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Analysis of Evacuation Strategies for Design and Certification of Transport Airplanes

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A method developed to assess the influence of the cabin arrangement in the emergency evacuation of transport airplanes is described. The method has been conceived for design and certification purposes and is not intended to reproduce aircraft accidents. The procedure is based on a seat-to-exit assignment algorithm and a set of operational restrictions and is aimed at minimizing the total distance traveled by all passengers along the escaping path and obtaining the most adequate sharing among the exits. Three restrictions are considered: limitation in exit capacity, obligation to egress through the nearest exit, and limitation in the distance covered by each passenger. More than 30 cabins, belonging to turboprops, narrow-body, and wide-body jets, have been analyzed. Seat-to-exit distance of all passengers and number of evacuees per exit are the main output variables. A procedure to estimate differences in evacuation time among diverse conditions of the same cabin, or between cabins of similar airplanes, is described. The results show the influence of left to right asymmetries and inappropriate matching between size and longitudinal location of exits.

Introduction

IT is well known that the deceleration forces are within human tolerances in many airplane accidents: impact-survivable crashes, emergency landings, aborted takeoffs etc. A meaningful fraction of fatalities occurring in these situations is related to fire and toxic environment. Therefore, a key safety factor is the ability to evacuate the airplane[1,2] quickly.

To improve survivability in such circumstances, airworthiness authorities require manufacturers and operators to meet a number of design and performance standards related to cabin evacuation.[3,4] However, questions have been raised by experts and third parties concerning the adequacy of regulations covering emergency evacuation.[1,5] One of the most controversial of these regulations is the 90-s rule which requires the demonstration in any new or derivative-type airplane that all passengers and crew members can safely abandon the aircraft in less than 90 s, with half of the usable exits blocked, minimum illumination provided by floor proximity lighting, and a certain age–gender mix in the simulated occupants.[3,4]

The rule was established in 1965 with 120 s, and has been evolving over the years to encompass the improvements in escape equipment,[1] changes in cabin and seat material,[5,6] and more complete and appropriate crew training.[2,7–9] Very recently, a new amendment has introduced new exit types, new conditions to perform or assess evacuation demonstrations, etc,[10] although some questions are still open. Table 1 summarizes the updated requirements, including the new type-B and type-C categories, and a series of statements regarding additional interactions and limitations.

The unique objective of the demonstration is to show that the airplane can be evacuated in less than 90 s under the aforementioned conditions. Hence, the demonstration provides only a benchmark for consistent evaluation and cannot represent accident scenarios nor is intended for system optimization.

Demonstrations are costly (in the order of millions of dollars) and dangerous.[1,11] Detailed statistics show that most demonstrations result in minor injuries, and about 2% of all participants suffer serious lacerations, burns, and fractures.[12] For example, during the certification program of the McDonnell Douglas MD-11, two people were critically injured, and the tests were canceled for about one year.

To reduce the risk while keeping the aim of the requirement, a combination of partial demonstrations (essentially component and/or partial cabin testing) and analysis can be used in lieu of full-scale evacuations. For example, the Federal Aviation Administration (FAA) accepted the use by Lockheed California and The Boeing Company of partial tests and simplified analysis based on the timely summation of evacuation steps as a proof of compliance in certification.[13,14] Also, the FAA agreed with McDonnell Douglas on a series of partial tests for the certification of the MD-11, in which the participants were evacuated to level platforms, instead of deployable slides, although in only 62 s (Ref. 1).

There are two main ways of gaining insight and understanding in the evacuation process: experimental evacuation trials and computer-based research.

Extensive trials on evacuation performance have been conducted in various institutions, particularly at the Civil Aeromedical Institute of the FAA and Cranfield University (England, U.K.), this latter under the sponsorship of the British Civil Aviation Authority. Many studies focus on the influence of alternative seating arrangements in the egress rates through different types of exits.[12,15–17] Other programs considered the influence of demographic characteristics (age, gender, and girth) in evacuation performance.[15,18,19] Last, cabin crew training and personality,[7,9] passenger motivation,[15] presence of nontoxic smoke,[18] and escape path distance[5] have also received some attention. Interestingly, there is no research facility for investigating wide-body airplanes, and the situation will worsen with the advent of super jumbo aircraft with up to 1000 passengers.[20,21]

Computer models try to match the real world but have significant limitations, for example, on how the information is introduced into the computer; on the number of data and variables the computer can handle efficiently; and on the quality of the data required to validate the model. All airplane manufacturers have more or less simple semi-empirical models that compute total escape times by the summation of the duration of successive phases of the process, with data derived from experiments and certification demonstrations.[1,13,14]

Very few airplane evacuation models are described in open literature, none in great detail, and most are not currently in use.[22] The Civil Aeromedical Institute of the FAA and NASA were pioneers in the field during the 1970s, with models focused, respectively, on certification[23] and postcrash analysis.[6,24] In the late 1980s, the Air Transport Association of America sponsored a project called AIREVAC,[25] to simulate certification tests and to evaluate the impact of transporting disabled passengers. More recently, two British research groups (from Cranfield and Greenwich Universities) have

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Table 1 Summary of updated FAR 25-807

Exit type	Dimensions, mm Width	Height	Evacuation capacity[a]
A	1066.8	1828.8	110[b]
B	812.8	1828.8	75
C	732.0	1219.2	55
I	609.6	1219.2	45
II	508.0	1117.7	40
III	508.0	914.4	35[c]
IV	482.6	660.4	9
Ventral, Type I	——	——	12
Tail cone	——	——	25[d]/15[e]
Hatch	482.6	508.0	?

