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Assessment of Narrow-Body Transport Airplane Evacuation by Numerical Simulation

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This paper presents the results obtained with a new agent-based computer model that can simulate the evacuation of narrow-body transport airplanes in the conditions prescribed by the airworthiness regulations for certification. The model, described in detail in a former paper, has been verified with real data of narrow-body certification demonstrations. Numerical simulations of around 20 narrow-body aircraft, representative of current designs in various market segments, show the capabilities of the model and provide relevant information on the relationship between cabin features and emergency evacuation. The longitudinal location of emergency exits seems to be even more important than their size or the overall margin with respect to the prescribed number and type of exits indicated by the airworthiness requirements.

Nomenclature

ETR = evacuation time ratio, $T_{\mathrm{eva}}/90$
N_{att} = number of cabin attendants
N_{flg} = number of flight crew members
$N_{\max}$ = maximum number of seats according to number and type of exits in cabin
N_{pax} = number of passengers onboard
N_{seat} = number of seats in cabin
$Oxyz$ = reference system to locate all elements of cabin
SCR = seating capacity ratio, $N_{\mathrm{seat}}/N_{\max}$
T_{eva} = evacuation time, $t_{\mathrm{end}} - t_{sta}$, s; also average evacuation time in a series of simulation runs
T_{95} = 95% confidence interval of evacuation time
t_{end} = time point when last occupant reaches ground or safe place
t_{fee} = time point when first exit is unoccupied
t_{lea} = time point when last exit is operative
t_{sta} = time origin of simulation run
σ_{eva} = standard deviation of evacuation time in series of simulation runs, s

I. Introduction

MAKING flight safer, simpler, and more efficient has been the very nature of aviation since early times [1]. Thanks to this synergistic approach, commercial aviation has evolved at an astounding pace, both in terms of passenger kilometers flown [2] and in technological achievements [3]. Coherently with the former leitmotif, the major drivers for the development of commercial aviation have been safety, performance, and cost, to which environment friendliness has been added in the last decades [4]. But safety has always remained the cornerstone of aviation development [5,6].

A relevant aspect of this evolution has been the proactive awareness of civil aviation authorities, airplane manufacturers, and airlines to commit altogether to continuously improve safety levels. This attitude has resulted in a continuous decline of aircraft accident rates [6]. On the other side, the public has understood the importance of such commitment, and air travel has become the favorite one for medium and long distances [2]. Obviously, the research community has also contributed to this positive trend by devoting skills and resources to many safety-related areas. Cabin safety is one these areas.

A meaningful fraction of fatalities occurring in crashes, emergency landings, etc. is related to fire and toxic gases. Consequently, a key factor for survival after the accident is the ability to quickly evacuate the airplane [7–9]. To assess the evacuation capability of a new transport airplane, airworthiness authorities have developed a set of requirements [10,11] that have to be met by airplane manufacturers and airlines to ensure a minimum in evacuation performance. One of these requirements is the 90 s rule: any new, or largely modified derivative, airplane must show by means of a real emergency evacuation trial that all occupants can safely abandon the aircraft in less than 90 s with a certain age–gender mix in the simulated occupants, half of the usable exits blocked, and minimum illumination provided by floor proximity lighting.

The rule was established after the advent of the jet era, in 1965, with 120 s, and it has been evolving to incorporate improvements in interior materials [8,12], escape equipment [9,13], and more complete and improved crew training [7,14–17]. Both American and European standards have gathered these requirements into their respective codes [10,11]. As indicated, the regulations change over time. Thus, a last amendment to Federal Aviation Regulations (FARs) [10], aimed at decreasing the controversy of the evacuation demonstration trial, has introduced new exit types and new conditions to perform and assess evacuation demonstrations. The updated exit types, with their dimensions and evacuation capabilities, are shown in Table 1. Such new requirements include new type B and C categories, which correspond to enlarged type I doors. Although, for most transport airplanes, the new requirements increase the evacuation capability, there are some situations where the result is just the opposite. This is the case of the B767, with two type A and two type III exits on each side of the fuselage, that was certified for 290 passengers and, with the updated regulations, would have been downsized to 285.

The only objective of the 90 s rule demonstration is to show that the airplane can be safely evacuated in that period of time, under the aforementioned conditions. Evidently, it does not represent an accident scenario, nor is it intended for system optimization. Furthermore, no statistical relevance can be deduced from a unique trial, conceived as an industrial benchmark for consistent evaluation. If the high costs and risk of injuries of a real demonstration are added to the former picture, it is easy to understand the existing controversy among authorities, manufacturers, crew members, and public associations [9,18–21] about the pertinence of such a rule.

For this reason, civil aviation authorities and airplane manufacturers have promoted the development of evacuation models that

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Table 1 Dimensions and evacuation capacity of exit types

	Minimum dimensions		Seating capacity
Exit type	Width, m	Height, m	(no. passengers)
A	1.07	1.83	110
B	0.81	1.83	75
C	0.76	1.22	55
I	0.61	1.22	45
III	0.51	0.91	35

could be used for design and certification, as well as for aircraft accident analysis [12,18–41]. Table 2 lists a set of relevant software, which will be briefly discussed.

The Federal Aviation Administration's (FAA's) Civil Aeromedical Institute (CAMI) undertook the task of developing the GPSS model in the late 1970s [26,27], intended to simulate the evacuation trials in certification scenarios. It was a network rule-based passenger behavior model, programmed in GPSS, an IBM simulation language. Its main drawbacks were the uniformity of passenger attributes, the lack of graphical interface, and a great dispersion of evacuation times.

Some years later, NASA sponsored the FIREVAC model [12], developed by Victor E. Middleton, from the University of Dayton Research Institute. The purpose of this model was to assess passenger survival during postcrash evacuation of transport airplanes. It was also a network model that included simple physiological effects of intoxicants. The software was programmed in FORTRAN, and the passengers had preassigned optimal routes that could be modified depending on the evolving circumstances. It was tested for verification but never validated because of the lack of data.

Following an FAA initiative, the Gourary Associates (GA) developed the GA model [28,29], again of a network type, to simulate realistic accident scenarios. It incorporated a graphical interface and ran in near-real time, but it had important operational limitations. No validation results were published in open literature.

The aircraft evacuation (AIREVAC) model [30,31] was developed by the South West Research Institute under the Air Transport Association's (ATA's) sponsorship, to simulate real emergency evacuations. It was very slow, did not include occupants' features, and had too many parameters. The project was later renamed ARCEVAC [32] and improved to run in real time, but it achieved no meaningful success.

The Fire Safety Evacuation Group of Greenwich University applied its extensive knowledge of building evacuation to develop the airEXODUS model [33–35], with the financial support of the U.K. Civil Aviation Authority (UKCAA). This ambitious software package is intended for aircraft design, certification testing, crew training, and accident investigation. It is programmed in C++ and may run on a variety of PCs and workstations. The model is of a network type with single-occupancy cells and rule-based behavior. It incorporates four submodules: movement, behavioral, hazard, and toxicity. The simulated passengers are assigned to the nearest available exit, unless redirected by crew or local conditions. It has been validated with Cranfield University partial trials and data from the Boeing B767-300ER certification test. Its main disadvantages are a cumbersome geometric definition and difficulty in interpreting the results.

Also, with financial support from the UKCAA, the risk assessment model (RAM) [36,37] was developed by Macey and Cordey-Hayes at Cranfield University. Again, it was a network, deterministic model, with rule-based behavior, conceived to analyze actual as well as certification evacuations. Fire and other hazards were probabilistically introduced in the scenario. It had a graphical user interface and a large airplane database. The model was validated with two narrow-body actual certification trials, but the simulated evacuation times were always overestimated, as a result of a suboptimal evacuation.

The Oklahoma object-oriented model (OOO) [19] was conceived as a join initiative by Oklahoma University and the FAA's Civil Aeromedical Institute to create a framework to handle evacuation simulation software models, both for real emergency cases and for certification trials. However, it was never fully implemented nor validated.

