A98-31692

ICAS-98-6,7,5

STRATEGIES FOR MINIMUM DISTANCE IN SIMULATED EVACUATION OF TRANSPORT AIRPLANES

Martínez-Val, R., Hedo, J. M. and Hernández, C.
ETS Ingenieros Aeronáuticos
Universidad Politécnica de Madrid

Abstract

The present paper describes the preliminary stages of the development of a new, comprehensive model conceived to simulate the evacuation of transport airplanes in certification studies. Two previous steps were devoted to implementing an efficient procedure to define the whole geometry of the cabin, and setting up an algorithm for assigning seats to available exits. Now, to clarify the role of the cabin arrangement in the evacuation process, the paper addresses the influence of several restrictions on the seat– to–exit assignment algorithm, maintaining a purely geometrical approach for consistency. Four situations are considered: first, an assignment method without limitations to search the minimum for the total distance run by all passengers along their escaping paths; second, a protocol that restricts the number of evacuees through each exit according to updated FAR 25 capacity; third, a procedure which tends to the best proportional sharing among exits but obliges to each passenger to egress through the nearest fore or rear exits; and fourth, a scenario which includes both restrictions. The four assignment strategies are applied to turboprops, and narrow body and wide body jets. Seat to exit distance and number of evacuees per exit are the main output variables. The results show the influence of airplane size and the impact of non-symmetries and inappropriate matching between size and longitudinal location of exits.

Introduction

Safety has been the major driving force in commercial aviation, since regular operations were established after the First World War, closely followed by performance, economics and, very recently, environmental issues [1]. The awareness on all aspects of aviation safety, apart from general public which intermittently awake worried and grieved after every accident, is permanent in designers and operators, and is particularly active in airworthiness authorities since they have the objective of improving safety levels and establishing appropriate regulations [2, 3].

As a multifactor concept, safety affects and is influenced by the aircraft itself, crew, passengers, the environment, etc, together with the standards to be followed in each appropriate case [4]. A particular issue, related to transport airplane safety, is emergency evacuation that must take place whenever, after an impact–survivable crash, emergency landing or aborted take–off, extreme hazards, like fire, toxic gases, etc, appear. It is well known that in many airplane accidents deceleration forces are within human tolerances and, therefore, a key factor of post–crash safety is the ability to quickly evacuate the airplane [5]. About 10 percent of fatalities are related to fire and toxic environment in, otherwise, survivable accidents [6, 7].

To improve survivability in such circumstances, the airworthiness authorities require manufacturers and operators to meet a number of design and performance standards related to cabin evacuation, although questions have being raised by experts and third parties concerning the adequacy of regulations about emergency evacuation among other debated issues [6, 8]. One of the most controversial of these regulations is the 90 second rule, which requires the demonstration that all passengers and crew-members can safely abandon

---

EXIT TYPE	DIMENSIONS (mm)		Evacuation Capacity[1]
	Width	Height	
A	1066.8	1828.8	[2] 110
B	812.8	1828.8	75
C	732.0	1219.2	55
I	609.6	1219.2	45
II	508.0	1117.7	40 40
III	508.0	914.4	[3] 35
IV	482.6	660.4	9
Ventral	Type I		12
Tail cone	-		[4] 25 / [5] 15
Hatch	482.6	508.0	?

TABLE NOTES

[1] Maximum number of passengers evacuated per exit.

[2] If an alphabetic type is used (A, B o C), There must be at least two type C or larger exits in each side of the fuselage.

[3] Combined maximum number of evacuees for all type III exits is 70 and 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.

[4] Dimensions $\geq$ 508 × 1524 mm; floor level.

[5] Dimensions $\geq$ type III; top height $>$ 1422 mm.

Table 1: Summary of updated FAR-25.807

the aircraft cabin in less than 90 seconds, with half of the usable exits blocked, with the minimum illumination provided by floor proximity lighting and a certain age–gender mix in the simulated occupants [2, 3].

The rule was established in 1965 with 120 seconds, and has been evolving over the years to encompass the improvements in escape equipment [6], changes in cabin and seat material [8, 9], and more complete and appropriate crew training [5, 10, 11]. Very recently, a meaningful move has modified the up to now classical approach with new exit types, new conditions to perform or assess evacuation demonstrations, etc [12], although some questions are still open. Table 1 summarizes the capacity of exits, including the new type B and type C categories. These capacities are completed in the regulations with 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 seconds under the aforementioned conditions. So the demonstration provides only a benchmark for consistent evaluation, which allows for comparisons among diverse seating arrangements or modifications in existing airplanes. Obviously, the demonstration can not represent accident scenarios and is not intended for system optimization. It is acknowledged that most airplanes currently in service could not meet the 90 second rule for random combinations of 50 percent of available exits [8]. Thence, the commonly accepted procedures are to use all exits in anyone of both sides of the fuselage, or taking one of each pair of exits (this is impossible to achieve in some airplanes which have a very non-symmetric and uneven placement of exits).

Demonstrations are costly and dangerous. The cost of conducting full–scale tests is around $2 millions and involves around 4000 people for wide body transports [6, 13], but airplane manufacturers indicate that their real concern is the risk of injuries to participants. Detailed statistics show that most demonstrations result in minor injuries and about 2 percent of all participants are seriously injured with lacerations, burns and fractures [14]. As an example, during the certification program of McDonnell Douglas MD–11 two people were so importantly injured that the tests were cancelled 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, FAA accepted the use by Lockheed and Boeing of partial tests and simplified analysis based on timely summation of evacuation activities as proof of compliance in certification [15, 16]. Also, FAA agreed with McDonnell Douglas on a series of partial tests for the certification of MD–11, in which the participants were evacuated to level platforms, instead of deployable slides, though in only 62 seconds [6, 7]. With the same aim of reducing risks, the authorities accept various age–sex distributions [6], for example with none under 18 and above 60, but impose restrictions on the selection of participants taking part in demonstrations. These age–sex distributions hardly represent the real flying passenger mix. Moreover, passenger demographics vary from country to country and seasonally.

There are two main ways of gaining insight and understanding on the evacuation process: studies on evacuation performance and computer comprehensive modelling. The studies on narrow body fuselages are easier and can be carried out in several countries [6], but 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 [17, 18].

Extensive research programs on evacuation performance have been conducted in various institutions, particularly at the Civil Aeromedical Institute of FAA and Cranfield University (United Kingdom), this last under the sponsorship of the British CAA. Some studies focus on the influence of alternative seating arrangements in the egress rates through different types of exits [14, 19, 20, 21] and have resulted in proposals for new standards. Other programs considered the influence of demographic characteristics in evacuation performance [19, 22, 23] and, as it could be expected, age, girth and gender (in this order) have the most important effect [23]. Last, cabin crew training and personality [11], passenger motivation [19], and escape path distance [8] among other topics have also received some attention. As an example of the type of results obtained, Fig. 1 depicts the egress rate in a number of finalized and abandoned evacuation experiments [19].