[a]Maximum number of passengers evacuated per exit.
[b]If an alphabetic type is used (A, B, or C), there must be at least two type-C or larger exits in each side of the fuselage.
[c]Combined maximum number of evacuees for all type-III exist is 70; combined maximum number of evacuees for two type-III exits in each side of the fuselage that are separated by fewer than three passenger seat rows is 65.
[d]Dimensions $\geq 508 \times 1524$ mm; floor level.
[e]Dimensions $\geq$ type III; top height > 1422 mm.

Table 2 Airplane database

Airplane	Passengers
Turboprops and Small Turbofans	
Fokker 50	50
Saab 2000	50
Canadair Regional Jet	50
BAe ATP	72
Casa 3000	78
Narrow-Body Turbofans	
BAC 1-11	74
Fokker 70	79
BAe 146-300	98
Fokker 100	107
B727-100	125
B737-500	132
B727-200	155
DC 9-S80	167
B737-400	168
A320-200	176
A321-100	200
B757-200 (8 exits)	212
B757-200 (10 exits)	217
DC 8-61	259
Wide-Body Turbofans	
A310-300	279
B767-200	290
B767-300	312
DC 10-30	399
L1011-200	400
A340-300	401
B777-200	496
B747-400	624
A3XX	854

developed comprehensive computer codes, mainly focused on studying aircraft accidents.[26–28]

The present paper describes a model that has been conceived for design and certification studies and is not intended (nor suitable) for aircraft accident analysis. The research work adopts a geometrical perspective and is somehow related and similar in results to a network-type model,[29] with the aim of determining the influence of the cabin arrangement in the evacuation process. The inherent limitations of the restricted perspective are largely counterbalanced by the capability of providing results that are independent from other, highly subjective factors such as cabin ambiance, demographic and psychological features of passengers, crew training and personality, etc.[1,5,7]

Cabin Database

The working material for the present paper is a set of cabin layouts corresponding to the aircraft appearing in Table 2. The airplanes have been grouped into three different categories: small transports, which include turboprops and the Bombardier Canadair Regional Jet (because of its relatively small size); narrow-body jets; and wide-body jets. Only two aircraft, CASA 3000 and Airbus A3XX are still on the design board, but fairly complete information on their cabins is available. Furthermore, the Airbus 3XX is the largest airliner ever conceived, with the additional interest of having a very large upper deck.

Number, location, and size of exits and aisles, as well as complete seating arrangement from each cabin are the essential input data for the purpose of the present study. All these data have been obtained from airport planning manuals, commercial brochures, JANE'S encyclopedia, and magazines. Whenever possible, data from different sources have been cross checked to improve reliability.

Because airplane manufacturers must fulfill the demands of a wide spectrum of operators, cabins are configured in a large variety resulting in different seating densities. For obvious reasons, high-density configurations have been used in the present work, corresponding in most cases to the maximum certified capacity.

No meaningful differences have been found when more than one cabin arrangement of the same airplane were available, with the exception of B757-200, which is duplicated. Two B757 cabins, one with 8 exits and 212 seats and another with 10 exits (including four type-III overwing exits) and 217 seats, have been included.

On the other hand, the upper and lower decks of B747-400 (85 and 539 seats) and A3XX (357 and 497 seats) are taken as fully independent entities. The method may handle the stair connections between decks as doorways, but these are assumed to be blocked in the present analysis.

All cabin data used in the study have been collected and filed in the computer with a systematic and efficient procedure, implemented in C++ language.[30] The geometry of a given cabin is defined by means of four groups or classes of data: exit, aisle, seat, and crew. Each class is made up of objects, each with several attributes. To locate all objects, a reference system has been established with the origin of coordinates at the aircraft nose, the x axis along the plane of symmetry and directed rearwards, and the y axis transverse, with positive values oriented starboard. Cabin data registered in this way are compatible with the future development of network or queuing models[22,29] and have all of the advantages of object-oriented programming.[11]

As an example, the exit class has N_{exit} objects, where N_{exit} is the total number of exits of the airplane. Each object has three attributes: longitudinal and transverse coordinates of the exit center and maximum number of passengers permitted to evacuate through the exit according to updated Federal Aviation Regulations (FAR) 25 (Ref. 10).

On their side, the aisles are modeled by a series of straight segments, with the same number of segments for all aisles. Each one requires $2\ (N_{sg} + 1)$ data, where N_{sg} is the number of segments.

To reproduce the seating arrangement efficiently, two intermediate concepts are introduced: block (a set of physically united seats) and zone (a set of blocks with the same number of seats, seat size, and pitch). Each zone has a master seat (the foremost and leftmost seat) and nine attributes: the number of blocks in the zone, the number of seats per block, the longitudinal and transverse coordinates of the left rear corner of the master seat, the seat width (seat back plus one armrest), the transverse displacement between consecutive blocks in the zone (0 in the cylindrical part of the fuselage), the longitudinal seat pitch, an identifying number of left aisle (0 if there is no aisle at left), and an identifying number of right aisle (0 if there is no aisle at right).

