to the supply capacity (the aisles and cross-aisles). This concept can be extended to cover the larger evacuation system involving the staircase and upper deck. For Scenario 3, the notion of a balanced evacuation system can be extended to cover the supply from the upper deck, the stair connecting the decks and the final exits. This can be expressed as follows:

Discharge (capacity) ˜ Stair (capacity) ˜ Supply (capacity) **Equation 3**

The above analysis would suggest that the flow rate down the stairs is less than the supply rate from the aisles i.e. stair < supply, creating a bottleneck at the head of the stairs and that the discharge capacity of the stairs is less than the discharge capacity of the exits resulting in the under utilised exits i.e. discharge > stair.

From the study of video footage from past certification trials, the flow rate normally achieved through main cabin aisles is approximately 77.4 people/minute [24,224]. This average excludes people running at full speed down the aisle, but includes people fast walking. Under similar conditions, airEXODUS produces an average flow rate of approximately 74 people/minute. The flow rate capacity for a standard stair as specified in the UK Building Code [229] is 40 people/minute/unit width. As with most data used in building codes this should be considered a conservative estimate. However, using this data, the staircase used in the UOGXXX would be conservatively rated according to the UK building code, with a capacity of approximately 80 people/minute. It should be noted that airEXODUS does not enforce a flow rate on stairs but specifies the behaviour and performance capabilities of passengers according to age, gender and direction of travel.

Table 12: Summary of results for Scenario 3a (use of lower deck only exits), Scenario 3b (as Scenario 3 with intelligent ACCM at the base of the staircase) and Scenario 3c (as Scenario 3b with alternating ACCM)

Scenario	All Decks					Upper de ck			Lower deck		
	TET (secs)	CWT (secs)	Dist (m)	PET (secs)	OPS	TET (secs)	Evacuees (pax)	OPS	TET (secs)	Evacuees (pax)	OPS
3a	149.0 [143.7-158.6]	26.7 [25.7-27.8]	13.9 [13.7-14.1]	48.3 [47.1-49.4]	0.64 [0.62-0.66]	N/A	N/A	N/A	149 [143.7-158.6]	580 [580]	0.64 [0.62-0.66]
3b	148.5 [144.1-160.9]	26.9 [26.0-27.9]	13.9 [13.8-14.2]	48.6 [47.7-49.6]	0.58 [0.51-0.65]	N/A	N/A	N/A	148.5 [144.1-160.9]	580 [580]	0.58 [0.51-0.65]
3c	160.6 [150.5-172.5]	27.1 [26.2-28.1]	14.8 [14.7-15]	49.6 [48.7-50.7]	0.52 [0.5-0.56]	N/A	N/A	N/A	160.6 [150.5-172.5]	580 [580]	0.52 [0.5-0.56]

Clearly, as the staircase is fed by two aisles, each with an average flow rate capability of approximately 74 people/minute, the net flow rate into the stairs is potentially 148 people/minute, the stair capacity of approximately 80 people/minute will not be able to cope with this flow. This then results in a bottleneck developing at the head of the stairs, as shown by the airEXODUS simulations. This hypothesis can be tested via improving the exit capacity at the base of the stairs. This can be accomplished though the use of cabin crew procedures.

7.3.8. Scenario 3b and 3c: Crew procedures addressing staircase performance

Two cabin crew were assigned duty stations on the lower deck (see Figure 26) by the bottom of the stairs. Each was given the task of optimising the evacuation via redirecting passengers to adjacent exits. This meant that the crewmember on the left of the aircraft could assign passengers to use doors L1 and L2, while the crewmember on the right of the aircraft could assign passengers to doors R1 and R2 (see Figure 27).

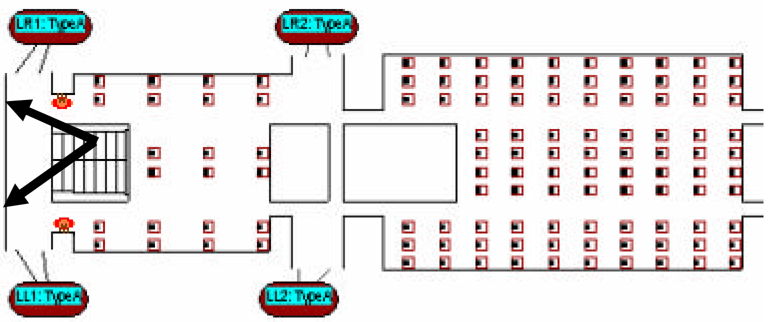

Figure 26: The cabin crewmember redirection stations (denoted by arrows) on the lower deck

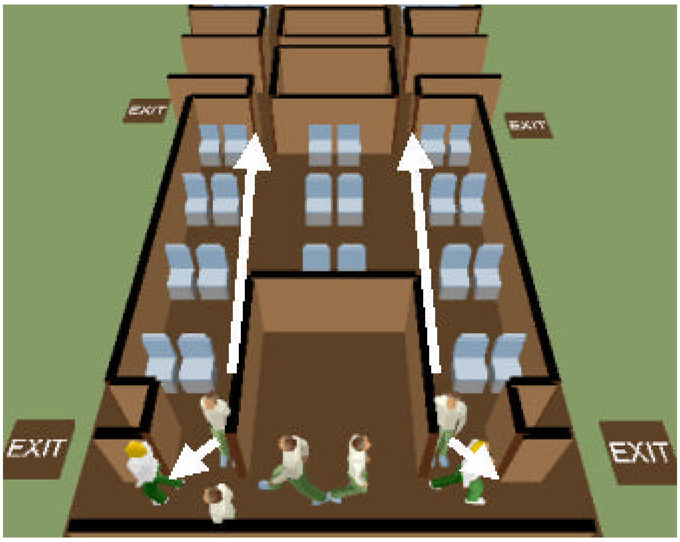

Figure 27: Example of crew exit responsibilities

Two methods of redirection were employed within the model. The first method used the airEXODUS ACCM system. As part of the ACCM system, crewmembers need to access and process a considerable amount of information. When controlling the flow between two exits, the crewmember needs to know, the number of passengers using each of their assigned doors at any time i.e. the congestion levels at the doors, the number of passengers that may require to use the door i.e. the number of passengers in the catchment area of the door, how each of their assigned doors is performing i.e. the achieved flow rate and the time it would require passengers to move between the doors. Crewmembers also have a radius of effectiveness in which they can exert an influence on the passengers i.e. effectively touch distance and voice control distance. The act of communicating with passengers also requires a certain amount of time during which other passengers may be able to get by without being influenced by the crewmember. Furthermore, passengers are given a compliance factor which determines how likely they are to follow the crewmembers instructions [228].

