Computer simulation of VLTA evacuation performance: A report from the VERRES project

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ABSTRACT

This paper reports on research work undertaken for the European Commission funded study GMA2/2000/32039 Very Large Transport Aircraft (VLTA) Emergency Requirements Research Evacuation Study (VERRES). A particular focus was on evacuation issues with a detailed study of evacuation performance using computer models being undertaken as part of Work Package 2. This paper describes this work and investigates the use of internal stairs during evacuation using computer simulation.

1 Introduction

This paper reports on research work undertaken for the European Commission funded study GMA2/2000/32039 Very Large Transport Aircraft (VLTA) Emergency Requirements Research Evacuation Study (VERRES). The VERRES consortium was made up of University of Greenwich, Cranfield University, The UK CAA, EADS Airbus, Virgin Atlantic and Sofreavia with ETF (SNPNC) and the JAA as observers. The purpose of VERRES was to investigate a number of issues relating to post-accident survivability of future large aircraft. A particular focus was on evacuation issues with a detailed study of evacuation performance using computer models being undertaken as part of Work Package 2. This paper describes this work and investigates the use of internal stairs during evacuation using computer simulation. This paper only represents a summary of the findings. The full report can be found on the FSEG web pages at: http://fseg.gre.ac.uk/fire/VERRES_Project.html.

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 [4] however, significantly greater seating capacity options are possible, with 822 passengers being suggested for the single class configuration [5]. 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 [5]. 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 [6]. 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 [7,8]. 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 [9]. 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 [10,11]. 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 [11]. In addition, within building codes it is recognised that to be effective the handrails must be within reach of staircase users [11]. Therefore building codes mandate that handrails must be within 30 inches of the “natural path of travel” [11]. 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 [12]. 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 [3]. In this paper we will demonstrate how computer based evacuation models can be used to investigate issues associated with VLTA configuration and crew procedures.

2 The airEXODUS Model

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 **[**13**,**14**,**15,16**]**, maritimeEXODUS [17,18] and airEXODUS [3,19,20,21,22,16,23] 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 [3,19,20,21,22,16,23] and so only the components relevant to this study will be briefly described here.

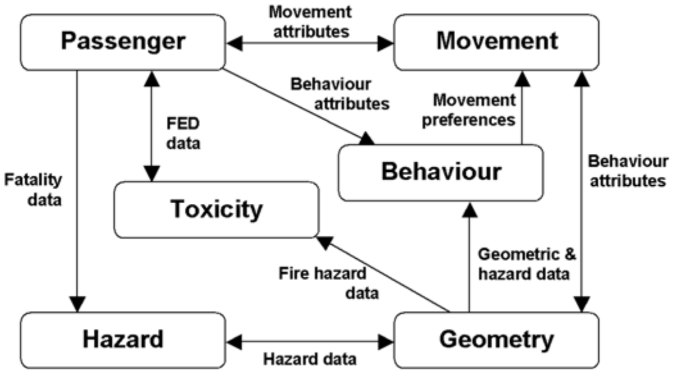

Figure 1: EXODUS Submodel Interacton

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 1). 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.

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.

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.

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 [1]. 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.

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.

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.

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.

2.1.6.1 Passenger Behaviour

While airEXODUS has the ability to represent “extreme” passenger behaviour of the type reported in actual aviation accidents [24, 25], 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 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 3). This assumes that the staircase design is similar to that found in buildings.

2.1.6.2 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 [7,8,26]. 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 [27,28] and during real emergency evacuation situations [29,30,31,32,33]. 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.

2.2 Certification Data used in airEXODUS

airEXODUS makes use of 90-second certification data [7] to specify certain model parameters [7]. 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 [3,7,35].

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 [34].

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.

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.

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 2).

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 [9]. 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 2.

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.

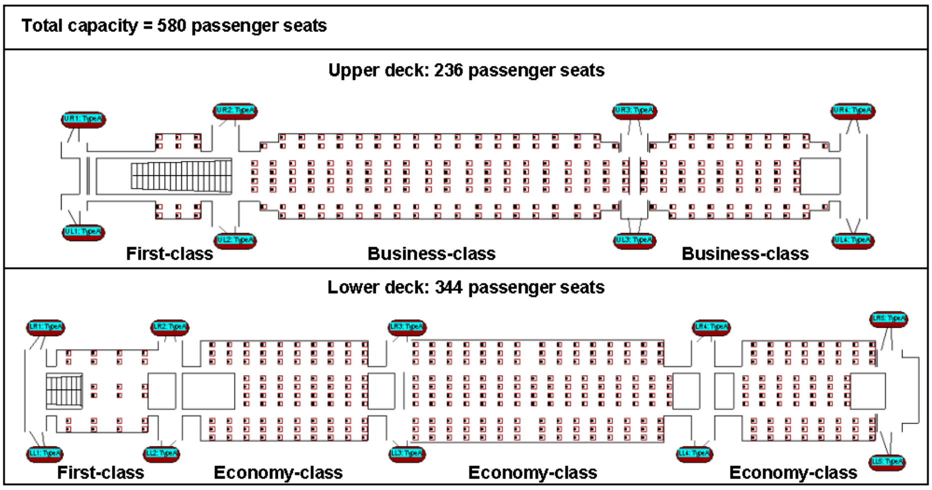

Figure 2: A schematic of the UOGXXX VLTA

3.2 Population Specification

The population complies with FAR requirements for certification testing [36]. 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 [2].