Seat class data are directly derived from zone class data. The representative point of each seat is assumed to be the point where the passenger stands up, approximately with the chest on the back of the seat in the former row. This leads to a class with only two data per object: the coordinates of the standing point. The seating arrangement is, thus, defined with high accuracy and is not limited

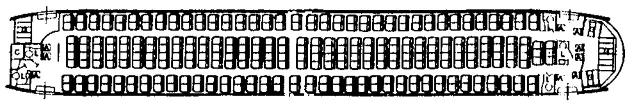

Fig. 1 Cabin of a high-density version of the Boeing B767-200 with 8 exits and 290 passengers.

to a node-matrix-type layout that can be found in most evacuation simulation studies.[6,14,24,27]

The fourth and last group is the crew member class, with two different kinds of objects: 1) the flight crew who will evacuate the airplane using the foremost available exit and 2) the cabin attendants who will leave the airplane using the nearest available exit to the assigned exit (this one included).

Figure 1 shows the cabin of a B767-200, which can be used to explain the aforementioned definitions. The exit class has eight objects, four type-A doors and four type-III overwing exits, which are numbered first port, fore to aft, and then starboard, fore to aft. The aisle class has two objects with only one segment, that is, they are straight lines running along the fuselage. Finally, the definition of the seat class requires data for nine zones, numbered in the same way as the exits: the first zone has 17 blocks with two seats; zone 2 has 2 blocks (with a larger pitch) with 2 seats each; zone 3 includes 17 blocks with two seats, and so on.

Formulation of the Problem

The computer model in the present analysis takes as starting point a seat-to-exit assignment algorithm[30] that can be combined with diverse rules and can be mathematically manipulated to search the minimum of an objective function through linear programming optimization. In the present approach, the objective function is the total distance run by all passengers along their escaping paths. Using the total distance has three major advantages: It is related to the reaction of all of the passengers; it is representative of the global performance of the cabin; and it admits linear programming over the whole study. On the other hand, the average distance, that is, the total distance divided by the number of passengers, is very appropriate for comparisons.

The total distance is defined as follows:

$$D = \sum_j \sum_i x(i, j) d(i, j) \tag{1}$$

where $d(i, j)$ is the distance between the ith seat and the jth available exit and $x(i, j) = 1$ if the ith seat is assigned to the jth exit, or is equal to 0 otherwise.

Within a purely geometrical perspective, the evacuation problem is considered here as a pseudo-Boolean linear optimization problem, where the variables are the Boolean (binary) elements of the assignment matrix $x(i, j)$ and the linear objective function is

$$F([A]) = \min(D) \tag{2}$$

Several constraints and scenarios, related to various evacuation strategies, are described as follows.

1) With constraint C0, each seat can only be assigned to an available exit. This rather obvious constraint is essentially a conservation law. Mathematically it corresponds to

$$\sum_j x(i, j) = 1 \tag{3}$$

2) With constraint C1, the evacuation capacity of the exits is size-limited according to updated FAR 25-807 (Ref. 10).

3) With constraint C2, all passengers must use the first exit found along their evacuation path.

4) With constraint C3, the distance covered by any passenger along the escaping path must be shorter than certain value. It is easy to see that limiting the maximum distance covered by any passenger leads to either lack of solution or one of the other constraints already considered.

Consistent with the constraints, four different scenarios have been conceived and studied in full detail in the present analysis. Each scenario is mathematically composed of the seat-to-exit assignment algorithm, one or more of the former constraints, and a linear programming optimization code.

Case RT0

No constraints have been imposed, except the obvious conservation-law-type C0. This case takes only into account the relative position of seats and available exits, without considering actual exit capacities. It can be interpreted as the pattern produced by the impulsive decision of passengers to go to the nearest exit, regardless of its size. It provides the absolute minimum value of the objective function for each cabin, although far from the minimum evacuation time, as will be shown in the next section.

Case RT1

This case adds constraint C1 to the former case. It can be interpreted as the evacuation capacity of a cabin from the viewpoint of the relative position between seats and available exits, but considering the size of exits. In other words, it can simulate the more sensible behavior of passengers who take a certain escaping route for its perceived evacuation potential: exit size and distance to the exit.

Case RT2

This case adds constraint C2 to the RT0 case. It represents the common condition that the passengers will use the first available exit found along their escaping paths. It seems very appropriate for narrow-body airplanes because there is no practical alternative to bypass the exit, even if it is crowded. However, in wide-body airplanes the situation is far less obvious due to the existence of the second aisle, which would require additional specific studies.

Case RT3

This case simultaneously includes constraints C0, C1, and C2. It is close to an actual, orderly evacuation performance of the cabin, as in certification demonstrations, and it represents somehow an optimum evacuation. Note that simultaneously fulfilling various constraints is very demanding and, in some cases, the linear optimization problem can only be solved if a certain increase in the evacuation capacity of exits is allowed.

The four assignment strategies (RT0–RT3) are applied to aircraft of different sizes and arrangements, including turboprops, narrow-body, and wide-body jets, as shown in Table 2. The output variables of the computer model are the number of evacuees through each available exit, seat-to-exit distance histograms, total and average distance, and increase in evacuation capacity in the case RT3 if required.