Aimed at simulating certification trials and real emergency evacuations, the Robbins and McKee discrete element method (DEM) [38] was developed by researchers from Strathclyde University. It is a deterministic model based on an analogy between passengers evacuating an airplane and spheres moving through pipes. The motion of spheres is solved, including friction and inertia forces and torque. In the analogy, the spheres were individually pulled by the exits. The validation tests were performed with B737-300 certification trial data, providing 81 s against the actual 75 s. Apart from just showing promising results, the functional analogy was questionable, and the validation of parameters lacked physical meaning.

Following a former model developed by the State University of New York at Buffalo for individual and crowd fire emergency evacuations, called Vacate [39], a new, specific application to simulate both certification and real evacuation situations of transport airplanes was elaborated under the name of VacateAir [40,41]. It is an optimization model validated with data from Cranfield University evacuation trials. The model considers that occupants move grouped, like flocks. Apart from this unrealistic performance, the model does not reproduce certification results with enough precision.

The present paper describes the results obtained with a new agent-based computer model, which can accurately simulate the evacuation of transport airplanes in the conditions prescribed by the airworthiness regulations for certification. It has been developed within a long-term research project, sponsored by the Spanish Ministries of Education and Innovation, which started with detailed studies of cabin geometry data gathering and evacuation strategies [20,44,45]. The model, which has been presented in detail elsewhere [42,43], has been tuned with data from the Airbus A320-100 emergency evacuation demonstration and open literature and verified with the evacuation trials of the Airbus A320-200 and the Boeing B757-200 eight-door version. Although the simulation model has been developed for helping in the certification process, as a reliable substitute of evacuation demonstrations, it can also be used in the design of new cabins, as will be shown later. To allow the reader a full understanding of the results, a summary of the model's main features is presented in the next section.

Table 2 Emergency evacuation software models

Name	Years	Institution	Purpose
GPSS [20,21]	1978–1980	CAMI-FAA	Certification
FIREVAC [7]	1984	NASA/Simulation Tech, Inc.	Fire accident reconstruction
GA [22,23]	1987–1992	FAA/Gourary Associates	Accident reconstruction
AIREVAC [24–26] AIRCEVAC	1991–1994	ATA/South West Research Institute	Certification
airEXODUS [27–29]	1993–	Greenwich University	Certification and accident reconstruction
RAM [30,31]	1994–1996	Cranfield University	Certification and accident reconstruction
OOO [12]	1996–1997	CAMI-FAA/Oklahoma University	Theoretical model
DEM [32]	2001–	Strathclyde University	Certification and accident reconstruction
VacateAir [33–35]	2008–	State University of New York at Buffalo	Certification (psychological aspects)
ETSIA [42,43]	2009–	Universidad Politecnica de Madrid	Certification and design

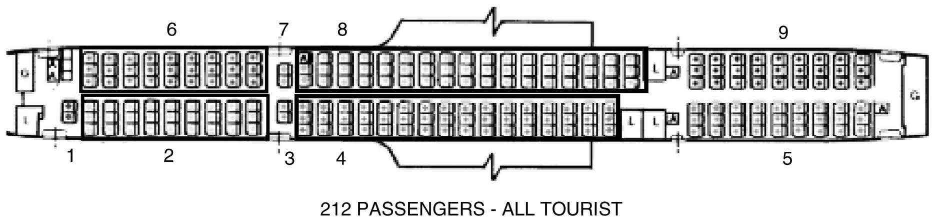

Fig. 1 Top view of a B757-200 cabin showing the seating arrangement and exit location.

II. ETSIA Computer Model

As formerly indicated, ETSIA is an agent-based computer model conceived for simulating the evacuation of transport airplanes in the conditions prescribed by the airworthiness regulations for certification. Its name stands for evacuation test simulation and investigation algorithm. It has been implemented in NetLogo [46], a user-open language capable of interacting with many other software packages. The model has been developed and verified for narrow-body aircraft, but it could be extended to wide bodies, multideck airplanes, and unconventional configurations, such as blended wing bodies and flying wings. For a better understanding of the model and the interpretation of the results, two key terms are first defined:

1) Egress is the process of abandoning an airplane performed by each occupant. It starts when the order to evacuate is given by the airplane captain, and it is finished when the occupant reaches a safe point out of the aircraft. In the ETSIA environment, the order to evacuate corresponds to the user hitting the run key, and the egress ends when the simulated occupant reaches the simulated ground or platform.

2) Evacuation is the set of all egress processes.

A. Submodels and Capabilities

As it is common to most evacuation simulation codes listed in Table 2, ETSIA has been conceived with three basic submodels: geometry, occupants, and time. The submodels are assembled to form the kinematic submodel. The following paragraphs will summarize the main features of these submodels.

The geometry submodel gathers all elements related to the cabin and the evacuation means: seats, aisles, exits, deployable slides, etc. To arrange and locate all these elements, a reference frame $Oxyz$ is defined, associated to the airplane at rest. The origin O is located in the aircraft plane of symmetry Oxz and on the Oxy ground plane (assumed to be horizontal). For practical reasons, it can be established below the aircraft nose. Moreover, Ox is the longitudinal axis directed rearward, and Oz is the vertical axis, positive upward.

All the information required for the evacuation modeling of each aircraft is arranged in an input data file, with data taken from detailed plan views of the cabin in a high-density version appearing in the manufacturers' documents, such as aircraft characteristics for airport planning (see, for example, [47,48]). Data are identified, measured, and logged in the input data file. The elements considered are seats, aisles, cross aisles, passageways, exits, and descent means. The whole cabin is taken as the appropriate entity for the evacuation simulation. It is foreseen to extend the present model to wide bodies, multiple deck aircraft, and unconventional configurations. In those cases, each cabin will be taken as the appropriate entity for evacuation simulation, and all decks will be integrated in the whole airplane evacuation.

Exits are defined by the airworthiness regulations, and they consist of doors and overwing exits. But, within the ETSIA model, the exit objects also include information on evacuation capacity and the associated descent means. Available exits have code names for left- and right-hand sides, fore to rear (L1, L2, ..., R1, R2, ...), and eight attributes: the first four are related to the exit, such as the longitudinal and traverse coordinates of its center, sill height, and evacuation capacity according to FAR rules [10]; and four additional data belong to the descent means, like the type of descent means (stair, slide, overwing, etc.), the horizontal lengths of the rigid and pneumatic parts (zero if not applicable), and the height from the end of the descent device to the ground.

Regarding the evacuation paths, three types are considered here as suitable for narrow-body airplanes: passages between seat rows, common aisles, and passageways leading to exit doors. To include all pertinent information, the total number of data is twice (for the x and y coordinates) the number of path segments plus one (to include both extremes) and the aisle width, which is considered constant over all its length.

With respect to cabin attendants, eight attributes are necessary to indicate their location and role: the two-dimensional coordinates of the folding seats, their orientation, the primary and secondary assigned exits, and three additional values to determine their position and orientation while directing the evacuation close to the exit. Flight crew members share the last five attributes, since at the beginning they are supposed to be standing on the border between the flight deck and the cabin. On its side, due to the great diversity of cabin arrangements, passenger seats require a more detailed explanation. First, two additional, intermediate classes are created: zone and block [20,44], a block being a set of joint seats and a zone being a set of blocks with the same arrangement and spacing. The zones are numbered fore to rear, first left and then right. The definition of each zone requires 11 attributes: the number of blocks, the numbers of seats per block, the x and y coordinates of the key seat's left rear corner (the key seat is the leftmost, foremost one in the zone), the seat width, the armrest width, the longitudinal pitch between blocks, the seat depth, the lateral displacement between subsequent blocks (if any), a flag digit to mark the existence of an aisle on the left, and another flag to mark a right aisle.

Figure 1 can help in the interpretation of the former paragraph. It represents an all tourist version cabin of B757-200 with eight exits. Nine seat zones can be identified: the first one with one block of two seats, then a second zone of nine three-seat blocks, and so on.

The movement of occupants through the cabin is treated as a continuum; however, to handle such movement in the model, all available floor area is converted into a grid of cells. The minimum discrete distance has been chosen as 0.1 m, which is considered appropriate for the required accuracy. The suitability of this value will be checked later as part of the model's robustness tests. All occupants are assumed to need a 0.5×0.3 m rectangular box, which means that the model works in a multicellular environment [42,49] with each person commonly occupying 15 cells.