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 [3,13,20] 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 [13,20]. The OPS can be calculated for each evacuation, providing a measure of the degree of performance. 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.

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 were investigated. 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. Here we present the results for scenarios 2, 3a, 3b, 3c and 4. The results for all the scenarios can be found in the full report (available on the web site).

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. Each simulation case detailed in this paper has been run 1000 times by airEXODUS to capture stochastic variations.

3.5 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 1). All of the simulations that were generated were under the 90-second certification trial testing requirement (see Figure 3).

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 of the simulations generated total evacuation times that were below 90 seconds. Figure 3 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.

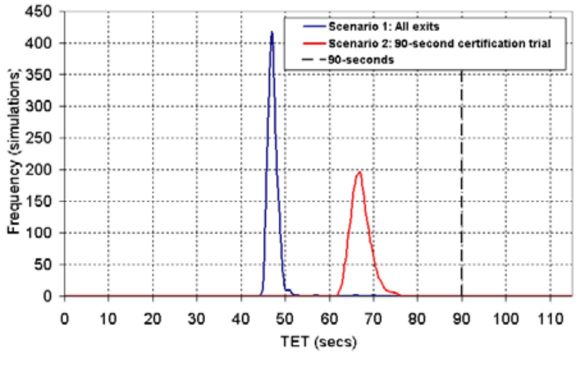

Figure 3: airEXODUS generated TET frequency distribution for scenarios 1 and 2

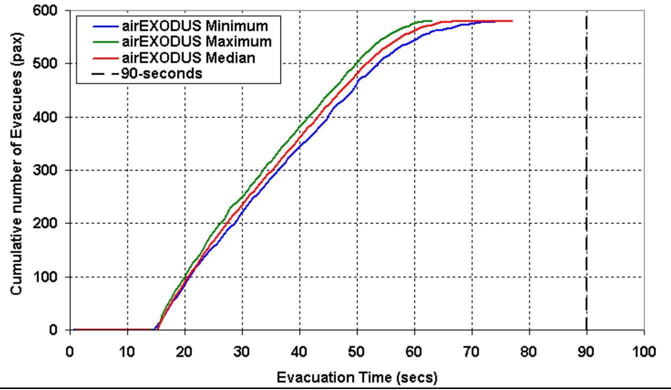

Figure 4: Cumulative number of evacuees as a function of time for scenario 2

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 1: 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)**	**# paxs**	**OPS**	**TET (secs)**	**# paxs**	**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.

3.6 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 2). In this scenario, all of the airEXODUS simulations are well in excess of the 90-second certification trial testing requirement (see Figure 5). 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 2) compared with 8.4m in Scenario 2 (see Table 1)) 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 [3].

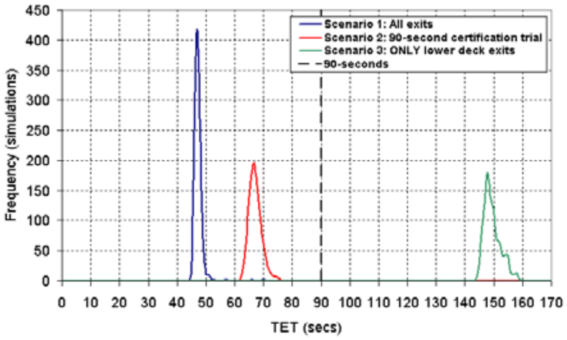

Figure 5: airEXODUS generated TET frequency distribution for scenarios 1, 2 and 3a

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.

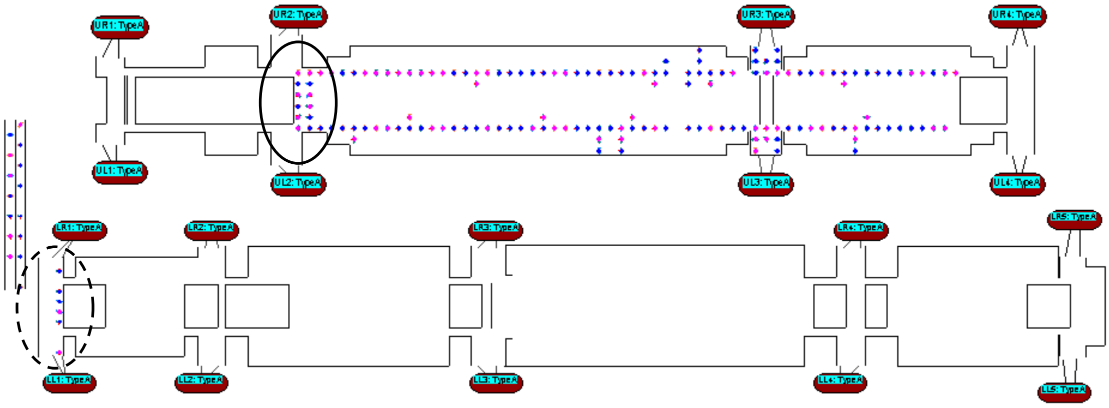

Figure 6: Graphic output from airEXODUS showing congestion at the top of the stairs 48 seconds after the start of the evacuation

Insight into the dynamics of this scenario was gained through examining the real time animation output from airEXODUS. Figure 6 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 6 reveals that the cross-aisle area at the foot of the staircase was sparsely populated (the dashed circle in Figure 6) in contrast to the densely populated reservoir at the top of the staircase (the solid circle in Figure 6). Furthermore, Figure 6 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.