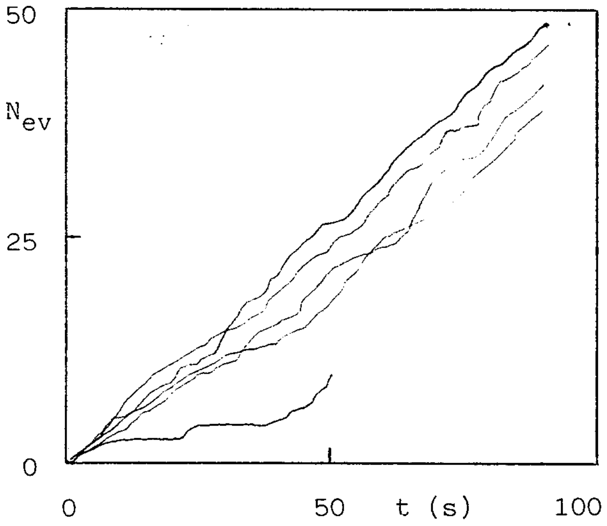

Figure 1: Representation of evacuation trials

Evacuation modelling

As stated above, analysis is not a valid proof of compliance for the certification of emergency evacuation provisions of airplanes, but airworthiness authorities accept the combination of analysis and partial demonstrations for this purpose. Therefore, since the cost and risk associated to full-scale tests are so important, a continuing effort is being done over the years to develop adequate computer models which could eventually be used in lieu of demonstrations and also for the analysis of aircraft accidents.

The development of a new model ends up with three last steps: first, the determination of the parameters appearing in the mathematical and logical expressions linking the variables; second, sensitivity assessment with respect to changes in input data and parameters; and third, validation with real world data taken from ad hoc experiments, demonstrations performed in scenarios that are reproducible in the model, and accident reconstruction [24].

All airplane manufacturers have more or less simple models that compute total escape times by summation of the duration of successive phases of the process. They are commonly semiempirical models that obtain data from experiments and demonstrations [6, 15, 16].

The computer models intended for certification need two modules: one to manage the cabin configuration, with complete information of the geometry and able to handle various exits and seating arrangements; and a second one to simulate human behaviour. This last is very problematic since human behaviour can be partly modelled but not fully simulated. If the model is intended for analysis of aircraft accidents it must also include a third module to simulate hazards such as fire, toxic gases, heat, etc [24].

There are two basic (and some intermediate hybrids) approaches to simulate evacuation: network models and queuing models [25]. Network models are frequently used in planning the evacuation of risky areas, such as buildings, chemical storage facilities or surroundings of nuclear power plants [6, 24, 25, 26]. In this approach flowing objects (persons, cars, etc) travel through specific paths which have certain nominal flow rate capacity. The overall performance is limited by the number and type of junctions and the capacity of the ultimate outflowing ways. In the case of airplane evacuation, the basic assumption is that the overall egress rate is limited by congestion at doorways [6, 7].

On the other hand, the queuing models describe the time-dependent and stochastic dynamics of waiting lines by the doorways [24, 25]. Passengers and crewmembers are individually identified by their original positions and are assumed to have certain demographic and personality characteristics. The movements of each person, in the successive simulation clock ticks, are determined according to some prescribed rules, the individual features, the individual environment and the probabilities provided by a random number generator; these probabilities are used to decide the next action to be undertaken by the simulated person.

In all cases the models account for personal characteristics such as age, girth and gender, which are known to significantly affect the results [6, 23]. It is not too difficult to include some factors like the hindering presence of excessive carry–on baggage, but other aspects such as bonding of husband and wife or parent and child have never been quantified [24]. Moreover, since the psycho–social reaction is different in accidents and in certification tests, the human behaviour module must be split in two different alternatives if the model is developed for both situations.

The models try to match the real world but have important limitations, mainly in the way the information of the system is introduced into the computer, and in the amount of data and variables that the computer can efficiently handle. Also, in the quality of the data needed to determine the value of the parameters, since most of them come from tests and experiments performed under not fully known circumstances. So, it is easy to understand that Boeing abandoned its simulation program in the 80s for the doubtful improvements it could bring to the evacuation evaluation and the low reliability of data and models [6].

Specific airplane evacuation simulations

Some airplane evacuation models are described in open literature, but none in full detail; and it seems that the majority are not currently in use.

In the early 70s the Civil Aeromedical Institute of FAA set up a model [27] based on an unusual simulation language, to analyze and assess the escape process for study of certification tests. It was used over the decade both in narrow body and wide body airplane studies but because of lack of appropriate information for further development and a fairly cryptic output it was abandoned [24].

A few years later, NASA undertook the setting up of a simulation model to assess post–crash passenger survival with fire as the major threat [9]. The model was applied to several cabins and had some further improvements, but could not be properly validated because of lack of data; in particular on how toxicants degrade passenger movement [28].

At the end of the 80s a personal–computer–based code was developed for FAA with the aim of reconstructing aircraft accidents. It was very limited in terms of human behaviour simulation but had a flexible software and produced a graphical display of the results. As examples and validation the model was able to reconstruct two accidents.

Again in the late 80s the Air Transport Association of America sponsored a project to develop a model to simulate certification tests. The model, of the queuing type, was called AIREVAC [29]. It was also used to evaluate the impact of transporting disabled passengers. Passengers features included many psycho–social and motivational variables.

EXODUS is a comprehensive expert–system–based simulation code developed in the early 90s intended for both certification studies and accident analysis [30]. It runs in a workstation, almost real time, with five interacting modules: passenger, behaviour, movement, hazard, and toxicity. The model has been used to simulate wide–body certification tests and accidents, and has been cross-checked with a series of controlled evacuation tests [19]. The computer simulation outputs agreed in trend with the tests, though the model exhibited some limitations regarding parameter modification.

The interest in evacuation modelling is not decaying, as shown by the increasing number of groups that are participating in the effort of studying aircraft evacuation strategies [13, 31]; partly due to the enormous growth in computational power, in terms of memory and speed, which allows an efficient use of new, powerful simulation languages and a broad range of rules, variables, processing and display of the results.

Materials and Method

The present paper describes the preliminaries of a new, comprehensive evacuation model conceived for certification studies. The first two steps, already finished and published [31], were the implementation of a procedure to define the whole geometry of the cabin with a minimum number of data, and the development of an algorithm for the initial assignment of seats to exits for evacuation; summaries of both aspects can be found in following paragraphs.

To reach a deeper understanding of the role of the cabin geometry in the evacuation process, the next step, which is the object of this paper, addresses the influence of several restrictions in the seat–to–exit assignment algorithm. The restrictions are maintained within a pure geometrical framework for consistency.

Cabin database

The working material for the present paper is the 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 some turboprops and the Bombardier Canadair Regional Jet (because of its comparative smaller size); narrow body jets; and wide body jets. Only two aircraft, CASA 3000 and Airbus A3XX are still in the design board, but complete information on its cabins is available. Furthermore, the CASA 3000 increases the statistics in the first group, and the Airbus 3XX is the largest airliner ever conceived. The table also shows the number of passengers in the cabin layout available of each airplane, which is in most cases the maximum certified capacity.

For the purpose of the present study the essential data from each cabin are the number, location and size of exits and aisles, and complete seating arrangement. All these data have been obtained from airport planning manuals, commercial brochures, JANE'S encyclopedia and magazines. In most cases data from different sources have been cross-checked to improve reliability.

Since airplane manufacturers must fulfill the demands of a wide spectrum of operators, cabins are configured in a large variety resulting in different densities of seating, although normally the number and type of exits are the same in all cases for a given airplane type and series; evidently, in the present work, high density configurations have been used.

No meaningful differences have been found with respect to exits when more than one cabin arrangement of the same airplane were available, with the exception of B757-200 which is duplicated because the documentation included one airplane with 8 exits and 212 seats and another with 10 exits (including four type III overwing exits) and 217 seats, and it was very difficult to foresee which one would be more demanding in terms of emergency evacuation.

On the other hand the upper and lower cabins of A3XX are considered as fully independent entities; the stair connections between both decks are taken as doorways but are assumed to be blocked in this preliminary stage of the work.