Aircraft occupants considered in the numerical simulation are either passengers or crew members, according to their role in the process [42].[‡] All of them are modeled as mobile agents characterized by their corresponding attributes. In the present status of the modeling, only age and gender have been taken into account, since they are the most relevant according to the literature [16,17,39]. Current regulations [10,11] indicate that, for the evacuation trial, passengers can be grouped into four types according to gender (male and female) and age (junior, less than or equal to 49 years, and senior), with certain minimum percentages for women and seniors. Thus, women must represent more or equal to 40% of all passengers, seniors must represent more or equal to 35%, and senior women must represent more than 15%. Occupants' reaction times, speed, etc., are statistically distributed around mean values, depending on age and

[‡]A380 evacuation trial video available at http://www.youtube.com/watch?v=XIaovi1JWyY [retrieved 1 June 2011].

Table 3 Average speed inside the aircraft cabin

	Average local speed, m/s
Narrow aisle	0.45
Main aisle	1.15
Cross Aisle	1.15
Passageways	1.30
Slide	2.00

Table 4 Mean and standard deviation of the kinematic factor for evacuation movements

Kinematic factor	Crew members and junior men	Junior women	Senior men	Senior women
Mean	1.10	0.97	0.88	0.78
Standard deviation	0.05	0.05	0.05	0.05

gender [42,43]. Crew members are considered to be in good physical conditions. According to that grouping, six different types of occupants, recognized by their colors, can be identified on the computer screen during the simulated evacuation process: junior man, junior woman, senior man, senior woman, cabin attendant, and flight crew member.

For a given occupant, the local speed depends fundamentally on the evacuation path width. The average local speed for the various path types used in the ETSIA model is shown in Table 3 [9,12,23]. On another hand, the ETSIA model uses a kinematic factor for each occupant, depending on his/her age and gender attributes, to determine the specific speed. This factor is assumed to follow a normal distribution with the mean and standard deviation, as shown in Table 4. Each individual speed is then obtained by multiplying the average local speed by a kinematic factor that has been stochastically assigned to him/her.

Randomness in the ETSIA model is introduced in a double sense in each simulation run:

1) On the one hand, the passenger mix (age–gender) is fixed by the regulations, but the kinematic attributes of the simulated passengers vary, obviously. As indicated in the former answer, the model assumes that such attributes are normally distributed, and it assigns each simulated occupant a random value;

2) On the other hand, the simulated passenger population is randomly seated all over the cabin. This is very important, since slow occupants generate delays in the evacuation. For example, the passenger occupying seat 3A may be a junior man in a simulation run or a senior woman in the next one: in each case, with a fully different kinematic factor.

Regarding the third submodel, time is taken as the background independent variable: it is continuously flowing behind the scene and marks the rhythm and performance of the simulation. The fundamental elements of this submodel are the time point and the time interval, or the period within two specific time points.

The chronogram, defined as a timeline of ordered subsequent time points, is a key tool in understanding the simulation evolution. Thus, Fig. 2 shows the chronogram for the complete evacuation process of the aircraft cabin. The evacuation takes place between the instant when the pilot says evacuate t_{sta} (here, the time origin for the simulation run) and the time point when the last occupant reaches the ground (see footnote ‡) or any other place accepted as safe for the certification t_{end}. It is required that $T_{\mathrm{eva}} = t_{\mathrm{end}} - t_{\mathrm{sta}} < 90$ s. But the evacuation analysis requires more detailed information. For example, the period $t_{fee} - t_{lea}$ corresponds to full capacity or maximum evacuation flow rate, and the ratio between the period of full capacity and the evacuation time is a measure of the evacuation efficiency. Cabin designers can use this and other proposed ratios [42,43] to improve the evacuation performance of new aircraft or new versions.

The time unit used in the model is 0.1 s, which is again considered enough according to the simulation features and the variables to be statistically modeled. Time sensitivity tests indicate that the overall process is independent from the former value.

The kinematic submodel rules the movement of all occupants through the stage and assembles all aforementioned features. The kinematic protocol proposed by ETSIA is a simple mathematical model able to reproduce all phenomena occurring in an evacuation demonstration.

Without loss of generality, the motion of an occupant can be considered a sequence of the following four basic movements: vertical displacement, lateral displacement, forward displacement, and turning (change of heading direction). The vertical and horizontal displacements can appear mixed, as when the occupant is sliding on a pneumatic ramp.

Further to age and gender, three attributes are assigned to each occupant: 1) the reaction time, randomly determined by a Weibull's biparametric statistical distribution [50,51]; 2) the kinematic factor, which is Gaussian and doubly dependent on age and gender (the actual occupant speed is the result of multiplying its kinematic factor by the mean speed value of the type of evacuation path occupied); and 3) the exit hesitation time between the arrival at the exit and the jumping onto the slide. It is randomly generated using a Poisson distribution [50,51] with a given mean value for each individual and exit. It is assumed to be zero when the occupant exits through an emergency window over the wing or when a rigid outer platform is used.

Since simulating the movement of humans on pneumatic slides with a dynamic model can be very complex, the procedure adopted here is limited to reproducing realistic transit times by adequately combining horizontal and vertical speeds.

A crucial step in the evacuation simulation is the assignment of seated passengers to the available exits. In the case of narrow-body airplanes, it is obvious that the initial flow will be the determinant of the occupants' performance. In the present simulation model, a set of divisions, one in between two consecutive available exits, is used to

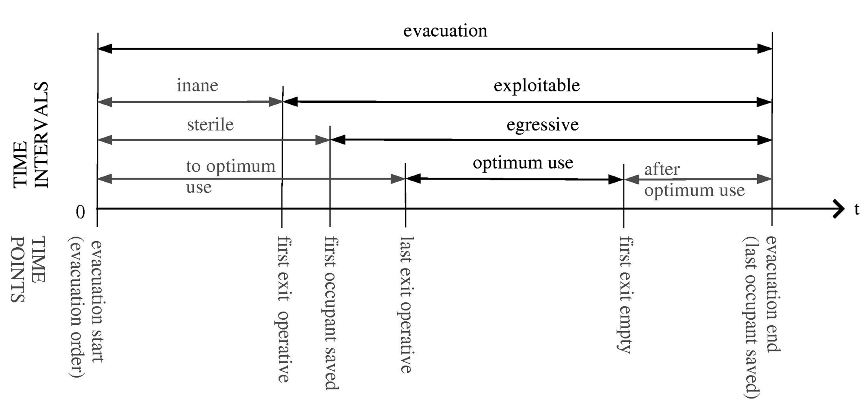

Fig. 2 Chronogram of evacuation process.

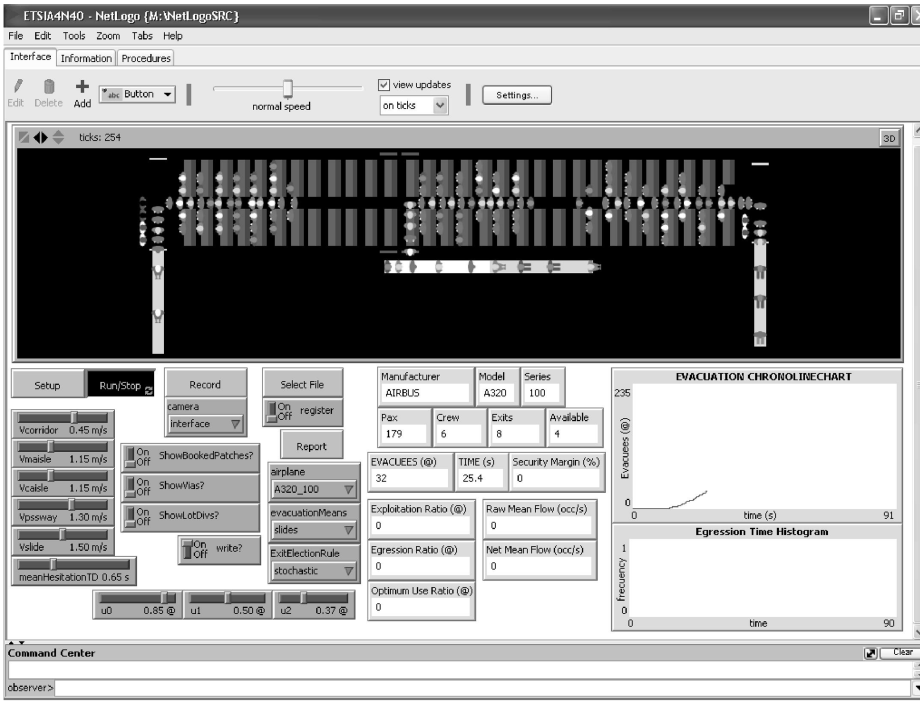

Fig. 3 Example of screen view during simulation.

separate flow senses. The division between two close overwing exits is just defined for the initial passenger flow, but once it is organized, the model considers that both close coupled exits behave without a border in between them. The location of such divisions is selected using parametric sweeping to improve uniformity among exit occupancy. This procedure perfectly simulates the behavior of observed passengers (see footnote ‡) and optimizes the evacuation process.