In the examples discussed here, the crew are considered to have complete knowledge of all the factors required to make perfect re-direction decisions. Furthermore, the passengers are considered to be compliant (see section 7.2.3). In this example – Scenario 3b – the crew will attempt to redirect passengers from the L1 and R1 exits only if they determine it will result in an overall net benefit to the evacuation time of the aircraft. Thus, this scenario should be considered to be an ideal case.

The results for this scenario are presented in Table 12 . As can be seen, the crew procedures at the bottom of the staircase did not improve the evacuation time of the aircraft. Results from the ACCM simulations (scenario 3b) indicate that only a very small number of passengers were redirected. In this case the crew determined that there would be no net benefit from redirecting the passengers to the other exit. What redirection has occurred has had virtually no impact on the average evacuation times however, the OPS has improved marginally (indicating a better usage of the exits) while the average personal evacuation time has increased marginally. This supports the conjecture raised in section 7.3.7 that it is not the capacity of the exits that is at fault in this case but the staircase design and location are the likely causes of the poor performance.

To demonstrate the flexibility of the ACCM procedures, the crew at the base of the stairs were given an alternative redirection procedure. In the modified case – Scenario 3c – the crew were instructed to redirect every other passenger descending the stairs to the number 2 exits. Using this procedure we note that the average distance travelled increases as the redirected passengers are forced to travel slightly further to exit the aircraft. More significantly, the average total evacuation time increases from 148.5 seconds to 160.6 seconds (see Table 12). These results further support the point made earlier that the flow capacity of the exit is not the cause of the long evacuation times and crew procedures at the base of the stairs cannot assist in reducing the overall evacuation times.

These cases serve to demonstrate that the exit discharge capacity is not the bottleneck in the evacuation system. Furthermore, congestion at the top of the staircase suggests that any supply is sufficient for the staircase. Thus, the model strongly indicates that the staircase is the bottleneck in the evacuation system.

7.3.9. Scenario 3d: Improving evacuation through the introduction of a wider staircase

To test the theory that the staircase was the bottleneck, three additional cases were considered. In these cases the capacity of the stairs was increased through incrementing the number of lanes. The results are presented in Table 13 and Figure 28 .

As hypothesised the average TET decreases as the number of stair lanes are increased. In other words, increasing the stair capacity from 2-lanes to 3-lanes resulted in the escape system becoming more balanced and the severity of the bottleneck to be reduced. In this scenario, airEXODUS suggests that an increase from two to three lanes would yield a decrease in evacuation time of 30.4 seconds (20.4%).

Table 13: Summary of the results of scenario 3d involving the introduction of a progressively wider staircase

	All Decks					Upper deck			Lower deck		
	TET (secs)	CWT (secs)	Dist (secs)	PET (secs)	OPS	TET (secs)	Evacuees (pax)	OPS	TET (secs)	Evacuees (pax)	OPS
2 Lanes	149 [143.7-158.6]	26.7 [25.7-27.8]	13.9 [13.7-14.1]	48.3 [47.1-49.4]	0.64 [0.62-0.66]	N/A	N/A	N/A	149 [143.7-158.6]	580 [580]	0.64 [0.62-0.66]
3 Lanes	118.6 [113-127.8]	19.8 [18.9-21.7]	13.6 [13.6-13.8]	41.3 [40.4-43.2]	0.58 [0.54-0.61]	N/A	N/A	N/A	118.6 [113-127.8]	580 [580]	0.58 [0.54-0.61]
4 Lanes	118.5 [112.8-138.6]	19.8 [18.9-21.9]	13.7 [13.5-13.9]	41.3 [40.5-43.1]	0.57 [0.55-0.64]	N/A	N/A	N/A	118.5 [112.8-138.6]	580 [580]	0.57 [0.55-0.64]
5 Lanes	116.3 [111.4-125.2]	19 [18.3-20]	13.5 [13.4-13.6]	40.3 [39.5-41.1]	0.57 [0.54-0.6]	N/A	N/A	N/A	116.3 [111.4-125.2]	580 [580]	0.57 [0.54-0.6]

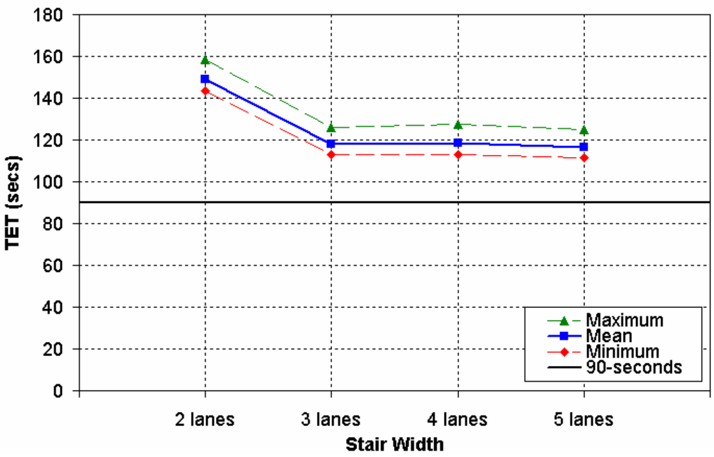

Figure 28: TET as a function of stair lane width

However, the TET formed a plateau (Table 13 and Figure 29 (a)) as the number of stair lanes was incremented beyond three. This indicates that the evacuation system has again become imbalanced. In this situation, either the discharge or supply capacity are insufficient to satisfy the capabilities of the four and five lane staircases. In order to derive a benefit from the four or five lane staircase the evacuation system must be balanced through improving the component that is restricting the flow capacity – either the discharge or supply capacity.