Evacuation Flow Rate and Time Analysis

The former process provides data to compute differences in evacuation time among various scenarios of the same cabin. Time differences between cabins of similar airplanes in the same scenario can also be obtained, although with lesser accuracy.

Let us consider some basic aspects of the evacuation process within the perspective of network-type models that operate with outflowing capacities. Certification demonstrations and experimental trials prove that the flow rate through emergency exits, F, depends primarily on exit size and very little on the distance the evacuees have to cover. In the case of doors, F is obtained by dividing the exit evacuation capacity (shown in Table 1) over 75 s (90 s minus a suitable time to open the door and have the slide fully deployed and usable).[31] Analogously, for type-III exits, F is close to $35/80 = 0.44$ persons per second.

As in any duct or pipe, the setting up of the flow requires some time, but a simple calculus shows that the exit always operates in a steady state. Figure 2 shows a typical seat-to-exit distance histogram. The rapidly changing evacuation flow at the beginning will form a wave when the point of maximum slope on the left-hand side of

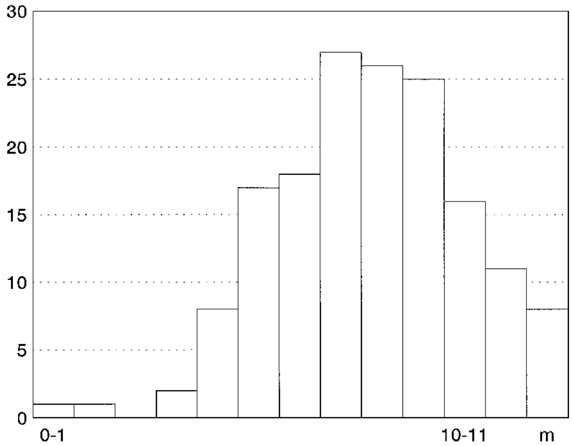

Fig. 2 Typical seat-to-exit distance histogram.

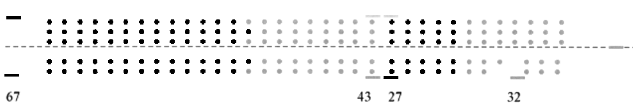

Fig. 3 Seat-to-exit assignment of case RT3 for DC9-S80 with all port exits available, indicating the number of passengers evacuated through each exit.

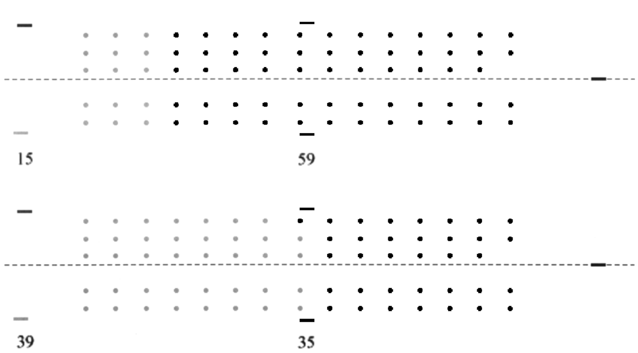

Fig. 4 Seat-to-exit assignment of cases RT0 (top) and RT3 (bottom) of the BAC 1-11.

the histogram reaches the exit. For example, in Fig. 2, with the maximum slope at 5 m, and typical speeds of 0.3–0.5 m/s for lateral displacement in the row and more than 1 m/s along the aisle,[6,14,24] the wave reaches the exit in about 6 s. For all exits of the airplanes studied, this time ranges between 4 and 10 s. Because the total time for opening the door and deploying the slide is typically between 10 and 20 s, the surroundings of the exit are full with ready evacuees from the instant it becomes practicable.

On adopting a geometrical perspective, two main evacuation problems can be distinguished: overcrowded exits due to uneven and inadequate sharing and reverse flow conflicts close to the border between seating areas corresponding to different exits.

For a better understanding of the border conflict, Fig. 3 shows the sharing in case RT3 of a DC9-S80 when exits L1, L2, L3 and L4 are available. Passengers on both sides of the aisle in row 14 are assigned to either exit L1 or L2. Consequently, they have to take opposite directions when reaching the aisle. This situation certainly slows down the movement in the row–aisle junction. Very likely, a delay of about 0.3 s (the typical row–aisle junction occupation per passenger) is produced every time a change in direction occurs. Moreover, the solution of the conflict can result in changing the destination of some passengers or, in other words, in overcrowding some exits.

Continuing the analysis, Fig. 4 presents the computer solutions of cases RT0 and RT3 for a BAC 1-11, which will serve as an example on how to compute increments in evacuation time. Scenario RT3 is taken as the reference, optimum case. In the solution of case RT0, exit L2 is overcrowded; that is, it is used by 59 passengers although its theoretical capacity is only 35. Extra passengers require extra evacuation time (seconds):

$$\Delta t = \Delta N_{\text{pas}} / F_{\text{III}} = 24/0.44 = 54.5 \tag{4}$$

but, at the same time, exit L1 attracts more evacuees than case RT3. Consequently, some time (seconds) must be discounted:

$$-\Delta t = -\Delta N_{\text{pas}} / F_C = -24/0.73 = -32.9 \tag{5}$$

The true increment is $54.5 - 32.9$, that is, 21.6 s. In other words, case RT0 would require 21.6 s more in the evacuation process than the RT3 case. The apparent reverse flow conflict of a passenger in row number 8 does not exist because the passenger is seated by the window, and the row–aisle junction will be vacant at his/her arrival to that point.