As a last item of this brief model description, Fig. 3 shows the visual interface developed to monitor the simulated trial. The upper half depicts the plan view of the cabin and other related items in subsequent moments of the evacuation. It can be updated at a controllable rate to simulate slide deployment, passenger displacement, etc. The bottom left area provides the user with all the selectors, buttons, and sliders needed to identify the airplane and to modify the evacuation parameters (displacement speed, hesitation time, etc.). The information on the instantaneous and accumulated performance of the evacuation is depicted in the bottom center area. The evacuation chronoline (saved evacuees vs time) and a detailed egress time histogram appear at the bottom right-hand side. Figure 4 presents the actual and simulated chronolines of the A320-100 evacuation, which is the one used for the tuning of the computer model.

The simulation process is fast enough to allow real-time monitoring of the evacuation simulation in the computer screen. The time margin in the computer speed for real-time processing is between one and two orders of magnitude for common personal computers, depending on the central processor unit and software employed [43]. Such a large margin will be used in future extensions for wide bodies and unconventional configurations that could require extra computing work.

One of the main potentials of any computer modeling is the capability of running as many simulations as desired to achieve a required statistical meaning, as opposed to the single trial performed in real certification procedures. Typically, 1000 trials are performed to determine suitable statistics on evacuation performance.

The evacuation time follows a Gaussian probability distribution [50,51], which has been confirmed by the χ^2 test done with a limited series of 255 runs of the A320-200 cabin (see Fig. 5). This case

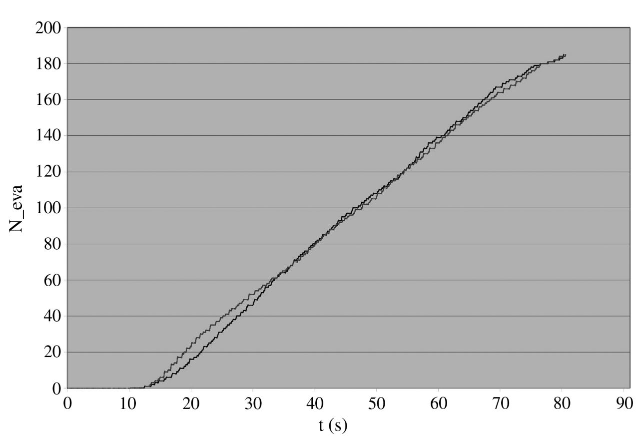

Fig. 4 Actual (gray line) and simulated (black line) chronolines of onground saved occupants as a function of time of the A320-100 evacuation.

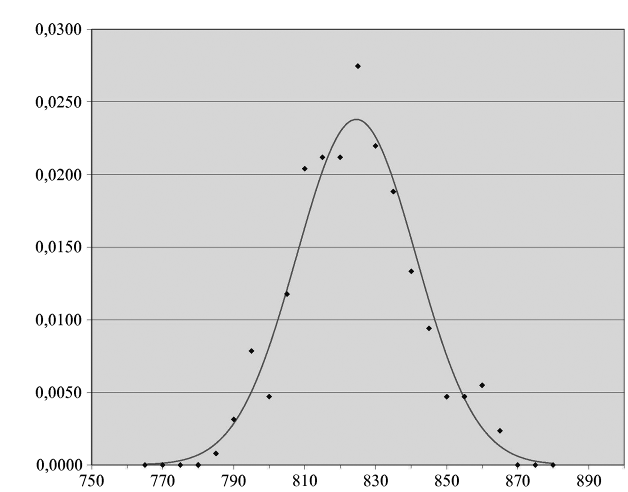

Fig. 5 Probability density distribution of a set of 255 simulation runs of the A320-100 cabin.

exhibits a Fisher's asymmetry coefficient of 0.03 and a Kurtosis coefficient of 0.02.

The ETSIA computer simulation model is capable of providing full details of the egress of each occupant, as well as full details of the overall evacuation process. Particularly useful to certification authorities and designers are the relevant times and efficiency of the process: Where are the bottlenecks, if any? Which are the cabin features that exhibit stronger influence on the evacuation performance? etc.

B. Model Robustness

A simulation tool is only valid if its outputs are consistent. ETSIA has to deal with the evacuation time and other random variables and parameters. Therefore, the model must be stable against the disturbances due to such randomness and other errors. Two types of tests have been performed to assess the model's robustness: stability against random variation of the intervening variables (internal consistency) and stability against input data errors (external consistency).

With respect to the random nature of the evacuation variables, the model's stability is confirmed by the extremely low variability found among five successive 1000-run simulation series, as can be seen in Table 5. The cabin chosen for this test belongs to an MD-87 with 130 seats, one type 1 and two type III exits on each side of the fuselage, plus a type V rear exit through the tail cone. It has been selected for this purpose because it represents a medium-sized narrow body that incorporates the peculiarity of the rear exit, and it exhibits no particular troubles from the evacuation point of view.

The global average of the evacuation time is 63.19 s, and all five of the series' means are within 0.1 s from this average. The maximum scatter is 0.07 s, about 200 times smaller than the standard deviation. These findings confirm both the stability of the results and the adequacy of the time unit selected for the computer simulation.

Incidentally, another series has been performed with the rear exit blocked. Although the mean evacuation time for 1000 runs is 88.9 s, a large number of the simulations took longer than the 90 s threshold and, therefore, were not acceptable from the certification perspective. The number of evacuees through the rear exit is only 25 when the exit is open, but even this moderate figure is crucial to alleviate the crowded overwing exits.

On the other hand, the model's robustness also means insensitivity to input errors that may affect the results. To assess this specific aspect of the model, a different aircraft, A320-100, has been used as test bed. It was certified under Joint Aviation Regulation (JAR) Part 25 [52] for 179 passengers on 26 February 1988. At that date, JAR 25.807 required two type I and two type III emergency exits on each side of the fuselage for airplanes with between 140 and 179 passengers. Now, to test the effects of input data variation on mean evacuation time, four cases have been conceived. In all cases, the input data shift is 10 cm, equivalent to one length quantum.

The four situations analyzed, each one with 255 simulations, are 1) U: unmodified cabin; 2) M01: L1 type C door shifted forward 10 cm, one length quantum; 3) M02: L4 type C door shifted backward one length quantum; and 4) M03: L1 type C door shifted forward and L4 type C door shifted backward, a length quantum each.

The results are summarized in Table 6. It is evident, from these results, that common input errors associated to mistakes or misinterpretations of cabin geometry do not affect the results, provided they are not much larger than a length quantum.

Table 5 Test on repeatability of results: evacuation simulation series for MD87 (each series consisting of 1000 simulations)

Series	T_{eva}, s	σ_{eva}, s
1	63.23	1.46
2	63.20	1.42
3	63.26	1.50
4	63.14	1.43
5	63.13	1.38
Mean	63.19	1.44

Table 6 Stability of results against input data errors for Airbus 320-100[a]

			Passengers per exit			
Case	T_{eva}, s	σ_{eva}, s	L1	L2	L3	L4
U	79.84	1.46	60	25	35	59
M01	79.88	1.51	60	25	35	59
M02	79.85	1.46	60	26	34	59
M03	79.87	1.47	60	26	34	59

[a]Case U: unmodified cabin; M01: fore exit shifted forward; M02: rear exit shifted rearward; M03: fore exit shifted forward and rear exit shifted rearward. All displacements are 0.1 m.