Table 14 : Summary of the results of scenario 3d with intelligent ACCM at the base of the staircase

	All Decks					Upper deck			Lower deck		
	TET (secs)	CWT (secs)	Dist (secs)	PET (secs)	OPS	TET (secs)	Evacuees (pax)	OPS	TET (secs)	Evacuees (pax)	OPS
2 Lanes	148.5 [144.1-160.9]	26.9 [26-27.9]	15.6 [13.8-19.5]	48.6 [47.7-49.6]	0.58 [0.51-0.65]	N/A	N/A	N/A	148.5 [144.1-160.9]	580 [580]	0.58 [0.51-0.65]
3 Lanes	118.8 [112.9-126.2]	19.7 [19.1-20.6]	14.0 [13.9-14.3]	41.6 [40.9-42.4]	0.49 [0.45-0.55]	N/A	N/A	N/A	118.8 [112.9-126.2]	580 [580]	0.49 [0.45-0.55]
4 Lanes	118.4 [111.8-125.5]	19.1 [18.2-20]	14.1 [13.9-14.3]	41.0 [40.1-42]	0.49 [0.46-0.55]	N/A	N/A	N/A	118.4 [111.8-125.5]	580 [580]	0.49 [0.46-0.55]
5 Lanes	117.4 [111.7-123.4]	19.0 [17.7-19.8]	13.8 [13.6-14]	40.6 [39.3-41.5]	0.49 [0.46-0.50]	N/A	N/A	N/A	117.4 [111.7-123.4]	580 [580]	0.49 [0.46-0.50]

Introducing intelligent ACCM as in scenario 3b again fails to improve the situation as can be seen from Table 14 and Figure 29 .

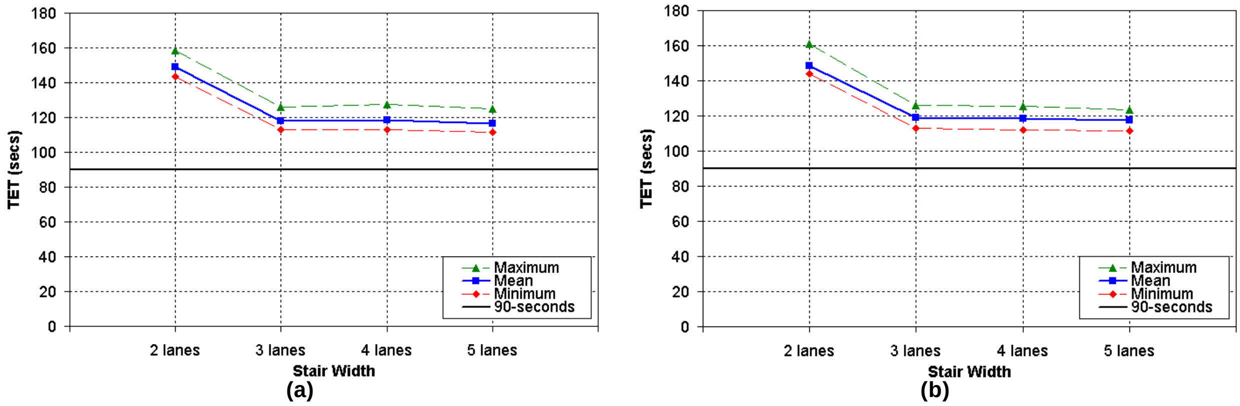

Figure 29: TET as a function of stair lane width (Scenario 3d), (a) without ACCM and (b) with intelligent ACCM

Examining the average exit flow rates generated by the lower deck L1 and R1 exits prior to the ACCM being employed (**71.9** passengers/minute and **70.9** passengers/minute) clearly indicates that the exits are not operating at their optimal flow rate (approximately 110 passengers/minute). Indeed the use of crew procedures at the base of the stairs simply pulled a few passengers away from these exits and further reduced their flow rates to **64.4** passengers/minute and **64.1** passengers/minute respectively.

Examination of the real time airEXODUS graphical output (see Figure 30) generated by airEXODUS in scenario 3d clearly indicates that the vestibule at the base of the staircase is not fully packed (the dashed circle in Figure 30). Consequently, the adjacent R1 and L1 Type-A exits are not operating to their full capacity in any of the cases thus far considered.

This suggests that the bottleneck must originate from the supply capacity at the top of the stairs. This hypothesis is strengthened through examination of the real time airEXODUS graphical output (see Figure 30). It is apparent from the graphical output that the density immediately adjacent to the top of the staircase is low (the solid circle in Figure 30) in the four and five lane staircase scenarios. Significantly, some *sub-queues* have developed within the upper deck aisles (see Figure 30).

Sub-queues form when a group of passengers of varying physical abilities travel suitably large distances to reach exits [**21**]. A sub-queue forms and the queue becomes segmented as fast moving passengers are forced to wait behind slower moving passengers. The effect of sub-queue congestion is twofold. Firstly, it slows down the movement of passengers involved in the queues and secondly it causes gaps to develop within the passenger flow. In this scenario the effect of gaps is that the smooth flow of passengers into the staircase is disrupted and the flow is sporadic.

This finding is not unexpected, as previous work suggests that the *practical exit separation threshold*, i.e. the maximum distance that passengers can travel to an exit without an adverse effect on evacuation time, ***decreases*** as the exit flow rate is ***increased*** [**21**]. In the case of the five lane stair case the throughput flow rate is expected to be very high. As a consequence the maximum distance that passengers should be allowed to travel is low. Hence in the four and five lane staircase examples, we witness sub-queue congestion effects over relatively small distances.

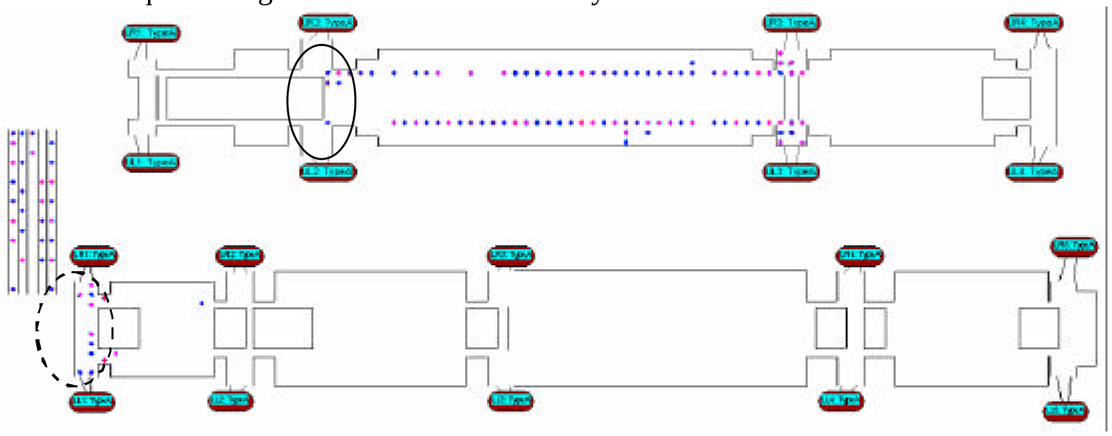

Figure 30: Graphic output from airEXODUS with a 2-lane exit staircase at 55 seconds when Active Cabin Crew Management

Further to this, the first-class section exhausts it's supply of passengers within 20 seconds after which time the stairs are fed by only two passenger aisles. The flow capacity of two main cabin aisles (approximately 148 people/min) is simply insufficient to service a five lane staircase (which is expected to be approximately 200 people/min using the building industry standards).
Improving the supply at the top of the stairs is a more complex issue which requires some modification to the aircraft interior layout. This is examined in Scenario 3e.