CATEGORY	AIRPLANE	PAX.
TPs and Small TFs	Fokker 50	50
	Saab 2000	50
	Canadair Reg. Jet	50
	BAe ATP	72
	Casa 3000	78
Narrow Body TFs	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 TFs	A310-300	279
	B767-200	290
	B767-300	312
	DC 10-30	399
	L1011-200	400
	A340-300	401
	B777-200	496
	B747-300	624
	A3XX	854

Table 2: Airplane Database

Data of all the cabin configurations considered in the study have been collected and filed in the computer with a systematic and efficient procedure, implemented in C++ language, which avoids errors and requires minimum memory size [31]. In this procedure all geometric data of a given cabin are grouped into four classes: exit, aisle, seat and crew. Any class is composed of objects, everyone with several attributes. A representative point of each object is located in real position with respect to a reference system, which has 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 collected in this way are compatible with the use of both network and queuing models [25] and have all advantages of object–oriented programming [13].

The exit class has N_{exit} (total number of exits which can be used to evacuate the airplane) objects, each one with three attributes: x_e, longitudinal coordinate of the exit center; y_e, transverse coordinate; and C_{exit}, maximum number of passengers permitted to evacuate through the exit according to FAR 25. Consequently, $3 \times N_{exit}$ data are necessary for this class. The sizes of all exits have been reviewed to take into account the last FAR modification with new types of exits [2].

Each object of the *aisle class* (i.e. each aisle) is modeled by straight segments with the following data: N_{sg}: number of straight segments (the same number for all aisles); $x_p(i)$, longitudinal coordinate of the point i and $y_p(i)$, transverse coordinate of the point i for each $N_{sg}+1$ segment extreme points. It results in $2*(N_{sg}+1)$ data per aisle.

In order to minimize the number of data required to reproduce the seating arrangement, the following concepts are introduced: *Block* is a set of physically united seats attached to the cabin floor; *Zone* is a set of blocks with the same number of seats, having the same seat size and pitch. A *master seat* is defined in each zone as the seat with the least values of x and y coordinates at its left rear corner.

Then, the *zone class* requires the following data: b number of blocks in the zone; s_b number of seats per block in the zone; X_z longitudinal coordinate of the left rear corner of the master seat; Y_z transverse coordinate of the left rear corner of the master seat; sw transverse seat pitch (1 back width + 1 armrest width); dt transverse displacement between consecutive blocks in the zone; sp longitudinal seat pitch; la identifying number of left aisle (0 if there is no aisle at left); ra identifying number of right aisle (0 if there is no aisle at right). Accordingly, there are 9 data per zone.

The zone class data are used to calculate the *seat class* data. Each seat has associated two coordinates (X_s, Y_s) as the coordinates of the point where the passenger stands up. It is located at the seat symmetry plane (which fixes Y_s) and $X_s = x(lrc) - sp + D$, where lrc is the left rear corner of the s seat and D is a constant length assumed to be 0.1 m; i.e. approximately to have the chest on the back of the seat in the former row. This leads to a class with only two data per object. The seating arrangement is thus defined with high accuracy, and is not limited to a node–matrix layout that can be found in most evacuation simulation studies [9, 16, 28].

The fourth and last object class is the *crew member class* in which two kinds are identified: 1) the flight crew which will evacuate the airplane using the foremost available exit; 2) the cabin attendants who will leave the airplane using the nearest available exit to his/her assigned exit (this one included).

For a better understanding of the aforementioned definitions, Fig. 2 depicts the cabin of B767-200 with 290 seats. The exit class has 8 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 (i.e. they are straight lines running along the fuselage). Finally, the definition of the seat class requires data for 9 zones, numbered in the same way as the exits: the first zone has 17 blocks with two seats; zone two has 2 blocks with 2 seats each; zone 3 includes 17 blocks with two seats; and so on and so forth.

Approach of the paper

This paper deals with the preliminary stages of a new model conceived to simulate evacuation of transport airplanes for certification studies. Only the cabin configuration module has been developed to some extent, but this module provides very important information on the role of the cabin geometry in the evacuation process, as it will be shown in the core of this work.

The starting point is the seat–to–exit algorithm mentioned earlier (MVal:97). This algorithm can be combined with different rules and constraints, and manipulated to search the optimum of some objective function.

Since the aim in actual evacuation demonstrations is to fulfill the 90 second mark, the approach followed here is to minimize the total distance run by all passengers along their escaping paths (or the average distance, which only implies a scale change in metrics).

Distance is closely linked to time and, at least in qualitative terms, may give an initial picture on the evacuation performance. Any other specified distance, like the maximum distance covered by the passenger with the longest path, could have been taken as objective variable to be optimized, but the total distance or the average distance have several advantages: they are

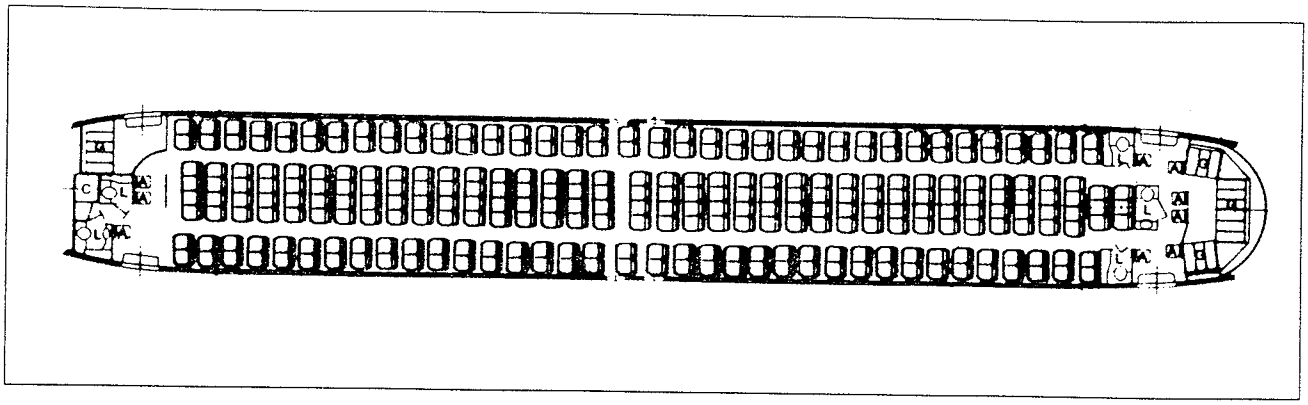

Figure 2: Cabin of a high density version of Boeing B767-200 with 8 exits and 290 passenger seats.

more representative of global performance; they admit linear programming of the whole study; they are more appropriate and reliable for comparisons among different arrangements or situations of the same cabin; etc. The average distance is better suited for comparisons among distinct airplanes.

In accordance with the former statements, the total distance, the mean distance and the number of passengers evacuated through each available exit have been determined in four different scenarios: first, the seat–to–exit assignment algorithm operates without limitations (in order to search the minimum mean distance for the overall cabin geometry); second, the algorithm is constrained by the number of passengers that can be evacuated through each exit according to the new FAR 25 figures (see Table 1); third, the operation tends to the best proportional sharing among exits but obliges a passenger moving in the immediate neighborhood of an exit to escape through it (i.e. he can not go to a distant, alternative, less loaded exit); and fourth, the combination of both former restrictions. The four assignment strategies are applied to medium to all aircraft, turboprops, as well as narrow body and wide body jets.

Formulation of the problem

This section presents the mathematical aspects of the seat-to-exit assignment using linear programming optimization. The objective function to be minimized is the total distance run by all the evacuees. However, in order to ease the comparisons and to provide more understandable values, the average distance is the common output. Total distance, mean distance, and other variables are defined in the next paragraph.

Nomenclature and definitions

Before going on with the formulation of the geometrical problem, let begin by explaining the notation used, which is related to the items defined in the cabin database section.

The cabin configuration provides the following variables:

N_{seat} Number of cabin seats.