III. Results

The aircraft analyzed in the present research work are listed in Table 7. They are representative of the narrow-body designs in America and Western Europe in the last decades. They cover a broad range of cases, including four turboprops that were selected to check possible differences with small regional jets; nine regional jets in the 50–100 seats category; nine more airplanes in the more typical 130–180-seat segment; and four large narrow bodies with more than 200 seats. The year of first flight, a relevant indication of the corresponding technology level, is scattered in about 40 years. Some peculiar airplanes are also listed, such as the BAe 146, with an uncommon high wing configuration or an old, highly stretched DC-8 series 61 with the largest seating capacity ever arranged in a narrow-body airliner. Table 7 includes the number and type of exits on each side of the fuselage; in the case of MD87 and B727-200, there is also a ventral exit *V* at the rear of the cabin. The table depicts the number of seats, cabin attendants, and flight crew members as well.

Except otherwise indicated, all evacuation simulations have been performed 1000 times with each airplane cabin to obtain statistically relevant data.

Table 8 gathers the most important results. Apart from the number of passengers and crew members to be evacuated, already shown in Table 7, key features are the maximum seating capacity (depending

Table 7 Database of narrow-body airplanes analyzed (exits on each side of fuselage)

Airplanes	First flight date	Exits	N_{seat}	N_{att}	N_{flg}
SAAB 2000	26 March 26 1992	I–III	50	2	2
FOKKER 50	28 Dec. 28 1985	I–III	50	2	2
CRJ 200	10 May 1991	I–III	50	2	2
EMB 145	11 Aug. 1995	I–III	50	2	2
ATR72-600	27 Oct. 1988	III–I	74	2	2
EMB 170	29 Feb. 2002	I–I	74	2	2
DASH8-Q400	31 Jan. 1998	I–I	78	2	2
CRJ 700	27 May 1999	I–III	78	2	2
FOKKER 70	4 April 1993	I–III	80	4	2
CRJ 900	21 Feb. 2001	I–III–III	90	2	2
EMB 190	12 March 2004	I–III–I	98	2	2
FOKKER 100	30 Nov. 1986	I–III–III	107	4	2
BAe 146-300	1 May 1987	C–C	110	3	2
A318-100	15 Jan. 2002	C–III–C	124	3	2
A319-100	25 Aug. 1995	C–III–C	126	5	2
MD-87	4 Dec. 1986	I–III–III–V	130	4	2
B737-200	8 Aug. 1967	C–III–C	130	4	2
B737-500	12 Feb. 1990	C–III–C	132	4	2
B727-200	27 July 1967	C–III–III–C–V	155	4	3
B737-400	19 Feb. 1988	C–III–III–C	162	5	2
A320-200	22 Feb. 1987	C–III–III–B	179	4	2
B737-800	31 July 1997	C–III–III–C	184	5	2
A321-200	11 March 1993	C–C–C–C	220	7	2
B757-200 (10e)	19 Feb. 1982	C–C–III–III–C	220	5	2
B757-200 (8e)	19 Feb. 1982	C–B–I–C	228	5	2
DC8-61	14 March 1966	C–I–III–III–I–C	259	8	3

Table 8 Results of narrow-body airplanes analyzed, grouped by category

Class[a]	Airplanes	N_{seat}	N_{max}	T_{eva}, s	σ_{eva}, s	T_{95}, s
TP	SAAB 2000	50	80	47.78	1.38	50.30
	FOKKER 50	50	80	39.77	0.89	41.23
	CRJ 200	50	80	49.09	1.47	51.51
	EMB 145	50	80	43.48	1.02	45.16
RJ	ATR72-600	74	80	59.57	1.51	62.05
	EMB 170	74	90	53.43	1.48	55.86
	DASH8-Q400	78	90	54.46	1.18	56.40
	CRJ 700	78	80	63.36	1.56	65.93
	FOKKER 70	80	80	67.12	1.63	69.80
	CRJ 900	90	110	60.51	1.45	62.90
	EMB 190	98	125	53.94	1.49	56.39
	FOKKER 100	107	110	71.36	1.48	73.79
	BAe 146-300	110	110	73.37	1.46	75.77
MNB	A318-100	124	145	65.83	1.51	68.31
	A319-100	126	145	66.53	1.49	68.98
	MD-87	130	130	67.85	1.57	70.43
	B737-200	130	145	66.17	1.33	68.36
	B737-500	132	145	68.35	1.37	70.60
	B727-200	155	175	68.76	1.53	71.28
	B737-400	162	175	71.62	1.54	74.15
	A320-200	179	195	74.32	1.79	77.26
	B737-800	184	175	81.09	1.69	83.87
LNB	A321-200	220	220	70.51	1.11	72.34
	B757-200 (10e)	220	230	83.24	1.73	86.09
	B757-200 (8e)	228	225	73.90	1.07	75.66
	DC8-61	259	265	78.78	1.99	82.05

[a]TP: turboprops; RJ: regional jets; MNB: medium-sized narrow bodies; LNB: large narrow bodies.

on the number and type of exits; see Table 1), the average and standard deviation of the evacuation time, and the right-hand side 95% confidence limit in the 1000 run series.

The main findings are as follows. As expected, the mean evacuation times are quite spread out, with a minimum of 39.8 s for the Fokker 50 and a maximum of 83.2 s for the B757-200 with 10 exits. The corresponding standard deviations also differ among the various aircraft, although with a smaller scatter. In all airplanes, both the average and the 95% confidence evacuation limit show suitable margins with respect to the 90 s rule.

As formerly indicated, the evacuation time follows a Gaussian distribution. Figure 6 uses this characteristic to provide an overall glance of all simulations. The Gaussian curves are centered in their mean values. But, since the curves are normalized in total probability (i.e., area), the airplanes with smaller standard deviations (i.e., narrower curves) appear with higher peaks.

Exceptionally, one of the simulation runs performed with the B757-200 cabin with 10 exits took longer than the 90 s threshold.

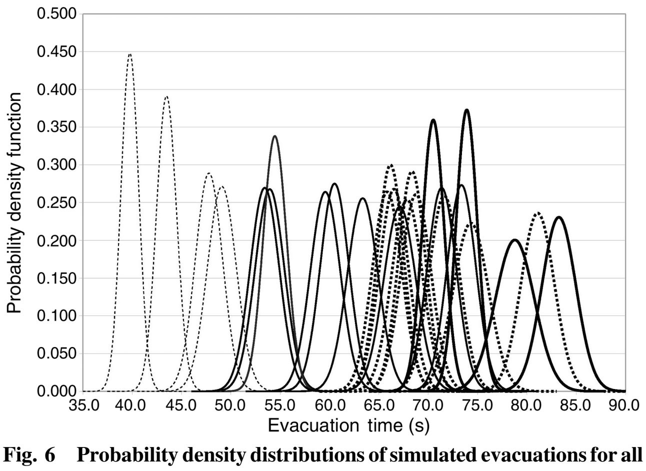

Fig. 6 Probability density distributions of simulated evacuations for all aircraft listed in Table 5.

That means a negligible 0.1% failure rate with respect to certification requirements for this aircraft cabin: the only one with such a problem among the 26 studied.

The regulations have evolved over time, with relevant implications on evacuation performance. Thus, the A320-100 was certified under JAR Part 25 for 179 passengers on 26 February 1988. JAR 25.807 compelled, at that time, the presence of two type I and two type III emergency exits on each side of the fuselage for airplanes with between 140 and 179 passengers. The new FAR Part 25 [10] requires at least one type B, one type C, and two close type III emergency exits on each side of the fuselage to accommodate 179 passengers.

To show the effect of this regulation change, ETSIA has been used to simulate both the old and the actual hypothetical evacuations. With type I exits, the mean evacuation time of a 1000-run series has been 79.0 s with a standard deviation of 1.7 s. When the process is repeated with one type B door at the cabin front and one type C door at the rear, the results are 74.8 and 1.5 s, respectively. The improvement in evacuation time is mainly due to the double evacuation lane slide in the type B door instead of the single lane corresponding to the old type I exit.