7.3.10. Scenario 3e: Improving the supply capacity through an alternative aircraft

This section examines the impact that improved passenger supply at the top of the staircase has upon the evacuation performance of the aircraft. One way of improving the supply to the stairs involves modifying the aircraft cabin layout. Arriving at an acceptable design is quite difficult as there are specific design requirements that have to be satisfied in order to improve the evacuation and to enable a direct comparison with the previous design. These requirements and their rationale are briefly described.
It is the authors view that improving the supply of passengers to the top of the staircase would improve the flow rate of passengers through the stairs and ultimately the exits. In order to increase the passenger density within the vestibule area at the top of the stairs, the supply of passengers from the aisles must be improved. Primarily, this can be accomplished through a design that generates a steady flow of passengers into the staircase vestibule from both the forward and aft directions. This would require the staircase to be located *centrally* within the aircraft cabin. Such a design has the added benefit of reducing the distance that passengers would have to travel to reach the staircase and should therefore reduce the likelihood of sub-queues developing. Finally, to enable a direct comparison with the previous scenarios it is necessary that the number of passengers on both decks is maintained.
These requirements severely limited the number of viable designs. The proposed design (see Figure 31) broadly meets our requirements. However, it should be noted that the design is purely theoretical and intended to demonstrate concepts only. In reality the design may not be viable for practical operational reasons.
The major difficulty with this design is that by relocating the staircase, many of the economy class seats were removed. In order to maintain the total passenger numbers with the previous design, the first-class cabin sections were replaced with business class seating on the upper deck and economy seating on the lower deck. From the perspective of profitability, this arrangement may be unattractive for most carriers. In addition a further reduction in available cabin space resulted from the inclusion of an additional vestibule on the upper deck adjacent to the top of the staircase.

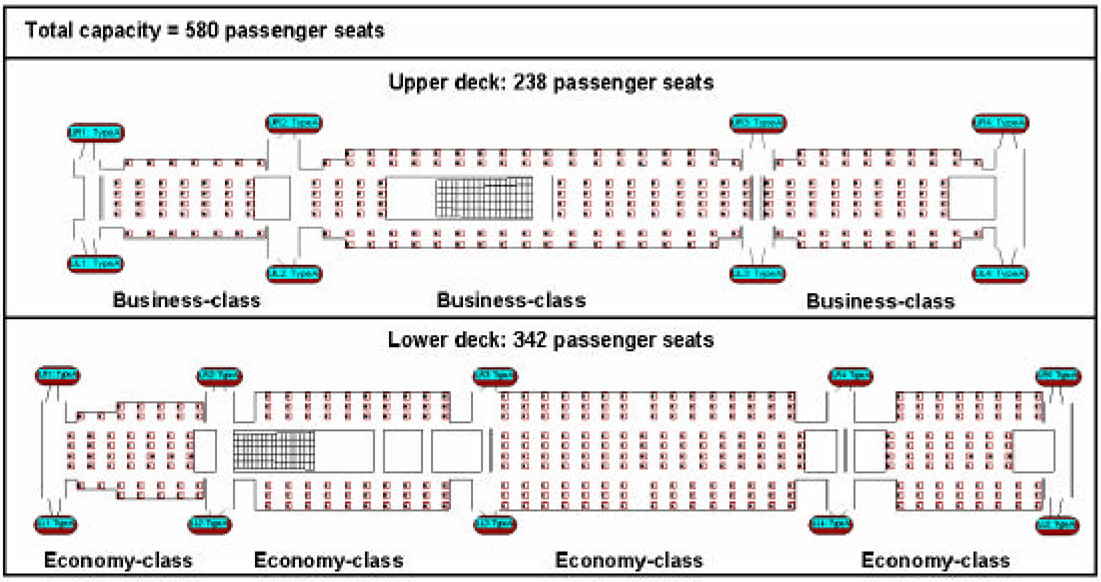

Figure 31: An alternative design – used in Scenario 3e - in which the top of the staircase is centrally located within the upper deck

It should be reiterated that an important objective of this design was to maintain the number of passengers onboard the aircraft. This objective was necessary as it enables a more direct comparison between the two designs.

One of the key features of the proposed design is that the number of passengers that travel aft into the staircase is increased. In the previous design only 12 passengers moved aft, whereas in the alternative layout 94 passengers move aft into the exit (see Figure 32). This should result in four flows of passengers into the top of the stairs, which will cause the vestibule at the top of the staircase to remain full for longer. This in turn should improve the operational flow rate of the staircase and ultimately the lower deck exits.

Sub-queue effects would also be reduced in the new design. This should occur for two reasons. Firstly, the distance that the average passenger has to travel to reach the staircase is reduced from 67 feet (21 metres) to 35 feet (11 metres). Secondly, if sub-queue congestion causes a gap to develop in one of the aisle queues there are three other aisles to compensate i.e. keep the staircase supplied. Thus, the likelihood of sub-queue formation occurring is reduced and the impact of instances of sub-queue congestion are likely to be reduced.