$i = 1, \ldots, N_{seat}$ Index of cabin seats (counting by zones, blocks and block seats.

N_{exit} Number of cabin exits.

$k = 1, \ldots, N_{exit}$ Index of cabin exit (counting from left to right and front to rear).

$C_{exit}(k)$ Maximum evacuation capacity of the k-th exit as stated in FAR 25-807.

$\text{æ}(k)$ Boolean availability function of the k-th exit (defined later)

$N_{\text{æ}}$ Number of cabin available exits

$j = 1, \ldots, N_{\text{æ}}$ Index of cabin available exit

$\bar{\eta}$ Mean utilization coefficient of cabin exits (≤ 1)

$$\bar{\eta} = \frac{N_{seat}}{\sum_{k=1}^{N_{exit}} \text{æ}(k)\, C_{exit}(k)}$$

Δ Relative mean utilization margin of the cabin exits

$$\Delta = 1 - \bar{\eta}$$

On the other hand, for the seat-to-exit assignment process some additional definitions are required:

$n_{exit}(j)$ Number of seats assigned to j-th exit

$\eta_{exit}(j)$ Utilization coefficient of the j-th exit

$$\eta_{exit}(j) = \frac{n_{exit}(j)}{C_{exit}(j)}$$

$\delta_{exit}(j)$ Relative utilization margin of the j-th exit (relative to $\overline{\eta}$)

$$\delta_{exit}(j) = \overline{\eta} - \eta_{exit}(j)$$

$\Delta_{exit}(j)$ Absolute utilization margin of the j-th exit (relative to maximum)

$$\Delta_{exit}(j) = 1 - \eta_{exit}(j)$$

As mentioned earlier, the availability of the exits requires the introduction of new concepts. Let k be an integer index corresponding to exits which can vary between 1 and N_{exit}. Then, the available exit vector is defined as

$$Æ_{1\times N_{exit}} = [æ(k)]$$

$$\begin{cases} æ(k) = 1, & \text{if the } k\text{-th exit is available} \\ æ(k) = 0, & \text{in other case} \end{cases}$$

The seat-to-exit distance matrix, that is the base for the assignment procedure, is defined as follows:

$$D_{N_{seat}\times N_{exit}} = [d(i,k)]$$

where $d(i,k) \in R$ is the distance from the i-th seat to the k-th exit

However, since the interest lies only in available exits, a new integer index j is defined, corresponding to available exits. This index varies from 1 to $N_{æ}$. Thus, the number of elements of the seat-to-exit distance matrix is considerably reduced to a box of the seat-to-exit distance matrix, which is only formed by the columns associated to indexes k which satisfy $æ(k) = 1$.

The resulting distance matrix is then:

$$D_{N_{seat}\times N_{æ}} = [d(i,j)]$$

where $d(i,j) \in R$ is the distance between i-th seat and j-th available exit

Fore the seat-to-exit assignment procedure a new matrix is defined as follows:

$$X_{N_{seat}\times N_{exit}} = [x(i,j)]$$

$x(i,j) = 1$, if the i-th seat is assigned to the j-th exit
$x(i,j) = 0$, otherwise

According to this definition, each seat is assigned to only one of the available exits, which implies

$$\sum_{j=1}^{N_{æ}} x(i,j) = 1$$

and each available exit will be used by a number of passengers (i.e. seats):

$$\sum_{i=1}^{N_{seat}} x(i,j) = n_{seat}(j)$$

Obviously:

$$\sum_{j=1}^{N_{æ}} \sum_{i=1}^{N_{seat}} x(i,j) = \sum_{i=1}^{N_{seat}} 1 = N_{seat}$$

The *total distance* is defined as follows:

$$D = \sum_{j=1}^{N_{æ}} \sum_{i=1}^{N_{seat}} x(i,j) d(i,j)$$

Analogously, the *mean distance* is:

$$\overline{D} = \frac{\sum_{j=1}^{N_{æ}} \sum_{i=1}^{N_{seat}} x(i,j) d(i,j)}{N_{seat}}$$

which only implies a scale change in metrics.

The *mean distance of seats assigned to the j-th exit* is defined as:

$$\overline{d}(j) = \frac{\sum_{i=1}^{N_{seat}} x(i,j) d(i,j)}{\sum_{i=1}^{N_{seat}} x(i,j)}$$

In opposition to the previous definitions, this last is not a linear expression of $x(i,j)$ because of the denominator.

Mathematical formulation

The approach followed here to formulate the geometrical evacuation problem, is to consider it as a pseudo-boolean optimization problem.

The variables of the problem are a finite set of boolean or binary variables (0-1), arranged in matrix form, the assignment matrix; i.e.

$$x(i,j) \in \{0,1\} \quad \forall i = 1 \ldots N_{seat} \quad \forall j = 1 \ldots N_{æ}$$

The optimization problem admits several objective functions depending upon the aims of the simulation process:

Possible linear objective functions obey to expressions like:

$$F([A]) = \min(d) \equiv F([A]) = \min(\overline{d})$$

Analogously, possible non-linear objective functions can be expressed as:

$$F([A]) = \min\left(\max_j \overline{d}(j)\right)$$

Since the optimization problem will be solved here as a linear optimization process, only the first type will be used.

For the purpose of the present work four constraints are considered. Its underlying principles and symbolic formulations are detailed in the following paragraphs.

Constraint C0: each seat can only be assigned to an available exit.

This constraint is typical of the assignment problem in linear programming (LP). On the other hand it has the strength of a conservation law. It can be formulated as an 'equal to' expression.

$$\sum_{j=1}^{N_{\ae}} x(i,j) \quad = \quad 1 \quad (i = 1 \ldots N_{seat})$$

Constraint C1: the evacuation capacity of the exits is limited for its size in accordance with regulation FAR 25-807(g) [2].

This constraints can be formulated in a 'less than or equal to' manner.

$$n_{exit}(j) = \sum_{i=1}^{N_{seat}} x(i,j) < C_{exit}(j) \quad (j = 1 \ldots N_{\ae})$$

Constraint C2: if a passenger encounter an available exit in his/her evacuation path, has to get out through it.

This constraint seems to be appropriate for narrow body airplanes, since there is no possibility to use an alternative aisle to bypass a crowded exit. However, in wide body airplanes this constraint may be less appropriate, although the traverse passageway linking the two exits of the given pair would very likely be blocked too.

This constraint can be formulated in LP as a combination of 'less than or equal to' constraints and fixed suitable variables. For all seats, the following steps must be covered: A) Let the seat-to-exit distance vector be:

$$\{d(i,j)\}, \quad (j = 1, \ldots, N_{\ae})$$

B) This vector can be ordered in arguments of increasing value:

$$d(i,j_1) \le d(i,j_2) \le \ldots \le d(i,j_{N_{\ae}})$$

C) Now:

C.1) If the nearest two exits are one at the front and another at the rear of the seat ($x_{j_1} \le x_i \le x_{j_2}$):

C.1.i) The distance covered by a passenger must be limited to the second value of the ordered vector to obliged the seat to be assigned to one of these two exits.

$$\sum_{j=1}^{N_{\ae}} x(i,j)\, d(i,j) \le d(i,j_2)$$

C.2) If the nearest two exits are both either front or rear of the seat, several cases may occurred:

C.2.i) There are only two available exits ($N_{\ae} = 2$):

- The assignment of the first exit is forced by fixing the corresponding variable $x(i,j_1) = 1$.
- The distance covered by a passenger is then limited to the first value of the ordered vector:

$$\sum_{j=1}^{N_{\ae}} x(i,j)\, d(i,j) \le d(i,j_1)$$

C.2.ii) There are more than two available exits ($N_{\ae} > 2$):

C.2.ii.a) If the third exit is at different side of the other two:

- The assignment of the second is prohibited by fixing the corresponding variable $x(i,j_2) = 0$.
- The distance covered by a passenger is limited to the third value of the ordered vector to permit only the assignment of the adjacent exits:

$$\sum_{j=1}^{N_{\ae}} x(i,j)\, d(i,j) \le d(i,j_3)$$

C.2.ii.b) If the third nearest is at the same side of the other two first:

- The (C.2.i) case must be applied

Constraint C3: limitation of the distance covered by a passenger along the escaping path.