The next section will present an in-depth analysis of all findings and will throw some light on the evacuation process itself and on the usefulness of simulation for airplane designers as well as for the certification officers.

IV. Analysis and Discussion

Let us first analyze the seating capacity of the aircraft studied. The maximum seating capacity of an airplane cabin depends on the regulation applicable on the date of certification. Superseded FARs allow different evacuation capacity than current requirements. For example, old rules had only type I and type A doors, while there are four of them today: namely, type I, type C, type B, and type A. The seating capacity ratio of the aircraft is the ratio between the number of passenger seats in a given cabin and the maximum number of passengers that can be evacuated according to the exits; that is, $SCR = N_{seat}/N_{max}$. This ratio should not be confused with the seat occupancy rate, also called the passenger load factor, which is N_{pax}/N_{seat}, indicating how occupied the cabin is, and has no relationship at all with the evacuation demonstration.

Two of the aircraft studied, the B737-800 and B757-200 with eight exits, exceed the maximum seating capacity allowed by their respective emergency exits. The B737-800 cabin has 184 seats, two type C and two coupled type III exits in each side of the fuselage that, according to Table 1, are appropriate for up to 175 passengers. Incidentally, this aircraft was certified for 189 passengers by means of analysis after previous demonstration trials of the B737-100 and B737-400 [42]. On its turn, one of the B757-200 cabins analyzed has 228 seats and four exit pairs (type C, type B, type I, and type C), allowing the evacuation of 225 passengers. However, it was certified for 239 after a successful demonstration. None of these two crowded cabins showed problems with respect to the 90 s rule in the 1000-run series performed with each cabin.

In spite of the differences between certified and maximum seating capacities in some aircraft, whenever the seating capacity ratio or the maximum seating are mentioned in the next paragraphs, the maximum number of passengers allowed in a given cabin has been computed in terms of its exits and the exit seating capacities given by Table 1.

A. Seating Capacity and Evacuation Time

The current FAR 25.807 [10] declares that the maximum seating capacity is a function of the number and type of emergency exits, similar to the initial regulations published in the 1960s. The requirement also indicates that the exits must be uniformly distributed, and it dictates a limitation in the distance between consecutive exits. It must be assumed that the objective of such a requirement was (and still is) to minimize the evacuation time needed in an actual evacuation, or at least to maintain it below a threshold, as in the evacuation demonstration.

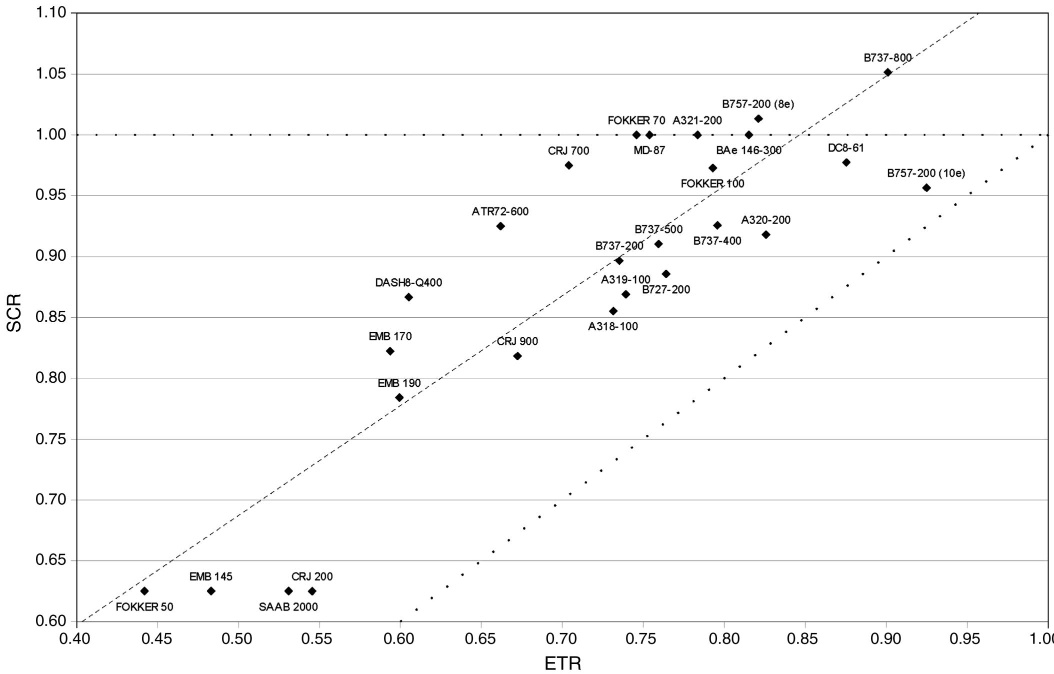

Fig. 7 Relationship between SCR and ETR for all aircraft analyzed.

Thus, let us hypothetically consider that the evacuation time is proportional to the seating capacity ratio, with a safety margin to take into account nonoptimal passenger distributions and other, not included, characteristics. Figure 7 confirms such a relationship with a quantitative linear link

$$\mathrm{ETR} = \frac{\mathrm{SCR} - 0.237}{0.895} \tag{1}$$

The evacuation time ratio (ETR) is the evacuation time T_{eva} divided by 90 s; that is, $\mathrm{ETR} = T_{\mathrm{eva}}/90$. The correlation coefficient is 0.84, which is rather high. However, when the picture is seen at a closer distance, it is possible to detect that other features modify the former linear link.

For example, Table 9 depicts that all aircraft with $\mathrm{SCR} = 1$ exhibit some scatter in their ETR. Again, Table 10 shows analogous results for the group of smaller aircraft, with a somewhat larger scatter. It is easy to check that size is not the key factor. On the one hand, the Fokker 70 and Fokker 100 are two airplanes with a very similar seating capacity ratio of 1.000 and 0.973, respectively, but average evacuation times of 67.12 and 71.36 s, respectively: the F100 being a larger aircraft. Contrarily, the MD87 and A321 are larger than the BAe146 but exhibit smaller ETR.

Table 9 Evacuation time ratio of a group of aircraft having a seating capacity ratio equal to 1

Airplane	SCR	ETR
Fokker 70	1.000	0.746
MD-87	1.000	0.756
A321-200	1.000	0.783
BAe 146-300	1.000	0.815

Table 10 Seating capacity ratio and evacuation time ratio for the group of smaller aircraft

Airplane	SCR	ETR
Fokker 50	0.625	0.442
EMB 145	0.625	0.483
Saab 2000	0.625	0.531
CRJ 200	0.625	0.545

B. Effects of Emergency Exit Location

The longitudinal position of exits is another relevant feature for the evacuation process. A good longitudinal distribution seems to be advantageous for evacuation time, but ad hoc trials have to be performed to quantify its effect.

Floor-level exits at both cabin ends have fixed locations, and there is no way to remove them without transgressing the rules. Only the exits located in the middle of the fuselage can be shifted or removed to investigate the impact of emergency exit location.

To test the effects of exit arrangement in the evacuation process, the cabin of the Airbus A320-100 [42] has been selected. It is identical (except for minor shifts in a few seats) to one of A320-200 included in Table 7 but with the advantage of knowing the actual certification evacuation data. Once the cabin is defined, four cases have been studied: 1) U, unmodified cabin; 2) M0, cabin with R2/L2 and R3/L3 type III exits shifted backward one row pitch; 3) M1, cabin without R2/L2 type III exits; and 4) M2, cabin without R3/L3 type III exits.

The results are summarized in Table 11. The improvement shown in the M0 case can be explained as follows. Because of the A320 configuration, the wing is relatively shifted forward with respect to the cabin, and so are the type III overwing exits. The number of passengers escaping through L1 and L4 do not change with respect to the original cabin, but there is a redistribution of passengers using both type III exits. If the exits are better centered (i.e., shifted rearward), more passengers will address the L2 exit, for its sharing with L1 and L3 is better balanced. A tool like ETSIA can study the effect of various locations at early design stages.