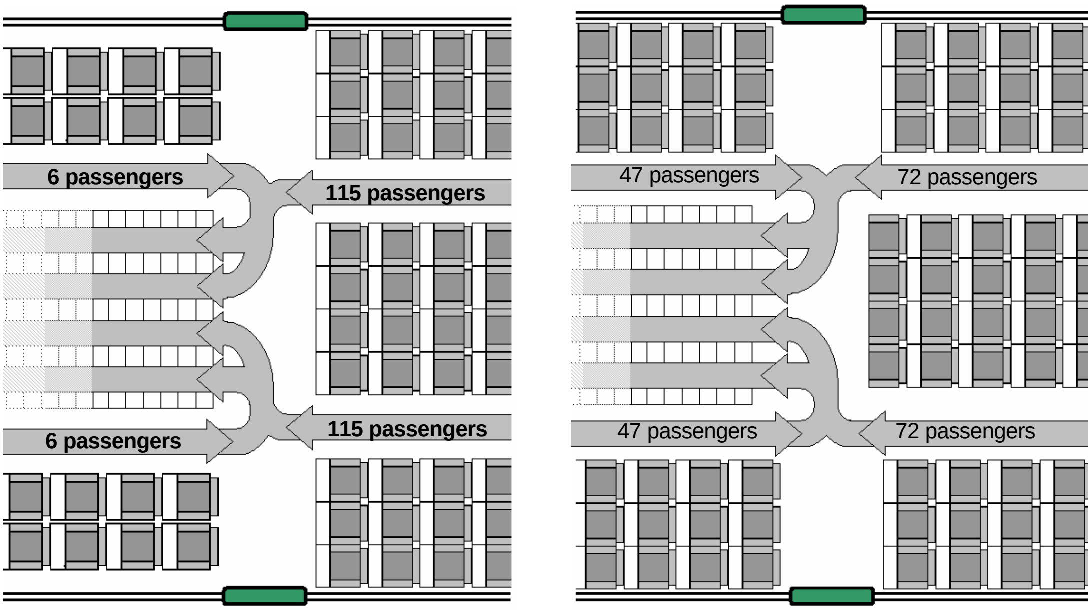

Figure 32: The number of passenger that would use forward and aft moving passenger aisle for (a) the original design and (b) the alternative design

The alternative design was simulated without introduction of ACCM at the base of the stairs. It can be seen that when using the alternative design the total evacuation time for the aircraft decreases as the number of staircase lanes is increased to five (see Table 15 and Figure 34 (a)). This is a direct result of the supply to the staircase on the upper deck being improved. Indeed, in the majority of simulations the design with a centrally located 5-lane staircase can be evacuated using only the lower deck exits in under 90-seconds (see Figure 33).

Table 15 : Summary of the results of scenario 3e involving the alternative cabin arrangement (without the use of ACCM)

	All Decks					Upper deck			Lower deck		
	TET (secs)	CWT (secs)	Dist (secs)	PET (secs)	OPS	TET (secs)	Evacuees (pax)	OPS	TET (secs)	Evacuees (pax)	OPS
2 Lanes	148.8 [144.7-158.8]	28.9 [28.1-29.8]	12.3 [12.2-12.5]	48.7 [47.9-49.7]	0.64 [0.62-0.67]	N/A	N/A	N/A	148.8 [144.7-158.8]	580 [580]	0.64 [0.62-0.67]
3 Lanes	111.9 [105.5-124.6]	21.2 [20.6-22.2]	12.2 [12.0-12.3]	40.9 [40.2-41.9]	0.57 [0.53-0.61]	N/A	N/A	N/A	111.9 [105.5-124.6]	580 [580]	0.57 [0.53-0.61]
4 Lanes	101.2 [93.6-111.9]	18.7 [17.8-19.6]	12.2 [12.1-12.3]	38.5 [37.6-39.4]	0.54 [0.49-0.58]	N/A	N/A	N/A	101.2 [93.6-111.9]	580 [580]	0.54 [0.49-0.58]
5 Lanes	84.5 [80-100.4]	16.5 [15.7-17.4]	12.1 [11.9-12.2]	36.2 [35.3-37.1]	0.46 [0.42-0.55]	N/A	N/A	N/A	84.5 [80-100.4]	580 [580]	0.46 [0.42-0.55]

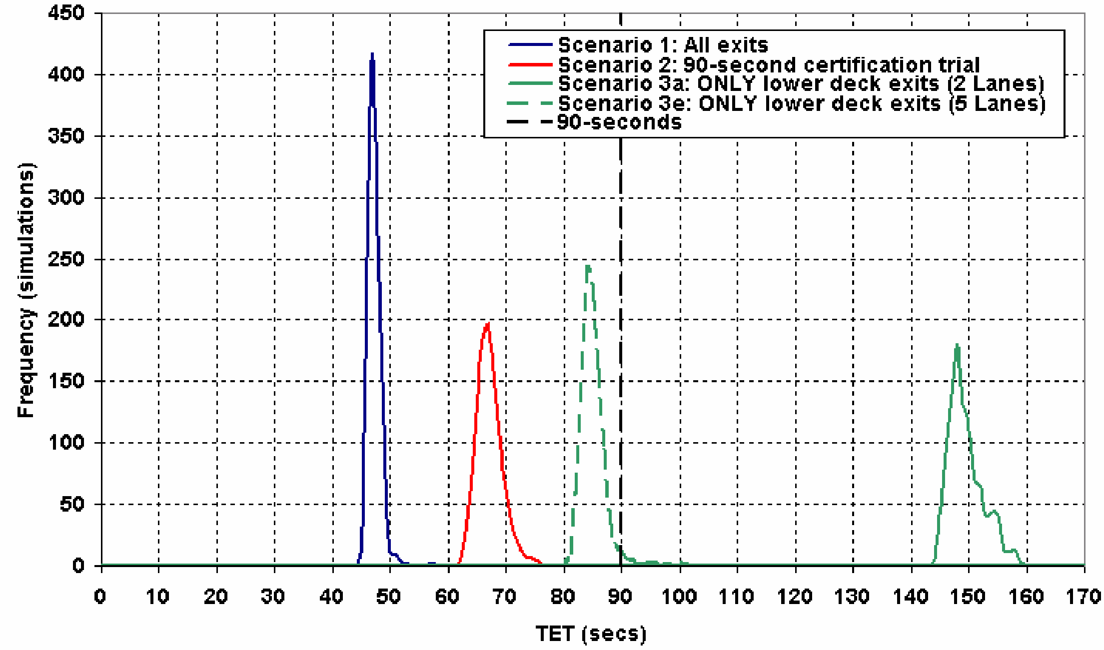

Figure 33: airEXODUS generated TET frequency distribution for scenarios 1, 2, 3a and 3e (with five lanes)