In more complex cabins, the process is similar, always using the most overcrowded exit in the nonreference case to compute the extra evacuation time, and the most overcrowded exit of the reference case to compensate partly that increase. The remaining exits do not influence the result.

The interest and applicability of this simple computation process result from it being based on the results of an optimization process subject to realistic constraints.

Results

A fairly large number of situations have been analyzed because the database includes 31 configurations, each cabin arrangement has been studied in four constraint scenarios, and various combinations of available exits have been checked for every scenario. The results shown here are only a fraction, though representative, of the type of output and possibilities provided by the method.

Note that although the new regulations are in general more generous and flexible with the evacuation requirement, a few currently flying airplanes have certified capacities above the figures corresponding to the new FAR 25-800s[10] shown in Table 1. For example, the studied cabin of A310-300 has 269 passenger seats, which is a little more than 265 for two type-A doors plus one type-I door. The same happens to B767-200, which has 290 seats that should be reduced to 285, corresponding to its two type-A doors and two coupled type-III overwing exits.

As an example of comparative results, Fig. 5 shows the evacuation assignment for the A320-200, with all port exits available, in the cases RT0 (no constraints), RT1 (limitation in the capacity of exits), and RT3 (all constraints simultaneously). In the first case, the cabin zones between exits are practically divided into halves; this yields a very unbalanced sharing with only 30 passengers assigned to the front door, 42 to the first type-III exit, 60 to the second overwing exit, and only 44 to the rear door. When the capacity limitation (case RT1) or all constraints are imposed (case RT3), the pictures of the cabin become more balanced, and the number of passengers assigned to each exit are closer to a real world performance.

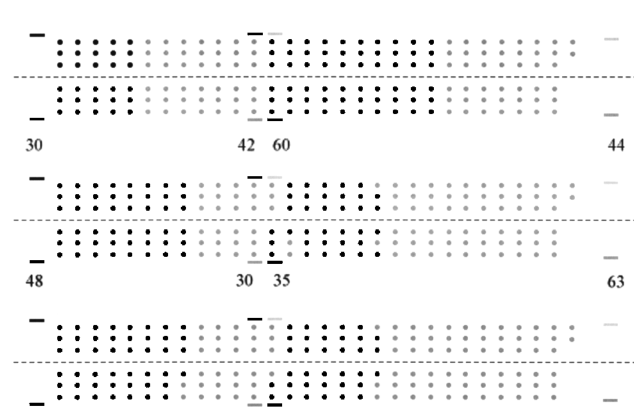

Fig. 5 Seat-to-exit assignment of cases RT0 (top), RT1 (center), and RT3 (bottom) of Airbus A320-200.

The most overcrowded exit found in this study, in absolute terms, corresponds to exit L2 (type-A door) of the L1011 in the unconstrained condition (RT0) with 160 passengers. This result is closely linked to the airplane configuration. The wing of the L1011 is shifted rearwards because of the third engine, and the wing–body junction, lying between exits L2 and L3, is quite long for a relatively low wing aspect ratio. Therefore, exit L2, which is located close to the center of the cabin, attracts too many passengers. In the same way, the most overcrowded exit in condition RT3, in relative terms, is door L1 of the DC9-S80 (see Fig. 3).

Apart from the number of evacuees per exit, the method also provides the individual seat-to-exit distances. Figures 6 and 7 show the histograms corresponding to the four port A doors of the L1011, for cases RT1 (limitation in exit capacity) and RT3 (all constraints), respectively. Exits L1, L2, and L3 show small differences between these two scenarios. However, exit L4 in case RT1 is assumed to receive passengers that are seated in an isolated cluster at about 20 m from that door; when constraint C2 is also applied in case RT3, those passengers are reassigned to L3 because they pass very near this exit in their route to exit L4.

Table 3 Mean distance and related results for turboprops and the regional jet

Available exits	RT0/2 d_{med}	RT1 d_{med}	RT3 Δ, %	RT3 d_{med}	$\rho(\frac{1}{0})$	$\rho(\frac{3}{0})$	$\rho(\frac{3}{1})$
Fokker 50							
L1/L2	5.8849	5.8849	0	5.8849	1	1	1
R1/R2	5.9129	5.9129	0	5.9129	1	1	1
L2/R1	5.8849	5.8849	0	5.8849	1	1	1
L1/R2	5.9129	5.9129	0	5.9129	1	1	1
BC Regional Jet							
L1/L2	3.8945	3.9551	0	3.9551	1.016	1.016	1
R1/R2	3.9175	3.9601	0	3.9601	1.011	1.011	1
L1/R2	3.8978	3.9584	0	3.9584	1.016	1.016	1
L2/R1	3.9142	3.9568	0	3.9568	1.011	1.011	1
Saab 2000							
L1/L2	4.1074	4.1382	0	4.1382	1.008	1.008	1
R1/R2	4.8830	5.0138	0	5.0138	1.027	1.027	1
L1/R2	5.8384	5.8384	0	5.8384	1	1	1
L2/R1				Not possible			
BAe ATP							
L1/L2	4.8918	6.2984	9	6.0250	1.288	1.232	0.957
R1/R2	4.3180	5.6677	0	5.6677	1.313	1.313	1
L1/R2	6.3887	6.3887	0	6.3887	1	1	1
L2/R1				Not possible			
Casa 3000							
L1/L2	4.8673	6.0234	3	5.9083	1.238	1.214	0.981
R1/R2	4.5977	5.5034	3	5.4002	1.197	1.175	0.982
L1/R2	4.8698	6.0260	3	5.9109	1.238	1.214	0.981
L2/R1	4.5950	5.5008	3	5.3976	1.198	1.175	0.982