The M1 and M2 cases are special situations, since the number of evacuees escaping through each remaining exit is much larger than

Table 11 Exit location effects in evacuation time for A320-100[a]

Case	T_{eva} (s)	σ_{eva} (s)	No. Pax evacuated			
			L1	L2	L3	L4
U	79,06	1,68	60	25	35	59
M0	77,98	1,12	60	28	32	59
M1	87,15	1,66	66	——	48	65
M2	87,20	1,65	66	48	——	65

[a]U: unmodified cabin; M0: type III exits shifted rearward one row pitch; M1 and M2: suppression of L2 or L3 type III exits, respectively.

Table 12 Characteristics of SAAB 2000 exits

Denomination	Exit Type	X coordinate, m
L1	I	4.675
L2	III	12.911
R1	III	12.911
R2	I	19.540

Table 13 SAAB 200 evacuation results

Available exits	T_{eva}, s	σ_{eva}, s
Port	47.78	1.38
Starboard	58.30	1.53

the allowed maximum given in Table 1; that is, all exits are overloaded to compensate that a type III exit has been removed. Their evacuation times and passenger-to-exit allocation are quite similar in both cases. The margin of evacuation time to the 90 s limit is very narrow, and around 6% of the simulations went over such a limit. The M1 results are slightly better, confirming the idea that a more centered exit location provides better evacuation performance.

C. Influence of Asymmetrical Exit Arrangement

The emergency exit pairs considered in the regulations need not be diametrically opposite, not even approximately (25.807 of [10,11]). The evacuation performance is determined by the most restrictive emergency exit arrangement. Thus, starboard doors, used for servicing access, are commonly the critical exits, since port doors, used for embarkation and disembarkation of passengers, are larger. Other than this exit size effect, the location of the various exits may also contribute to making some evacuations much slower than others.

In the database used in this research, there is only one case of exaggerated asymmetry: the Saab 2000, for which the emergency exits have the distribution shown in Table 12.

To check how the airplane evacuation is affected by this peculiar asymmetry, the simulation has been performed with two different options: either the port exits or the starboard exits are only available. The evacuation times for both cases are shown in Table 13.

These results are a consequence of two facts. On the one hand, there is a difference in the number of people seated closer to the type I exit (26 in the port case against 22 in the starboard case), which makes the sharing between exits more balanced. On the second hand, the average passenger-to-exit distance is slightly shorter for the port case. Both factors, acting in the same direction, lead to different evacuation times.

As indicated in the paragraph devoted to exit location effects, this type of analysis shows the possibilities of a tool like ETSIA. In the case of a small regional aircraft, like the Saab 2000, the evacuation margin to the 90 s limit is quite wide. Consequently, none of the cases considered is problematic. However, if the evacuation margin of an airplane is tighter, it would be interesting to check at the early design stages for any troubles that could be determinant for the evacuation. Evidently, this information is very relevant for the design engineer but also for the certification officer, who can ask for the most critical case when the evacuation trial is being programmed. The computer simulation tool provides all this information at no risk and negligible costs.

V. Conclusions

An agent-based computer model to simulate the evacuation test performed for the certification of transport airplanes has been developed. The model incorporates main cabin features and relevant occupants' attributes with high accuracy. Its applicability has been verified with real certification trials of narrow-body airplanes, although the concept could be valid for any airplane configuration.

This new numerical tool has been applied to a database of 26 narrow-body aircraft covering all segments and configurations. Each cabin has been studied through a set of 1000 runs to obtain statistically meaningful results. The main findings of this research work are as follows:

1) The model output includes seat-to-exit distance for all passengers, egress time for all occupants, number of evacuees per exit, evacuation chronolines (per exit and global), evacuation time, and a set of efficiency parameters of the evacuation process.

2) In all airplanes analyzed, both the average evacuation time and the 95% confidence value are well below the 90 s limit prescribed in the airworthiness requirements. Exceptionally, one simulation of a certain cabin took longer than the prescribed 90 s. This means a 0.1% of evacuation failures in just one aircraft.

3) There is a linear relationship, with a meaningful regression coefficient, between the evacuation time of the various aircraft and their seating capacity ratio (i.e., the actual number of seats in the cabin divided by the maximum number of passengers according to the number and type of exits), which indicates that it is the primary variable determining the evacuation performance. However, its effect is largely modified by the influence of exit location, asymmetrical arrangements, and similar factors.

4) The tool is capable of providing the impact of exit type modification (for example, from type I to type B), exit shifting, or exit suppression.

5) The model allows a better understanding of the evacuation process itself, but it can also serve airplane designers and certification officers in their respective roles.

6) In the end, the ETSIA tool could eventually substitute the actual evacuation demonstration, since it can reproduce all relevant features of the evacuation performance, and provide detailed information at cabin or individual scale at no risk and negligible cost.

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References

[1] McCormick, B. W., *Aerodynamics, Aeronautics and Flight Mechanics*, 2nd ed., Wiley, New York, 1995, pp. 15–19.

[2] Jarrett, P., *Modern Air Transport: Worldwide Air Transport from 1945 to the Present*, Putnam, London, 2000, pp. 95–122.

[3] Anderson, J. D., Jr., *The Airplane: A History of its Technology*, AIAA, Reston, VA, 2002, pp. 183–359.

[4] Martinez-Val, R., and Perez, E., "Aeronautics and Astronautics: Recent Progress and Future Trends," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, Vol. 223, No. 12, 2009, pp. 2767–2820. doi:10.1243/09544062JMES1546

[5] McIntyre, G. R., *Patterns in Safety Thinking: A Literature Guide to Air Transport Safety*, Ashgate, Aldershot, England, U.K., 2000, pp. 1–15.

[6] Krause, S. S., *Aircraft Safety: Accident Investigations, Analyses, and Applications*, 2nd ed., McGraw–Hill, New York, 2003, pp. 3–10.

[7] Mohler, S. R., Swearingen, J. J., McFadden, E. B., and Garner, J. D., "Human Factors of Emergency Evacuation," Federal Aviation Administration Civil Aeromedical Research Inst., TR AM-65-7, Oklahoma City, OK, Sept. 1964.

[8] "Task Force Report on Emergency Evacuation of Transport Airplanes, Volume I: Summary Report," Federal Aviation Administration TR DOT/FAA/VS–86/1.I, Washington, D.C., 1986.

[9] "Aircraft Evacuation Testing: Research and Technology Issues. Background Paper," U.S. Congress Office of Technology Assessment, OTA-BP-SET-121, Washington, D.C., 1993.

[10] "Code of Federal Regulations. Aeronautics and Space. Part 25: Airworthiness Standards: Transport Category Airplanes," Federal Aviation Administration Dept. of Transportation, Washington, D.C., 1 January 2008.

[11] "Certification Specifications for Large Aeroplanes CS-25: Amendment 4," European Aviation Safety Agency, Cologne, Germany, 27 December 2007.

[12] Middleton, V. E., "A Computer Simulation of Aircraft Evacuation with Fire," NASA CR 166511, Moffett Field, CA, 1984.