This constraint can be formulated with a 'less than or equal to' expression.

$$d(i) = \sum_{j=1}^{N_{\ae}} x(i,j)\, d(i,j) \le d_{max}, \qquad (i = 1, \ldots, N_{seat})$$

Linear optimization

Several versions of the linear optimization problem can be conceived by using the previous limitations.

Case RT0

No constraints have been imposed, except the obvious conservation–law type C0. This case takes only into consideration the relative position of seats and available exits, without considering the size of exits.
It can be interpreted as the geometrical evacuation capability of a cabin. Also it can simulate the impulsive decision of passengers to go to the nearest exit, regardless of the evacuation capacity of the exits.
It serves as a reference to the other cases, since it provides the minimum value of the objective function.

$$\min_X \; D(X) = \sum_{i,j} d(i,j)\,x(i,j)$$

s.t. :

$$\sum_{j=1}^{N_{\ae}} x(i,j) = 1 \qquad (i = 1,\ldots,N_{seat})$$

$$x(i,j) \in \{0,1\} \quad (i = 1\ldots N_{seat};\; j = 1\ldots N_{\ae})$$

Case RT1

This case adds the C1 constraint to the former case. It can be interpreted as the evacuation capacity of a cabin from the view point of relative position between seats and available exits, but considering the size of exits. Therefore it implies that the evacuation capacity of each exit is limited because of its size. Analogously to a former explanation it can simulate the redirection of passenger according to the perceived evacuation potential (size and distance) of the exits.

$$\min_X \; D(X) = \sum_{i,j} d(i,j)\,x(i,j)$$

s.t. :

$$\sum_{j=1}^{N_{\ae}} x(i,j) = 1 \qquad (i = 1,\ldots,N_{seat})$$

$$\sum_{i=1}^{N_{seat}} x(i,j) < C_{exit}(j) \qquad (j = 1,\ldots,N_{\ae})$$

$$x(i,j) \in \{0,1\} \quad (i = 1\ldots N_{seat};\; j = 1\ldots N_{\ae})$$

Case RT2

This cases adds the C2 constraint to the RT0 case. This is the case of assignment constrained by the imposition of exiting through the first available exit encountered by a passenger in his/her path.
It can be interpreted as the evacuation capacity of a cabin regarding the longitudinal position of each exit and the seats in its neighborhood, which are the candidates to be assigned to it.

$$\min_X \; D(X) = \sum_{i,j} d(i,j)\,x(i,j)$$

s.t. :

$$\sum_{j=1}^{N_{\ae}} x(i,j) = 1 \qquad (i = 1,\ldots,N_{seat})$$

$$\sum_{j=1}^{N_{\ae}} d(i,j)\,x(i,j) = d(i,j_{k(i)}) \qquad (i = 1\ldots N_{seat})$$

$$k(i) = \begin{cases} 1 & x(i,j_1) = 1 \\ 2 & \text{free} \\ 3 & x(i,j_2) = 0 \end{cases}$$

$$x(i,j) \in \{0,1\} \quad (i = 1\ldots N_{seat};\; j = 1\ldots N_{\ae})$$

Case RT*

This case adds the C3 constraint to the RT0 case. This is the case of assignment constrained by a limit of maximum distance covered by each passenger.
It can be interpreted as the capacity of a cabin to be evacuated considering the maximum distance covered by a passenger in the evacuation path.
It is trivial to see that it has solution only if d_{max} is selected to match one of the previous cases (RT0, RT1, RT2) and has no solution otherwise. Hence, the C3 constraint will not be included in case RT3.

$$\min_X \; D(X) = \sum_{i,j} d(i,j)\,x(i,j)$$

s.t. :

$$\sum_{j=1}^{N_{\ae}} x(i,j) = 1 \qquad (i = 1,\ldots,N_{seat})$$

$$\sum_{i=1}^{N_{seat}} x(i,j) < d_{max} \qquad (j = 1,\ldots,N_{\ae})$$

$$x(i,j) \in \{0,1\} \quad (i = 1\ldots N_{seat};\; j = 1\ldots N_{\ae})$$

Case RT3

This case includes constraints C1 and C2.
It is closer to the actual evacuation performance of the cabin. It must be noticed that the linear optimization problem can only be solved if certain increase in the evacuation capacity of exits is allowed. The computer runs will take this last possibility in to account to find the appropriate solution.

$$\min_X \; D(X) = \sum_{i,j} d(i,j)\,x(i,j)$$

s.t. :

$$\sum_{j=1}^{N_{\ae}} x(i,j) = 1 \qquad (i = 1,\ldots,N_{seat})$$

$$\sum_{i=1}^{N_{seat}} x(i,j) < C_{exit}(j) \qquad (j = 1,\ldots,N_{\ae})$$

$$\sum_{j=1}^{N_{\ae}} d(i,j)\,x(i,j) = d(i,j_{k(i)}) \qquad (i = 1\ldots N_{seat})$$

$$k(i) = \begin{cases} 1 & x(i,j_1) = 1 \\ 2 & \text{free} \\ 3 & x(i,j_2) = 0 \end{cases}$$

$$x(i,j) \in \{0,1\} \quad (i = 1\ldots N_{seat},\ j = 1\ldots N_{\ae})$$

Results

The total number of computer runs (i.e. geometrically simulated evacuations) is very large since the cabin database includes 31 configurations, each one of them has been studied in four scenarios, and various combinations of available exits have been checked in most situations. Hence, the results shown here are only a fraction, though representative, of the type of output and possibilities provided by the method.

First, it must be noticed that a few currently flying airplanes have certified capacities above the figures corresponding to the new FAR 25-800s (FAR–25) which can be derived from Table 1. For example, the studied cabin of A310-300 has 269 passenger seats, which is a bit more than 265 corresponding to 2 type A doors plus one type I door. The same happens to B767-200 which has 290 seats that should be reduced to 285, for its to 2 type A doors and 2 coupled type III overwing exits. But in general the new regulations are more generous and flexible with the evacuation requirement.

Figure 3 depicts the evacuation assignment for the A320-200, with all port exits available, in three scenarios corresponding to cases RT0 (no constraints), RT1 (limitation in the capacity of exits) and RT3 (all constraints simultaneously). In the first case, cabin sections between exits are practically divided into halves; this yields a very unbalanced sharing with only 30 passengers assigned to the front door, 42 at the first type III exit, 60 through to the second overwing exit, and only 44 to the rear door. In this scenario the mean evacuation path distance is 5.97 meters, in contrast to 5.72 meters corresponding to A321 which is its stretched version. This is so because of the more evenly lengthwise distribution of exits in A321. When all constraints are imposed (i.e. case RT3) the picture of the cabin is more reasonable and the number of passengers assigned to each exit is closer to the real world performance: 46, 30, 35 and 63, respectively.

The most extreme case for an exit, in terms of overloaded capacity, corresponds to exit number 2 (type A door) of L1011 in the unconstrained condition (RT0) with 160 passengers, as shown in Fig. 4. In this airplane the wing is somewhat shifted rearwards for the third engine and the wing-body junction is quite long. Hence, exit number 2, which is located in the middle of both sections, attracts many passengers leading to the former figure.