A given exit type can play quite a different role in different types of airplanes. Thus, in the RT3 situation of small airplanes, the type-C exit of a CASA 3000 gets most of the passengers (42 out of 78); in a BAe ATP the figure falls to 34 out of 72, decreasing even more in an F50 with 22 from 50, and reaching a minimum value in absolute and relative terms with only 15 out of 50 in the regional jet. In this airplane, the overwing exit is very well centered and gets many more passengers than the type-C door, without overflowing its capacity.

A comprehensive summary of distance-related results is shown in Tables 3–5 for the three groups of airplanes considered. The main output is the average distance, presented in the third, fourth and sixth columns, for certain combinations of scenarios and available exits. Consistent with the mathematical approach followed in this study, the average distances of case RT0 (no constraints) are always shorter than those in cases RT1 or RT3. The results show that the average distance is only weakly related to airplane size. Note that the Saab 2000 and BAe ATP exhibit large differences between the results corresponding to combinations L1/L2 and L1/R2 due to lack of symmetry, and Fokker 50 and BAe146 show the longest average distance in the small aircraft and narrow-body groups, respectively, because in both airplanes their high wings enforce the exits to be shifted to both extremes of the cabin. Also, paradoxically, the average distance is always longer in the A320 than in its stretched version, A321, due to the better location of exits in the latter.

On the other hand, the fifth column shows the increase in evacuation capacity required to meet the RT3 condition. This increase, as explained in a preceding section, is required by the linear optimization problem solver in some situations. Both small and wide-body aircraft perform quite well; that is, they do not require meaningful increases (except in one condition of BAe ATP). However, narrow-body jets pose some problems, essentially due to the unevenly distributed exits along the fuselage. The most extreme cases correspond to the DC9-S80 with 23% extra capacity required (in exits L1 and L2 as shown in Fig. 3) and DC8-61 with 18%.

The relative lengthening ρ of the mean escaping distance due to limitation in exit capacity (constraint C1) is presented in the seventh column. This lengthening is remarkable in some situations of three airplanes of similar size: BAe ATP (1.31), BAC 1-11 (1.24), and CASA 3000 (1.24). The same occurs in the very stretched DC8-61 and in the two smaller wide bodies, B767- 200 (1.21) and A310-300 (1.18), which marginally overflow the updated emergency evacuation regulation. A parallel situation occurs when all constraints are considered simultaneously, as shown in the eigth column.

Remarkably, the most problematic situations occur in two conditions: first, when there are too many passengers assigned to one or more exits in a too slender cabin (DC9-S80) and second, when the difference between the average distances of cases RT1 and RT3 are larger than 3% (BAe ATP, F100, B727-200, B757-200-10e, DC8-61, and L1011) because this implies a mismatch between location and capacity of the exits. In this last situation, the evacuation potential of the exits are deceitfully perceived by the passengers and some of

Table 4 Mean distance and related results for narrow-body jets

Airplane	Available exits	RT0/2 d_{med}	RT1 d_{med}	RT3 Δ, %	RT3 d_{med}	$\rho(\frac{1}{0})$	$\rho(\frac{3}{0})$	$\rho(\frac{3}{1})$
BAC 1-11	R1, R2	5.2334	6.4694	0	6.5000	1.237	1.243	1.005
F70	R1, R2	5.3149	5.3149	0	5.4139	1	1.019	1.019
BAe 146-300	R1, R2	7.0084	7.0084	0	7.0084	1	1	1
F100	R1–R3	5.8329	6.3183	15	5.9959	1.084	1.028	0.949
B727-100	C1, R1–R3	5.2729	5.2754	0	5.2754	1.001	1.001	1
B737-500	R1–R3	5.3412	5.9960	0	5.9960	1.123	1.123	1
B727-200	C1, R1–R4	5.1474	5.7480	11	5.3895	1.117	1.048	0.938
DC9-S80	L1–L4, C1	5.7322	6.0160	23	6.0265	1.05	1.052	1.002
B737-400	R1–R4	5.7898	6.1534	0	6.1534	1.063	1.063	1
A320-200	L1–L4	5.9731	6.4433	0	6.4624	1.079	1.082	1.003
A321-100	L1–L4	5.7246	6.1362	0	6.1362	1.072	1.072	1
B757-200 (8e)	R1–R4	6.0754	6.6188	0	6.6188	1.09	1.09	1
B757-200 (10e)	R1–R5	5.9823	6.3246	16	6.0195	1.058	1.007	0.952
DC8-61	R1–R6	5.2099	6.6688	18	5.7840	1.281	1.111	0.868