[13] Goslin, P. D., and Riches, C. G., "Towards Meeting VLTA Challenges for Evacuation Slides and Slide-Rafts," *The Aeronautical Journal*, Vol. 107, No. 1070, 2003, pp. 185–199.
[14] Edwards, M., and Edwards, L., *The Cabin Aircraft: Managing the Human Factors*, Gower Technical, Aldershot, England, U.K., 1990, pp. 58–82.
[15] Learmounth, D., "Crew Direction Aids Evacuations by 50 Percent," *Flight International*, Vol. , No. , Feb. 1993, p. 9.
[16] Muir, H. C., and Cobbet, A., "Influence of Cabin Crew During Emergency Evacuations at Floor Level Exits," Civil Aviation Authority Paper 95006, London, 1995.
[17] Muir, M., and Thomas, L., "Passenger Safety in Very Large Transport Aircraft," *The Aeronautical Journal*, Vol. 107, No. 1070, 2003, pp. 201–206.
[18] Barthelmess, S. A., "An FAA Analysis of Aircraft Emergency Evacuation Demonstration," Aerospace Congress and Exposition, Anaheim, CA, Soc. of Automotive Engineers, Paper 821486, Warrendale, PA, Oct. 1982.
[19] Court, M. C., and Marcus, J. H., "Use of Object-Oriented Programming to Simulate Human Behavior in Emergency Evacuation of an Aircraft's Passenger Cabin," Federal Aviation Administration Civil Aeromedical Inst. Rept. DOT/FAA/AM-97-20, Oklahoma City, OK, 1997.
[20] Martínez-Val, R., and Hedo, J. M., "Analysis of Evacuation Strategies for Design and Certification of Transport Airplanes," *Journal of Aircraft*, Vol. 37, No. 3, 2000, pp. 440–447. doi:10.2514/2.2617
[21] Poudel, M., "Aircraft Emergency Evacuation: Analysis, Modelling and Simulation," Ph.D. Thesis, Toulouse Univ., Toulouse, France, 18 June 2008.
[22] Parks, D. L., and Ostrand, R. A., "EVAC Computer Simulation of Personnel Performance in Airplane Evacuation," *Human Factors and Ergonomics Society Annual Meeting Proceedings*, Vol. 26, No. 11, 1982, pp. 974–978.
[23] Cagliostro, D. E., "A User-Operated Model to Study Strategy in Aircraft Evacuation," *Journal of Aircraft*, Vol. 21, No. 12, 1984, pp. 962–965. doi:10.2514/3.45069
[24] Watts, J. M., "Computer Models for Evacuation Analysis," *Fire safety Journal*, Vol. 12, No. 3, 1987, pp. 237–245. doi:10.1016/0379-7112(87)90008-7
[25] Marcus, J. H., "A Review of Computer Evacuation Models and Their Data Needs," Federal Aviation Administration Civil Aeromedical Inst. Rept. DOT/FAA/AM-94-11, Oklahoma City, OK, 1994.
[26] Folk, E. D., "GPSS/360 Computer Models To Simulate Aircraft Passenger Emergency Evacuation," Federal Aviation Administration U.S. Department of Transportation Rept. DOT/FAA/AM-72-30, Washington, DC, 1972.
[27] Chandler, R. F., Garner, J. D., and Cook, E. A., "GPSS Computer Simulation of Aircraft Passenger Emergency Evacuations," Federal Aviation Administration Civil Aeromedical Inst. Rept. DOT/FAA/AM-78-23, Oklahoma City, OK, 1978.
[28] Gourary, B. S., "PC-Based Simulation of the Evacuation of Passengers from a Transport Airplane," TR, Gourary Assoc., Montclair, NJ, 1994.
[29] Gourary, B. S., "PC-Based Simulation of the Evacuation of Passengers from a Transport Airplane," *Proceedings of the Eleventh International Cabin Safety Symposium*, Southern California Safety Inst., Los Angeles, CA, 1994.
[30] Schroeder, J. E., and Turtle, M. L., "Development of an Aircraft Evacuation [AIREVAC] Computer Model, Phase I: Front End Analysis and Data Collection," Southwest Research Inst. TR 12-4099, San Antonio, TX, 1991.
[31] Grant, J. E., and Turttle, M. L., "Modeling Human Behavior in Aircraft Evacuations," *Proceedings of the 1992 Winter Simulation Conference*, edited by J. J. Swain, and D. Goldsman, Georgia Inst. of Technology, Atlanta, GA, 1992, pp. 1312–1319.
[32] "Development of ARCEVAC: An Emergency Evacuation Simulation Model-Beta Version 1.0," Aviation Research Corpor. Transportation Development Center TR RJS-92-122, Montreal, 1994.
[33] Owen, M., Galea, E. R., Lawrence, P. J., and Filippidis, L., "The Numerical Simulation of Aircraft Evacuation and its Application to Aircraft Design and Certification," *The Aeronautical Journal*, Vol. 102, No. 1016, 1998, pp. 310–312.
[34] Galea, E. R., Blake, S. J., Gwynne, S., and Lawrence, P. J., "The Use of Evacuation Modelling Techniques in the Design of Very Large Transport Aircraft and Blended Wing Body Aircraft," *The Aeronautical Journal*, Vol. 107, No. 1070, 2003, pp. 207–218.
[35] Galea, E. R., "Proposed Methodology for the Use of Computer Simulation to Enhance Aircraft Evacuation Certification," *Journal of Aircraft*, Vol. 43, No. 5, 2006, pp. 1405–1413. doi:10.2514/1.20937
[36] Macey, P., and Cordey-Hayes, M., "Probabilistic Risk Assessment Modelling of Passenger Aircraft Fire Safety," Cranfield University, TR IERC, Cranfield, England, U.K., 1995.
[37] Macey, P., and Cordey-Hayes, M., "A Computer-based Simulation and Risk-Assessment Model for Investigation of Airliner Fire Safety," *PEP 88th Symposium on Aircraft Fire Safety*, Dresden, Germany, CP-587, Oct. 1996.
[38] Robbins, C. R., and McKee, S., "Simulating the Evacuation of a Commercial Airliner," *The Aeronautical Journal*, Vol. 105, No. 1048, June 2001, pp. 323–328.
[39] Xue, Z., DesJardin, P. E., and Bloebaum, C. L., "A Particle Swarm Optimization Based Behavioral and Probabilistic Fire Evacuation Model Incorporating Fire Hazards and Human Behaviors," *NIST 2007 Annual Fire Conference*, Gaithersburg, MD, 2007.
[40] Xue, Z., and Bloebaum, C. L., "A Particle Swarm Optimization-Based Aircraft Evacuation Simulation Model: VacateAir," 46th AIAA Aerospace Sciences Meeting, Reno, NV, AIAA Paper 2008-0180, Jan. 2008.
[41] Xue, Z., and Bloebaum, C. L., "Experimental Design Based Aircraft Egress Analysis Using VacateAir: An Aircraft Evacuation Simulation Model," 12th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, Victoria, B.C., Canada, AIAA Paper 2008-6061, 2008.
[42] Hedo, J. M., "Modelización Computacional del Ensayo de Evacuación de Emergencia de Aviones de Transporte," Ph.D. Thesis, Univ. Politécnica de Madrid, Madrid, May 2009 (in Spanish).
[43] Hedo, J. M., and Martinez-Val, R., "Computer Model for Numerical Simulation of Emergency Evacuation of Transport Aeroplanes," *The Aeronautical Journal*, Vol. 114, No. 1161, 2010, pp. 737–746.
[44] Hedo, J. M., Martinez-Val, R., and Hernandez, C., "Cabin-Layout-Based Algorithm to Assess the Evacuation of Transport Airplanes," *Aviation Safety*, edited by H. M. Soekkha, VSP, Utrecht, The Netherlands, 1997, pp. 213–227.
[45] Hedo, J. M., and Martinez-Val, R., "Computer Model for Numerical Simulation of Emergency Evacuation of Transport Airplanes," *AIRTEC 2008*, Frankfort, Germany, Nov. 2008.
[46] Wilensky, U., "NetLogo V4.0.2," Center for Connected Learning and Computer-Based Modeling, Northwestern Univ., Evanston, IL, Dec. 2007, http://ccl.northwestern.edu/netlogo/ [retrieved 1 June 2001].
[47] "A320, Airplane Characteristics for Airport Planning," Airbus, Blagnac, France, 1995.
[48] "737, Airplane Characteristics for Airport Planning," Boeing, Seattle, WA, 2005.
[49] Langston, P. A., Masling, R., and Asmar, B. N., "Crowd Dynamics Discrete Element Multi-Circle Model," *Safety Science*, Vol. 44, No. 5, 2006, pp. 395–417. doi:10.1016/j.ssci.2005.11.007
[50] Kenett, R. S., and Zacks, S., *Modern Industrial Statistics: Design And Control Of Quality And Reliability*, Duxbury Press, Pacific Grove, CA, 1998, pp. 109–125, 214–215.
[51] Ibe, O. C., *Fundamentals of Applied Probability and Random Processes*, Academic Press, Burlington, MA, 2005, pp. 130–152.
[52] "JAR: 25 Large Aeroplanes," Joint Aviation Authority, Nordwijk, The Netherlands, 1987.