Apart from global data, like number of passengers assigned to each exit, the method also provides the individual seat–to–exit distance, from which it is possible to obtain the corresponding histograms, which are related to the evacuation flow rate [7] and to the homogeneity of the seating arrangement. Figures 5 and 6 exhibit the histograms corresponding to the four exits of L1011, for cases RT1 (limitation in exit capacity) and RT3 (all constraints), respectively. Exits number 1, 2 and 3 are about equally loaded, but exit number 4 loses some passengers that in case RT1 are about 20 meters from that door; in their route to exit number 4 they pass by exit number 3 and are re-assigned to it (constraint C2).

A given exit type plays quite different roles in distinct airplanes. For example Fig. 6 shows the utilization of type C exits in small airplanes, in the RT3, fully constrained situation. In CASA 3000 42 passengers out of 78 are assigned to this exit; in Bae ATP the figure is 34 out of 72, in F50 they are 22 from 50, and in Regional Jet only 15 out of 50 (in this last case the location of exits is so uneven that the type III exit is much more loaded than the type C door).

Tables 3, 4 and 5 show the mean distance (columns 3, 4 and 6) in the three groups of airplanes considered in the present study. The scenario is defined by the combination of available exits (second column) and constraints (cases RT0, RT1 and RT3). As indicated in the Materials and method section, the RT3 condition may require some increase in the nominal capacity of the exits to reach a solution in the linear optimization problem. The increase, if any, appears in the fifth column (zero implies no increase). In this particular aspect the small aircraft behave very well, as expected, since they have relatively few seats but need a door to emplane the passengers; and therefore they are oversize.

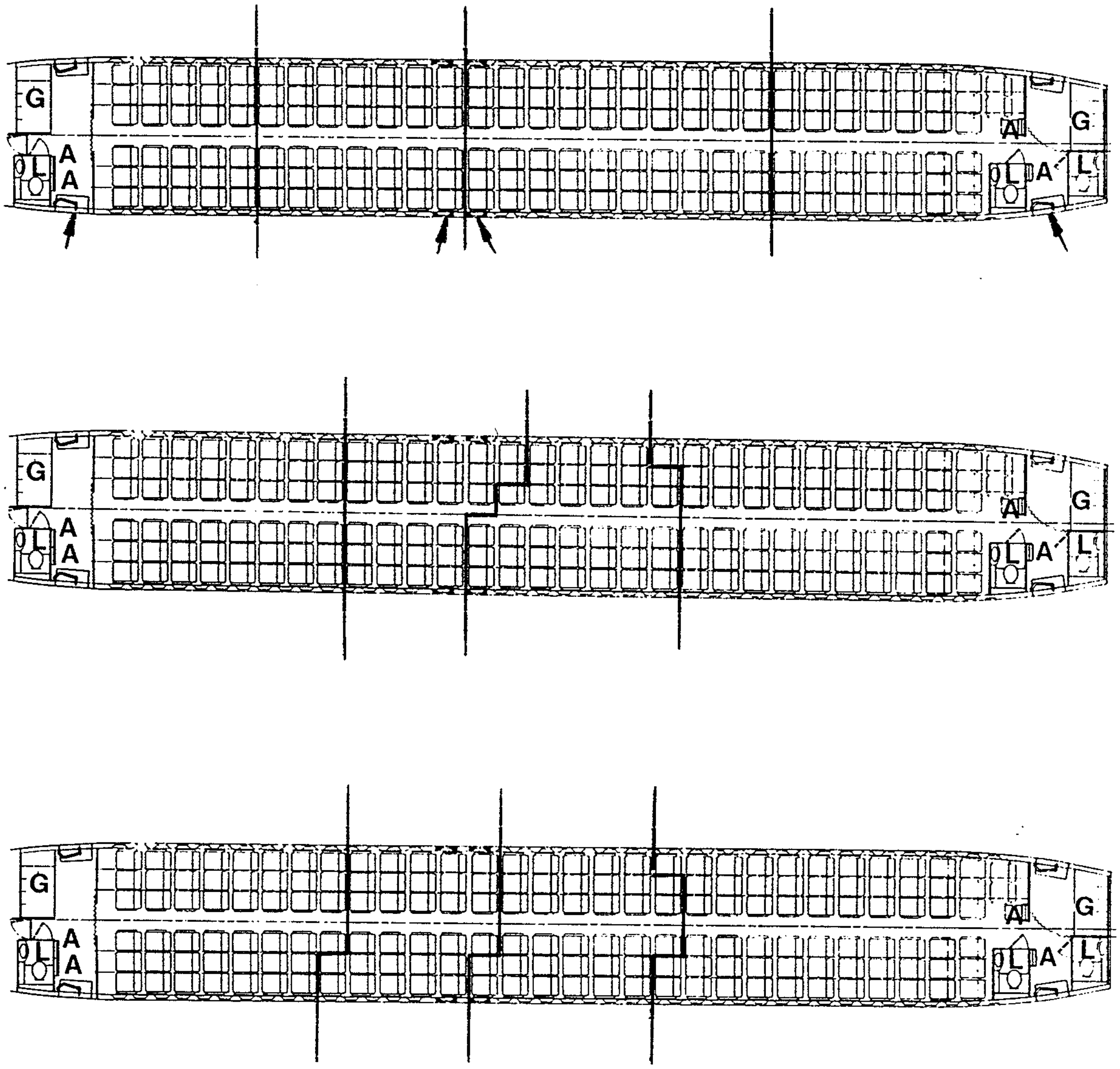

Figure 3: Evacuation assignment for A320-200 corresponding to cases RT0 (top), RT1 (centre) and RT3 (bottom)

AIRPLANE	Available Exits	RT0/2	RT1	RT3		$\rho(1/0)$	$\rho(3/0)$	$\rho(3/1)$
		d_{med}	d_{med}	Δ(%)	d_{med}			
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 Reg. 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

Table 3: Mean distance and related results for turboprops and Regional Jet

AIRPLANE	Available Exits	RT0/2	RT1	RT3		$\rho(1/0)$	$\rho(3/0)$	$\rho(3/1)$
		d_{med}	d_{med}	Δ(%)	d_{med}			
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 4: Mean distance and related results for narrow body jets

AIRPLANE	Available Exits	RT0/2	RT1	RT3		$\rho(1/0)$	$\rho(3/0)$	$\rho(3/1)$
		d_{med}	d_{med}	$\Delta(\%)$	d_{med}			
A310-300[1]	L1-L3	7.2871	8.6065	0	8.6065	1.182	1.182	1
B767-200[2]	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
B747-300	L1-L5	7.3943	7.4672	0	7.4672	1.01	1.01	1