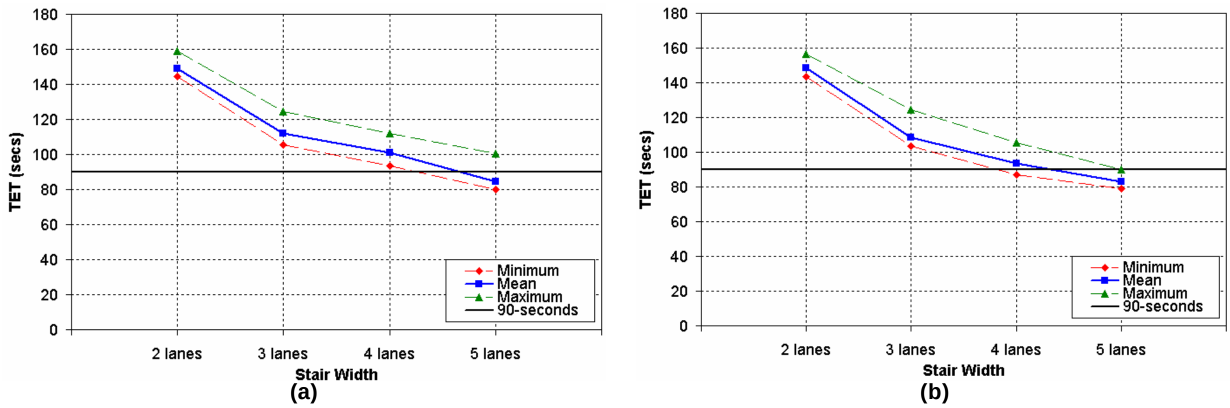

Figure 34: TET as a function of stair lane width for the alternative design (Scenario 3e) (a) without ACCM (b) with intelligent ACCM

Examination of the real time graphical output from airEXODUS revealed that the flow of passengers into the top of the staircase was such that the vestibule was fully occupied for the majority of the flow period (the solid circle in Figure 35). Furthermore, while sub-queue congestion still occurs (see Figure 35), their impact is reduced as other aisles may compensate for temporary gaps in passenger flow.

Examination of the exit flow rates for the R2 and L2 exits revealed that they have improved significantly. Recall that the average exit flow rates of the exits nearest to the stair discharge (the R1 and L1 exits in the previous 5-lane staircase design) were **71.9** and **70.9** passengers/minute. By contrast the new design generated average exit flow rates of **107.2** and **105.7** passengers/minute for its nearest exits (the R2 and L2 exits). These exit flow rates are closer to those achieved in 90-second certification trials. This indicates that they are operating at near to maximum capacity with the centrally located 5-lane staircase design [24].

Finally, the evacuation could be improved still further through the use of crew procedures at the base of the stairs (see Figure 31 (b)). Similar to scenario 3c, two crew members could be placed adjacent to the base of the stairs and instructed to regulate the flow of passengers between the lower deck R1/R2 and L1/L2 exits. For the 5-lane staircase all the simulations using the alternative design - that included ACCM at the base of the stairs - were completed under 90-seconds.

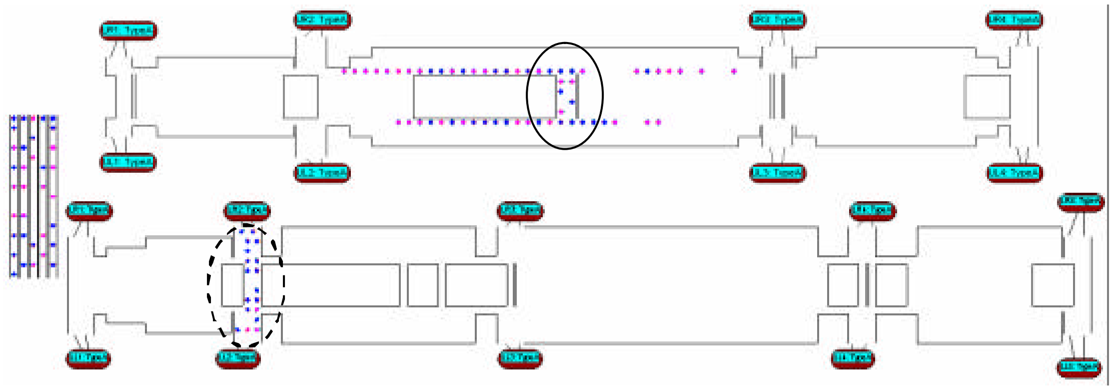

Figure 35: Graphic output from airEXODUS with a 5 -lane exit staircase at 46 seconds

To summarise, the scenario in which all of the upper deck passengers were forced to evacuate using lower deck exits was problematic with the evacuation times originally generated by this scenario being very high (on average 149 seconds). However, this was improved through a more *evacuation efficient* design. It was shown that the small number of staircase lanes initially served as a bottleneck to the entire evacuation system. Whilst some improvement could be gained by increasing the stair width to three lanes, further improvement through the addition of more staircase lanes could not be achieved due to the poor supply of passengers to the top of the stairs. An *evacuation efficient* design was proposed in which the main staircase was moved to a central location. The new design improved supply to the staircase and reduced sub-queue effects. Furthermore, in the majority of simulations involving the improved cabin layout with a five lane staircase the aircraft could be evacuated in under 90-seconds (see Figure 33).

7.3.11. Scenario 4: A scenario involving partial inter-deck movement

In scenario 4 we return to the original cabin layout with the two lane staircase located at the front of the cabin (see Figure 17) to investigate a scenario in which ***some*** passengers may be required to move between decks. The scenario involves a situation where only the rear exits on both decks are available. This may be for example due to a fire engulfing the front part of the aircraft.

In this scenario only exits L/R3 and L/R4 on the upper deck and L/R4 and L/R5 on the lower deck are available. Thus, in total eight exits from four exit pairs are available from a total of 14 exits. This represents more than 50% of the available exits. Two cases were considered. Firstly, a base-case for this scenario (scenario 4a) is established in which the passengers are prohibited from using the stairs during their evacuation. A second case is considered (scenario 4b) in which ACCM is used to redirect some passengers to use the stairs in order to expedite the evacuation of the aircraft.

The average evacuation time for the aircraft in scenario 4a was 121.9 [116.5-129] seconds. On average the lower-deck concluded its evacuation after 121.9 [116.5-129] seconds while the upper deck completed its evacuation after 80.0 [97.2-116.4] seconds.