Table 5 Mean distance and related results for wide-body jets

Airplane	Available exits	RT0/2 d_{med}	RT1 d_{med}	RT3 Δ, %	RT3 d_{med}	$\rho(\frac{1}{0})$	$\rho(\frac{3}{0})$	$\rho(\frac{3}{1})$
A310-300[a]	L1–L3	7.2871	8.6065	0	8.6065	1.182	1.182	1
B767-200[b]	L1–L4	6.9789	8.3610	2	8.4791	1.199	1.215	1.015
A3XX c2	L1–L4	7.5784	7.8374	0	7.8374	1.035	1.035	1
DC10-30	L1–L4	7.1895	7.4609	0	7.4609	1.038	1.038	1
L1011-200	L1–L4	7.7239	8.4905	5	8.2108	1.1	1.064	0.968
A340-300	L1–L4	7.8303	8.3736	0	8.3736	1.07	1.07	1
B777-200	L1–L5	7.3427	7.6816	0	7.6816	1.047	1.047	1
A3XX c1	L1–L5	7.6140	8.3656	0	8.3656	1.099	1.099	1
B747-400	L1–L5	7.3943	7.4672	0	7.4672	1.01	1.01	1

[a]With 55 passengers through type-I exit.
[b]With decoupled type-III exits.

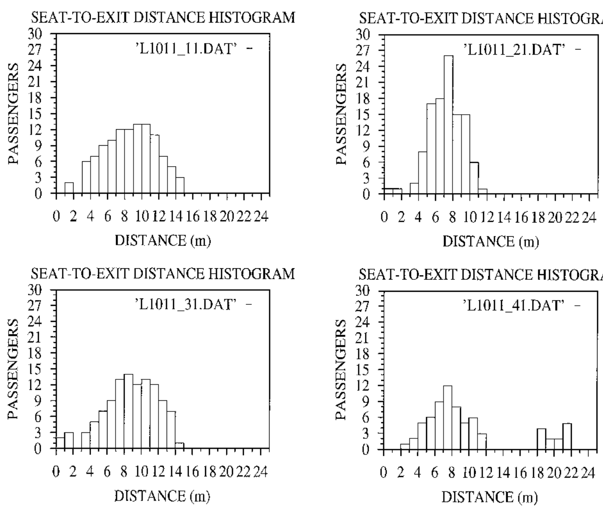

Fig. 6 Seat-to-exit distance histogram of case RT1 for the L1011.

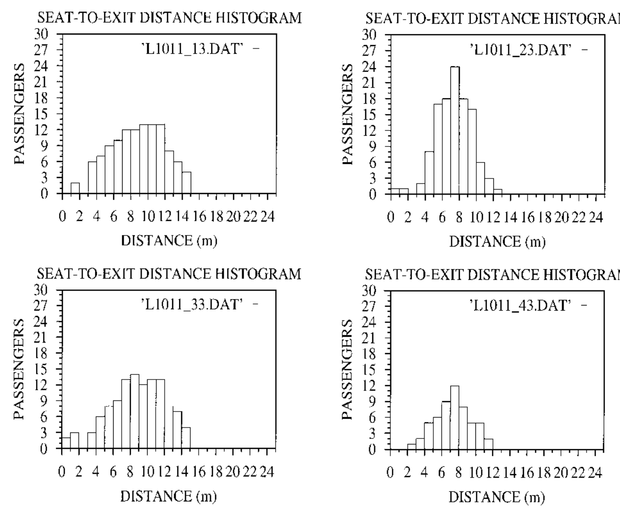

Fig. 7 Seat-to-exit distance histogram of case RT3 for the L1011.

them address to mistaken exits, with the subsequent unbalance in the sharing and slowness in the process.

An important application of the direct results, that is, the number of evacuees per exit and the seat-to-exit distance, is the capability of computing the increase in evacuation time between different cases of the same airplane or between the same scenario but distinct aircraft; a process that was described at the end of the preceding section.

Let us start with the A320 data presented in Fig. 5. The number of evacuees through exit L3 is much higher in case RT0 than in case RT3. On the other hand, all other exits are far from their maximum capacity. Therefore, no time discount needs to be considered. A few border conflicts in case RT3 hardly introduce a minor correction. The result (seconds) is then

$$25/0.44 - 7x0.3 = 54.7 \tag{6}$$

which indicates that case RT0 is much slower than case RT3, as expected for the underlying philosophy in both constraint scenarios.

The same sequence, applied to cases RT1 and RT3 (the latter being always the reference) results in

$$2/0.73 - 2/1 = 0.7 \tag{7}$$

which implies that both scenarios are very similar indeed. As a matter of fact, there are very little differences in the A320 between cases RT1 and RT3, both in terms of the number of evacuees in the various exits and in the average escape distance (see Table 4).