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

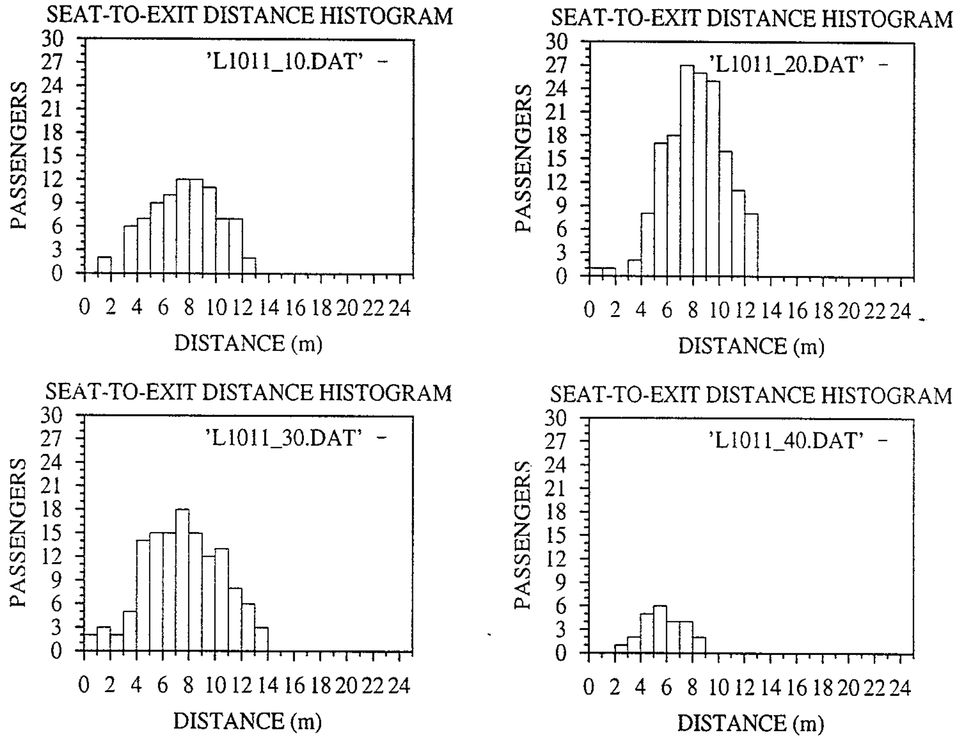

Figure 4: Distance histograms of L1011-200 exits. Case RT0

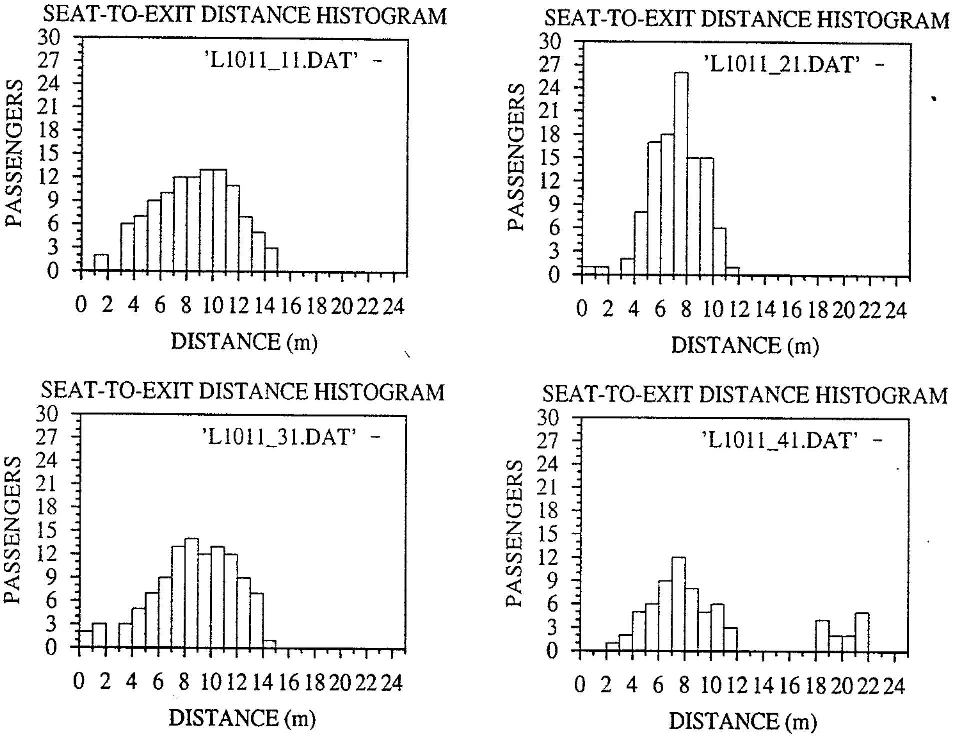

Figure 5: Distance histograms of L1011-200 exits, Case RT1

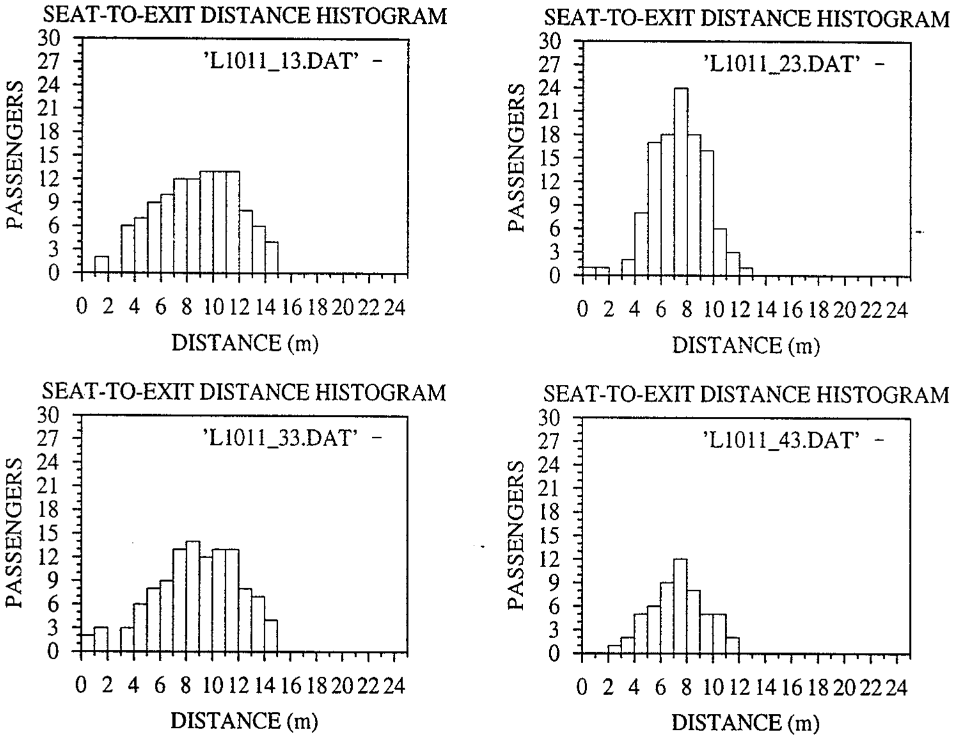

Figure 6: Distance histograms of L1011-200 exits, Case RT3

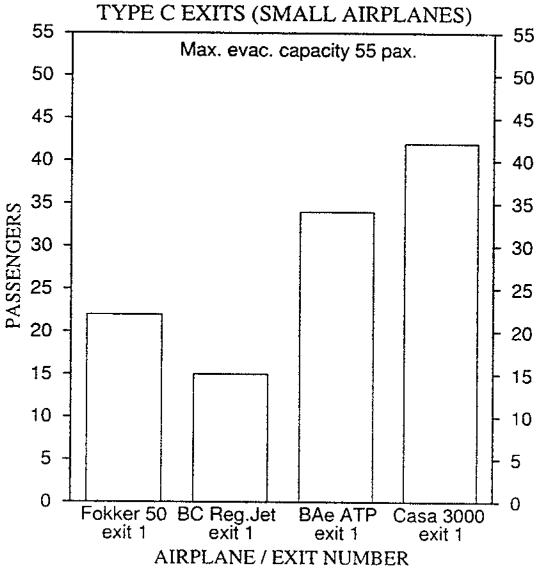

Figure 7: Comparison of type C exits for small airplanes

The worst group includes the narrow body jets, that have a variety of exits unevenly distributed along the fuselage; several highly loaded exits are required to manage the evacuation, the most extreme case being DC9 S80 with 23 percent extra capacity. On the other hand, the lengthening of the mean escaping distance due to the constraints (seventh or eighth columns) is particularly noteworthy in three airplanes of similar size: BAe ATP (1.31), BAC 1-11 (1.24) and CASA 3000 (1.24); and the two smaller wide bodies, B767–200 (1.21) and A310–300 (1.18) which are marginally out of the updated regulation, as commented at the beginning of this section.