Table 16 : Summary of the results of scenario 4 with partial movement of passengers between decks

	All Decks					Upper deck			Lower deck		
	TET (secs)	CWT (secs)	Dist (secs)	PET (secs)	OPS	TET (secs)	Evacuees (pax)	OPS	TET (secs)	Evacuees (pax)	OPS
Scenario 4a No stair use	121.9 [116.5-129]	28.5 [27.3-29.8]	12.9 [12.8-13]	48 [46.9-49.2]	0.5 [0.47-0.53]	80.0 [75.9-85.4]	236	0.45 [0.43-0.49]	121.9 [116.5-129]	344	0.39 [0.35-0.43
Scenario 4b With ACCM and stair use	113.4 [98.3-132.9]	26.3 [24.8-28.2]	13.5 [13.3-13.7]	46.5 [45.2-48.2]	0.41 [0.36-0.46]	109.7 [97.5-130.3]	274 [252-290]	0.48 [0.43-0.55]	109.3 [96.9-132.9]	306 [290-328]	0.43 [0.38-0.52

The exit flow rates that were generated in this scenario were very low. For example, the upper deck R3 and L3 and the lower deck R4 and L4 exits generated flow rates of **85.8** and **79.8** passengers/minute and **75.7** and **75.6** passengers/minute respectively. Similar to scenario 1, part of the reason for low exit flow rates in scenario 4 is that only a single passenger aisle supplies each dual lane exit. Furthermore, the supply to the exits is compounded by the presence of sub-queue congestion on both decks. The formation of sub-queue delays should be expected, as the distances that passengers had to travel to reach exits were relatively large. For example, on the upper deck the maximum distance that a passenger had to travel to reach an exit was **77** feet (24 metres) and on the lower deck, **119** feet (37 metres). This has the effect of disrupting the continuous supply of passengers to the exits.

As highlighted in previous research, the effects of excessive travel distances are likely to be more significant in real emergencies in cases where passenger mobility may be impaired and the number of passengers onboard the aircraft is reduced [21]. As such, this scenario could be more challenging in the event of a real crash scenario involving fire, injuries and a decreased passenger load.

The disparity in the finishing time of the two decks originates from the number of passengers seated on the upper and lower decks and the exit availability of the scenario. The disparity led to upper deck clearing its passengers faster (on average 41.9 seconds) than the lower deck. In other words the upper deck exits were idle for the final 41.9 seconds of the evacuation. This represents a waste of useable exit capacity on the upper deck. Through the use of well informed cabin crew, it may be possible to achieve a reduction in overall evacuation time through a better utilisation of the upper deck exits. Such a scenario is examined in scenario 4b.

Scenario 4b considers a crew procedure that involves directing some of the lower deck passengers up the stairs to the upper deck. The aim of this procedure is to minimise the total evacuation time for the aircraft as a whole. To perform this task the ACCM was used and six specific cabin crew were modelled on the lower deck (Figure 36). These crew are located at the inactive lower deck exits L/R1, L/R2 and L/R3. The procedures implemented here are purely for demonstration purposes and are not intended to represent a recommended practice. The crew located at the identified left side exits had the task of redirecting passengers between the lower deck L4 and upper deck L3 exits while the crew located on the right side were responsible for redirecting passengers between the lower deck R4 and the upper deck R3 exits (see Figure 36).

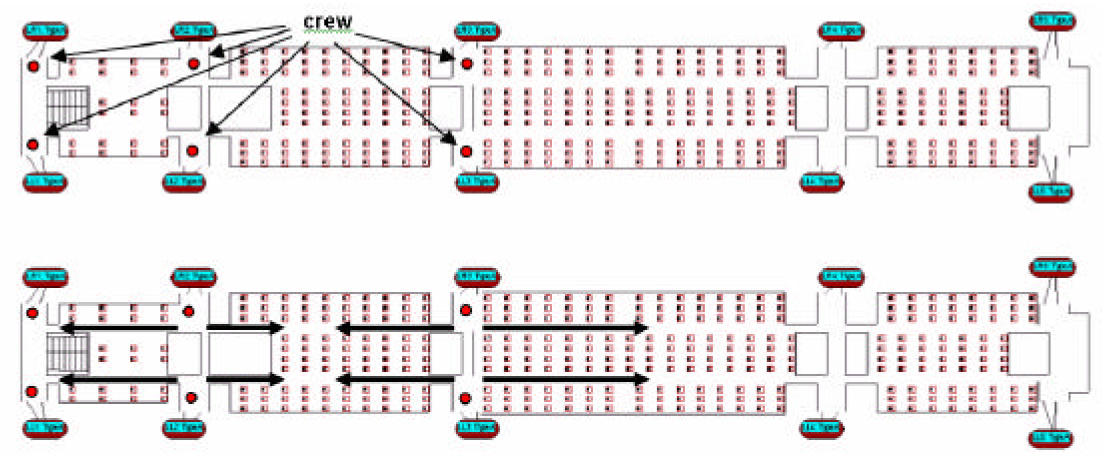

Figure 36: Lower deck cabin crew duty stations (top) and their responsibilities (bottom) in Scenario 4b

The practicalities and technology required to implement such a procedure is currently the subject of much debate. Certainly this type of cabin crewmember procedure would require considerable crew communication and coordination. For example, it would require an assessment and subsequent communication of useable exits between the upper and lower deck crewmembers. Survivor testimonies from real accidents suggests that crew coordination during a real emergency evacuation is no easy task [213,214,226,227]. The problem is likely to be even more acute when cabin crewmembers are situated on different decks. To make such procedures viable on aircraft such as the UOGXXX may require the introduction of crew communication devices such as head-sets.

However, a thorough discussion of the practicalities of such a communication system is beyond the scope of this work. In this scenario we simply examine the possible benefits that may result from such a procedure being implemented. The procedure was implemented within airEXODUS by giving the crew complete knowledge of the situation at the exits that they were directing passengers to. Thus, for example, the lower deck crew would know the situation at the lower deck exits as well as the upper deck exits to which they were directing passengers. As the crew have complete knowledge of their exits, they can make appropriate decisions as to when to redirect passengers in order to minimise the evacuation time. As with the other cases, this scenario was run 1000 times.

Quite complex behaviour is generated in Scenario 4b that requires some explanation. The six cabin crewmembers stationed at inactive exits on the lower deck were assigned a position adjacent to their exit. In the first 14 seconds of the evacuation (i.e. prior to the exits being fully prepared) the crew simply blocked their inactive exits whilst ushering passengers aft, towards their nearest active exit. Consequently, the six crew highlighted in Figure 36 directed ALL of the lower deck passengers aft towards the R/L4 and R/L5 exits. Similar to Scenario 4a, this resulted in the formation of long exit queues for the lower deck R/L4 exit which extended all the way forward to be approximately inline with the R/L2 exit vestibules.