The whole process has been repeated for the four port type-A doors of the L1011 cabin. Case RT0 requires an evacuation time 30 s longer than case RT3 for three factors: There are 45 extra passengers in exit L2, all other exits are below the L2 exit utilization level, and there are two passengers in the conflicting border area between exits L3 and L4. The seating assignment of case RT1 (see Fig. 6) demands special attention because there is a group of 13 people located between exits L2 and L3 but assigned to exit L4. In real life, these passengers would go to either exit L2 or L3 (a solution not provided by the computer), and the time increase would vary between 1.4 and 5.4 s depending upon the splitting of the group. Case RT3 for the L1011 is shown in Fig. 7.

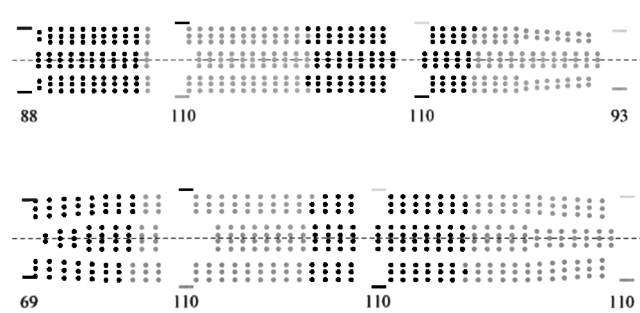

Fig. 8 Seat-to-exit assignment of case RT3 for the A340 (top) and DC10 (bottom) with all port exits available.

Comparing the same scenario (case RT3) but distinct airplanes needs more elaboration and is less accurate, although the quantitative information can also be very useful. For example, the A320 and the B737-400 have eight exits each with a very similar number of passengers in the cabins studied, but some exits are different in size and evacuation capacity. The time analysis indicates that, in spite of having a somewhat smaller cabin, the B737-400 requires 4.1 s more than the A320 for 3 extra passengers in the front type-C exit. Following an analogous process, the evacuation of the A310 takes 2.9 s longer than that of the B767-200.

An easier situation occurs when comparing the largest wide bodies, A340, DC10, and L1011: All have the same number and size of exits and almost the same number of passengers. The seating assignment distributions of the A340 and the DC10 are very similar (see Fig. 8), except for the more dense DC10 rear cabin. The

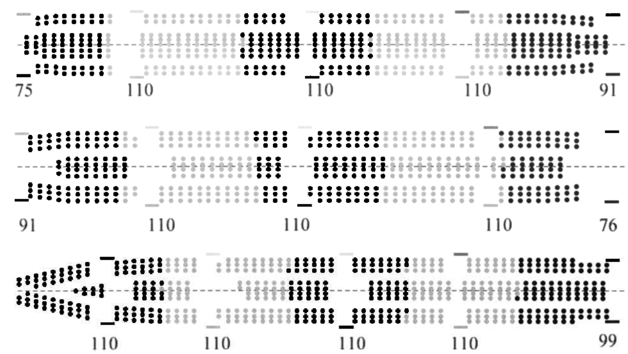

Fig. 9 Seat-to-exit assignment of case RT3 for the B777 (top), lower cabin of the A3XX (center), and the B747-400 (bottom) with all port exits available.

time analysis results in no difference between these two aircraft. However, the L1011 is less evenly distributed, with a half-loaded rearmost exit and some extra occupation in the other three (5 passengers in each one), implying about 3.4 s longer evacuation with respect to the aforementioned airplanes.

Finally, the B777 and the lower decks of the B747-400 and A3XX have again the same number and size of exits and similar seating arrangements (Fig. 9). In scenario RT3, exits L2, L3, and L4 of these three airplanes are equally loaded, with the maximum capacity; the other exits do not affect the result and, hence, the time analysis indicates that there are no differences at all in evacuation performance.

Conclusions

A method to study the evacuation of transport airplanes for design and certification purposes has been developed. The method is based on a seat-to-exit assignment algorithm that can be combined with diverse rules and constraints and can be mathematically manipulated through linear programming optimization to search the most appropriate sharing among the exits. The process is later completed with a simple flow rate analysis. The main findings of this work can be summarized as follows:

1) Very meaningful information on the influence of the cabin arrangement in the evacuation process can be obtained within a geometrical approach. This information provides useful guidelines for studying emergency evacuation demonstrations and allows computation of the difference in evacuation time between diverse scenarios of the same cabin or between different cabins under the same conditions.

2) The configuration of the airplane, particularly the wing-to-body relative position, is a key factor for the location of exits and, therefore, for the evacuation performance of the cabin.

3) Inadequate sharing among exits may result in long-lasting evacuations, with up to 30 s of extra evacuation time.

4) Uneven longitudinal distribution of exits and lack of left-to-right symmetry enhance the difficulties in evacuation.

5) The exits located closer to the center of the cabin attract relatively more evacuees that those at the extremes of the cabin.

6) The mean distance covered by the passengers along their escaping paths is only weakly dependent on airplane size. Some stretched versions exhibit better performance because of larger exits in the midsection of the cabin.

7) The evacuation capacity of small airplanes does not pose problems due to the presence of relatively large entrance and service doors.

8) Narrow-body jets have, in general, more evacuation problems due to their large cabin slenderness and the presence of small overwing exits.

9) Problematic cabin arrangements, due to mismatch between location and size of the exits, can be identified through either the existence of overloaded exits or by detecting differences in the results corresponding to the case with limitation in evacuation capacity of exits (RT1) and the case representing the most realistic scenario (RT3).

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