Conclusions

A new model conceived to study emergency evacuation of transport airplanes for certification purposes is being developed. The first stages include the setting up of a seat–to–exit assignment algorithm that can be combined with various rules and constraints in a purely geometrical framework. By means of this algorithm several evacuation simulation runs have been performed on various scenarios and a number of airplane cabins. The main findings of the work carried out can be summarized as follows:

very meaningful information on the influence of the cabin arrangement on evacuation can be provided within a purely geometrical approach.

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

mean distance covered by all passengers along their escaping paths increase, in general, with airplane size; but stretched versions perform sometimes better for requiring larger exits in the middle section of the cabin.

as expected, uneven lenghtwise distribution of exits and lack of symmetry enhance the difficulties in evacuation.

small airplanes result commonly oversize in evacuation capacity for the presence of relatively large entrance and service doors.

narrow body aircraft exhibit, in general, more evacuation problems for the relatively large cabin slenderness and the presence of small overwing exits.

as much as 23 percent extra capacity in some exits is required in some scenarios to allow the evacuation of all assigned passengers.

References

[1] L. Taylor. *Air Travel. How safe is it?* BSP Professional Books, Oxford, UK, 1988.

[2] Anonymous. *Code of Federal Regulations. Aeronautics and Space. Part 25 - Airworthiness Standards: Transport Category Airplanes.* Office of the General Register, Washington, DC, USA, 1981.

[3] Anonymous. *Joint Aviation Requirements. JAR-25. Large Aeroplanes.* Joint Aviation Authorities, Gatwick, UK, 1989.

[4] M. Edwards and E. Edwards. *The Cabin Aircraft: Managing the Human Factors.* Gower Technical, 1990.

[5] Stanley R. Mohler, John J. Swearingen, Ernest B. McFadden, and J. D. Garner. Human Factors of Emergency Evacuation. Technical report, Civil Aeromedical Research Institute, Oklahoma City, Oklahoma, USA, September 1964.

[6] Aircraft evacuation testing: Research and technology issues. Background Paper OTA-BP-SET-121, Office of Technology Assessment, Congress of the United States, Washington, DC, USA, 1993.

[7] R. Martínez-Val and C. Hernández. Simple analysis to assess the evacuation of transport airplanes. In *Proc. 20th ICAS Congress*, volume 2, pages 1871–1878, Sorrento, Napoli (Italy), 8-13 September 1996.

[8] Task force report on emergency evacuation of transport airplanes, volume i – summary report. Report dot/faa/vs–86/1.i, Federal Aviation Administration, Washington, DC, USA, 1986.

[9] Victor E. Middleton. A Computer Simulation of Aircraft Evacuation with Fire. Nasa contractor report 166511, NASA, Ames Research Center, Moffett Field, California, USA, 1984.

[10] D. Learmounth. Crew direction aids evacuations by 50%. *Flight International*, page 9, 17-23 February 1993.

[11] H. Muir et al. Cabin staff behaviour in emergency conditions. Report applied psychology unit, College of Aeronautics, Cranfield University, Cranfield, UK, 1995.

[12] Type and number of passenger emergency exits required in transport category airplanes. Amendment No. 25-88, Federal Aviation Administration, 1996. Washington, DC, USA.

[13] M.C. Court and J.H. Marcus. Use of object-oriented programming to simulate human behavior in emergency evacuation of an aircraft's passenger cabin. Report dot/faa/am–97/20, Civil Aeromedical Institute, Federal Aviation Administration, Oklahoma City, Oklahoma, USA, 1997.

[14] Sharon A. Barthelmess (Federal Aviation Administration). An FAA Analysis of Aircraft Emergency Evacuation Demonstration. Technical report, SAE, October 1982.

[15] Lockheed 1011. technical and operations summary. Doc. coa 1323, Lockheed California Company, Burbank, California, USA, 1971.

[16] Donald L. Parks and Robert A. Ostrand. EVAC Computer Simulation of Personnel in Airplane Evacuation. In *Proceeding of the Human Factors Society*, 1982.

[17] K. Knowles and R. Martínez-Val. Conventional and unconventional configurations for ultra-high capacity aircraft. In *Proc. 19th ICAS Congress*, volume 1, pages 656–664, Los Angeles, 1994.

[18] T. Muñoz R. Martinez-Val, E. Perez and C. Cuerno. Design constraints in the payload–range diagram of ultra–high capacity aircraft. *Journal of Aircraft*, 31:1268–1272, 1994.

[19] H. Muir et al. Aircraft evacuations: the effect of passenger motivation and cabin configuration adjacent to the exit. CAA paper 89019, Civil Aviation Authority, UK, 1989.

[20] Garnet A. McLean, Charles B. Chittum, Gordon E. Funkhouser, Gregory W. Fairlie, and Earl W. Folk. Effects of Seating Configuration And Number of Type III Exits on Emergency Aircraft Evacuation. Report dot/faa/am–92/27, Civil Aeromedical Institute, Oklahoma City, Oklahoma, USA, August 1992.

[21] G.A. McLean, M.H. George, C.B. Chittum, and G.E. Funkhouser. Aircraft Evacuations Through Type-III exits. I: Effects of Seat Placement at the Exit. Report dot/faa/am–95/23, Civil Aeromedical Institute, Oklahoma City, Oklahoma, USA, July 1995.

[22] H.C. Muir et al. Aircraft evacuations: Competitive evacuations in conditions of non–toxic smoke. Caa paper 92005, Civil Aviation Authority, London, UK, 1992.

[23] G.A. McLean and M.H. George. Aircraft Evacuations Through Type-III exits. II: Effects of Individual Subject Differences. Report dot/faa/am-95/25, Civil Aeromedical Institute, Oklahoma City, Oklahoma, USA, August 1995.

[24] J.H. Marcus. A review of computer evacuation models and their data needs. Report dot/faa/am–94/11, Civil Aeromedical Institute, Federal Aviation Administration, Oklahoma City, Oklahoma, USA, 1994.

[25] J.M. Watts. Computer models for evacuation analysis. *Fire Safety Journal*, 12:237–245, 1987.

[26] A.K. Rathi and R.S. Solanki. Simulation of traffic flow during emergency evacuations: a microcomputer based modeling system. Report de–ac05–84or21400, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA, 1993.

[27] R.F. Chandler J.D. Garner and E.A. Cook. Gpss computer simulation of aircraft passenger emergency evacuations. Report faa–am–78–23, Civil Aeromedical Institute, Federal Aviation Administration, Oklahoma City, Oklahoma, USA, 1978.

[28] D.E. Cagliostro. A user-operated model to study strategy in aircraft evacuation. *Journal of Aircraft*, 21(12):962–965, December 1984.

[29] J.E. Schroeder and M.L. Tuttle. Development of an aircraft evacuation (airevac) computer model, phase i: Front end analysis and data collection. Technical report swri project number 12–4099, Southwest Research Institute, San Antonio, Texas, USA, 1991.

[30] E.R. Galea and J.M. Perez Galparsoro. Exodus: An evacuation model for mass transport vehicles. Caa paper 93006, Civil Aviation Authority, London, UK, 1993.

[31] J.M. Hedo R. Martínez–Val and C. Hernández. Cabin–layout–based algorithm to assess the evacuation of transport airplanes. In H.M. Soekkha, editor, *Aviation Safety*, Utrecht, NL, 1997. VSP. pp. 213-227.