After 14 seconds all of the active exits are fully prepared for evacuation and passengers began to evacuate. At this stage Scenario 4b begins to differ from Scenario 4a as the lower deck cabin crew gain knowledge of the upper deck exits that are active, (e.g. the R/L3 and R/L4) and begin to consider redirecting passengers.

Initially redirection takes place at the periphery of the lower deck R/L4 exit queue which is located approximately inline with the lower deck R/L2 exit vestibule. As such early redirections are performed by the crew at the R/L2 exit vestibule. Whilst the lower deck crew at the R3/L3 exit vestibules recognise the need for redirection they do not redirect passengers as they are unable to communicate with passengers at the R/L2 area. Furthermore, they determine that redirecting passengers that are within their communication range would not assist the evacuation but merely cause confluence with passengers moving aft wards.

As the evacuation progresses lower deck R/L4 exit queue begins to shrink until the periphery of the queue is within the communication range of the lower deck crew at the R/L3 exit vestibule. At this point, they begin to assist and to redirect passengers forwards towards the upper deck L/R3 exits. Throughout the evacuation the crew at the lower deck L/R1 exit vestibule usher passengers up the stairs through the evacuation.

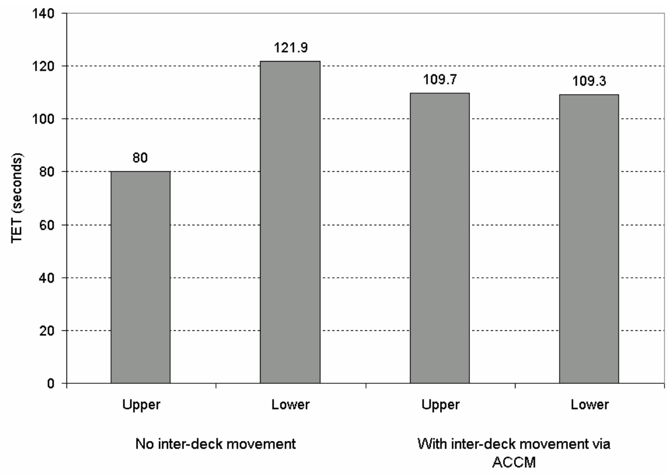

Figure 37: Summary of the finishing time of upper deck and lower deck exits with and without inter-deck movement

When redirection is employed in the manner described the average total evacuation time is reduced to **113.4** [98.3-132.9] seconds (see Table 16). The evacuation of the aircraft is completed on average some **8.5** seconds sooner than previously.

The average personal evacuation time of passengers has also decreased, from 48.0 seconds in scenario 4a to 46.5 seconds in scenario 4b. Thus, on average passengers personal evacuation times have also been improved in this scenario.

However, in the inter-deck scenario the passenger that travelled the greatest distance to reach an exit was initially located on the lower but made use of an upper deck exit. His travel distance was **131** feet (41 metres). In contrast, the maximum distance travelled by lower deck passengers that evacuated via lower deck exits was **77** feet (24 metres). Overall passengers were required to travel greater distances in scenario 4b, as indicated by the increase in the average distance travelled by passengers (see Table 16).

While sub-queue congestion formed on both decks, by far the most extreme examples were present on the upper deck. This was due for the most part by the reduction in travel speed incurred by passengers while ascending the stairs. This reduction in travel speed increases the distance between the back of the exit queue on the upper deck and front of the line created by ascending lower deck passengers. Given this increase in travel distance and the need to ascend the stairs, the merit of this procedure in a real emergency evacuation is questionable. Situations in which passenger mobility may be impaired due to original disability, impact injury or due to the progressive degradation resulting from fire conditions would require further investigation. It should be noted that while the current version of airEXODUS can accommodate all of these factors, they were considered to be beyond the scope of this work.

To summarise, this section has demonstrated the evacuation of the aircraft using only the aft exits. It has been shown to be problematic, involving passengers travelling large distances to reach exits. A successful attempt at improving the evacuation time through inter-deck cabin crewmember procedures was demonstrated. However, whilst in these simulations it led to a decrease in overall evacuation time, it also results in a significant increase in the maximum travel distances incurred by some passengers. As such the merit of the proposed procedure in a real emergency evacuation is questionable, especially in evacuations involving fire and mobility impaired passengers. While these scenarios could be examined using the present model, they have not been considered here.

7.4. Conclusions

This report has demonstrated how aircraft evacuation models can be used to address a range of issues associated with the design of conventional.

When considering the evacuation efficiency of aircraft design, much can be learned about the potential performance of the aircraft layout by considering the aircraft as an escape system made up of a series of sub-components. These sub-components have a supply and discharge capability that must be balanced in order to achieve an efficient evacuation performance. Using this concept and the results from a detailed modelling exercise, it was shown that staircase design and location are critical factors in evacuation scenarios where passengers are required to use the lower deck exits on a double deck aircraft. In the specific design investigated, it was shown that the two-lane staircase could not cope with the passenger flow generated by the two main cabin aisles resulting in a bottleneck at the head of the stairs and under-utilisation of the main deck exits. Suggestions for improving the overall evacuation time under such conditions include, widening the staircase or providing an additional staircase. If the staircase was widened, relocating the staircase to a more central location with access to additional lower deck exits would also be required in order to reap the full benefits afforded by additional stair capacity.

It was also shown how crew procedures could be represented in aircraft evacuation models and how this could be used to assist in the development of crew procedures, and for exploring the potential usefulness of devices such as communication head sets for relaying information that would otherwise not be available to the crew.

An important issue that must be borne in mind is that gaps exist in our understanding of human behaviour and the quantification of human performance in some of the configurations examined. One of the areas that requires further attention is the collection of passenger exit hesitation time data at high sill height exits. While some data exists, more data is required to increase the confidence in model predictions. Another area that requires attention is the performance of passengers on stairs in these type of aircraft. In the work presented here, it was assumed that this would be similar to human performance on building stairs.

However, where data does not exist in abundance, models can also be used to limit and refine the design concepts that may need testing in experimental facilities. Clearly, a sensible balance of modelling and experimentation is required to address all of the challenging issues posed by VLTA aircraft.

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