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:

$$\textit{Discharge (capacity)} \approx \textit{Stair (capacity)} \approx \textit{Supply (capacity)} \qquad (1)$$

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 [7,35]. 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 [40] 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 2: 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 deck**			**Lower deck**		
	TET (secs)	**CWT (secs)**	**Dist (m)**	**PET (secs)**	**OPS**	**TET (secs)**	**# paxs**	**OPS**	**TET (secs)**	**# paxs**	**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.

3.7 Scenario 3b and 3c: Crew procedures addressing staircase performance

Two cabin crew were assigned duty stations on the lower deck 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 7).

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 [39].

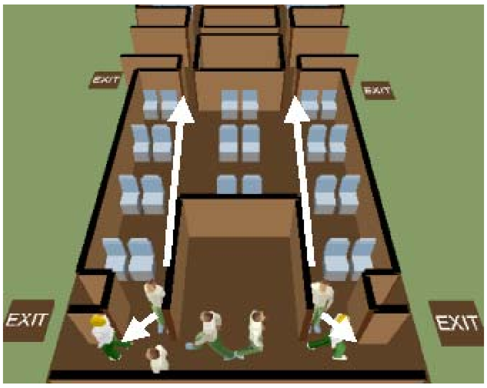

Figure 7: Example of crew exit responsibilities

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 2.1.6.2). 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 2. 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 3.6 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 2). 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.

3.8 *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 2) 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 3: 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)**	**# paxs**	**OPS**	**TET (secs)**	**# paxs**	**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 [3]. 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 8). 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 8).

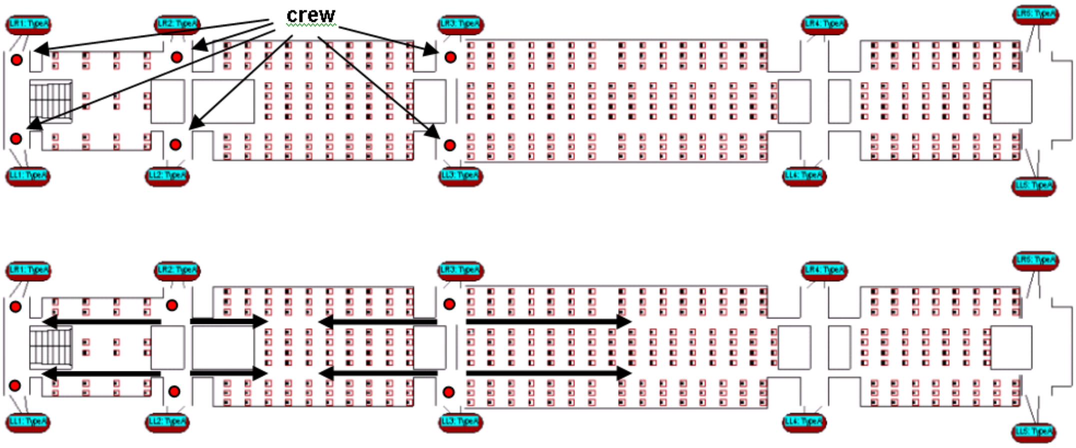

Figure 8: Lower deck cabin crew duty stations (top) and their responsibilities (bottom) in Scenario 4b

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 [24,25,37,38]. 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 8 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.

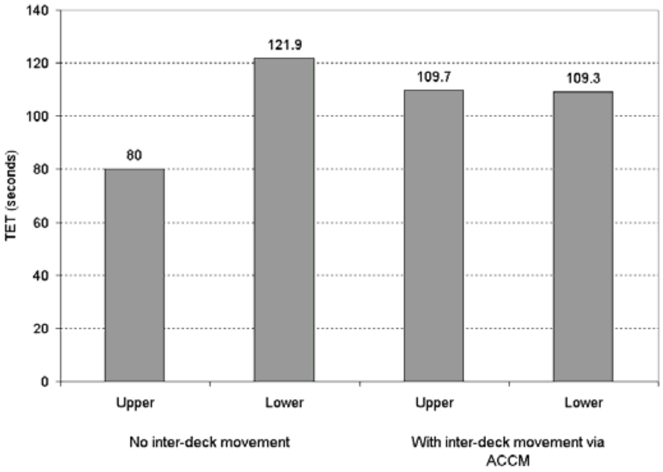

Figure 9: Summary of the finishing time of upper deck and lower deck exits with and without inter-deck movement

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 3). 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 3).

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.

4 Conclusions

This paper 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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