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Study of a Lower-deck Galley for Airliners

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Abstract: *The present work is concerned with the preliminary design of a new galley concept for long-haul airliners. Usually, galley systems are placed in the main deck of airliners or even in some cases in the lower-deck cargo compartment. The present concept considers placing trolleys, components that occupy significant room in galley installations, in the lower-deck compartment and transport them to the passenger deck by a dedicated lift system. The main advantage of this proposal is that more room becomes available in the passenger cabin for the accommodation of additional passengers. By a careful analysis, which considers the required structural modifications that must be incoporated into the airplane configuration to accommodate the new concept, the payoff of the present proposal is investigated. This was carried out by using the PADLAB® 2.4 software package, written for MATLAB®, and an in-house routine to evaluate aircraft performance and calculation of direct operating costs per seat mile. PADLAB® is tailored to the design of the cabin and the device and systems aimed at operating the trolleys by the passenger cabin crew; the in-house routine was validated against data obtained for the category of airliners under consideration.*

Keywords: *Aircraft Design, Airplane Interior, Aircraft Performance, Airliner.*

LIST OF SYMBOLS AND ABBREVIATIONS

BOW	Basic operating weight
CLmax	Maximum lift coefficient
CAD	Computer-aided design
CRT	Cathode ray tube
DOC	Direct operating cost
EADS	European Aeronautic Defense and Space
EFIS	Electronic flight and instrument system
FAR	Federal Aviation Regulation
ILR	Institut für Luft - und Raumfahrt der Technischen Universität Berlin
MTOW	Maximum takeoff weight
OEW	Operational empty weight
PAX	Passengers
TAT	Turnaround time

INTRODUCTION

The present work has proposed and analyzed a new galley configuration for long-haul airliners. The galley is the compartment of a ship, train or aircraft, where food is cooked and prepared.

The Douglas Aircraft DC-3 was the first airplane with a planned galley for food service. Galleys on commercial airlines typically include not only facilities to serve and store food and beverages, but also flight attendant jump seats, emergency equipment storage, as well as anything else flight attendants may need during the flight (Wikipedia, 2012).

The activities utilizing galleys can be basically divided into two categories: preparation for the next flight, and the remaining activity being characterized by flight attendants' duties when the airplane is airborne. Galleys are also used before flight, when the passenger boarding is not cleared yet. They have a strong impact on passenger's evaluation of the service that is provided by the flight attendants. The galley of the airplane has a crucial impact on TAT at the airport. In this context, it is of primary concern how long it takes from the moment passengers leave the cabin up to the time the passenger cabin crew is ready to service the next batch of customers. The ground service team at the airport shall clean the cabin and cater the aircraft in the shortest possible time, under stringent safety rules. In this area, there is provision for garbage disposal and communication equipment. There is usually an extra seat, in the shape of a revolving chair, for the comfort of the cabin crew during a flight.

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Aircraft in operation today mainly use the familiar trolley system. This system was introduced in the late 1960s, at the same time a new generation of large wide-bodied airplanes were entering into service with the airlines. The significantly larger number of passengers on these aircraft meant that meals could no longer be efficiently delivered by hand, as they had been up to that point (Wikipedia, 2012). Since then, galley concepts did not change significantly and could not be considered efficient anymore for the current air transportation scene (Fig. 1). Major drivers for a design review are workload for cabin crew is high; galley area is not pleasant for passengers and safety must be improved.

Figure 1. This picture of an Airbus A-340 galley compartment reveals how inappropriate the galley design of current airliners can be (Wikipedia, 2012).

Many airliners are fitted with more than just a galley installation. The number of galleys is strongly dependent on the seating capacity of passengers. Typical figures for sizing are employed according to the numbers of passengers that a single galley can service. For smaller single-aisle airplanes, ranging from regional jets to Boeing 737 and Airbus A320, the main galley is usually located at the rear part of the fuselage, with an auxiliary smaller galley at the forward part, close to the cockpit. For two-aisled airplanes, the position may vary a lot. However, the composition of the galley, regarding its mechanical components and specially its geometrical size, is not heavily modified. This happens because in double-aisled cabins the galley cannot occupy the whole diameter of the fuselage, being restricted to the area within the two aisles.

Galleys usually accommodate from six to eight trolleys, which are stowed and loaded when necessary. In addition, galleys have just a small area for preparation of food or other items, and equipment for in-flight service other than additional stowage room on the upper portion. The equipment usually consists of ovens, trash compactors, and kettle for hot water. More than one of those facilities is necessary to hold the catering cargo required to serve all passengers. Galley location in the passenger cabin is defined by their total loading capacity. A typical galley is able to accommodate up to eight trolleys, which can stow food and beverage for approximately 120 passengers.

There is already a trend to accommodate some facilities in the lower deck of long-haul airliners. The four-engine Airbus A340 airplane is an example. Some Airbus A340-600, which are operated by Lufthansa, accommodate in their lower deck lavatories, galleys and crew rest areas (Schliwa, 2000). Access to those facilities is provided by stairs and lift allow trolleys from going from the main to the lower deck and vice versa (Fig. 2).

Figure 2. Lufthansa Airbus A340-600. Lower-deck lavatory entrance.

Both the 777-300ER and 777-200LR Worldliner offer overhead crew and attendant rest areas in the fuselage crown above the passenger cabin (Fig. 3). Most airplanes have crew rest areas either in the passenger cabin or in the cargo compartment. By moving crew and attendant quarters off the main deck, 777 operators can free as many as four-to-seven revenue passenger seats (Boeing, 2011a). Alternatively, using overhead crew rest areas frees up room for additional capacity in the cargo compartment, up to six LD-3 containers. This revenue-generating capability is another innovation that the competitor's airplane, the A340, cannot match because of the A340's constrained cross-section design (Boeing, 2011a).

Figure 3. Boeing offers 777 customers new innovations, like the crew resting area in the overhead space of fuselage (Boeing, 2011a).

Trolleys need considerably large areas in order to be accommodated in galley installations. Therefore, the present concept focuses on them. They shall be accommodated in the lower deck instead, and be transported to the passenger deck by a special purpose lift system (Fig. 4).

GALEY DESIGN

The methodology that was employed for the design of the new galley system is described in this section. In order to evaluate the impact of the new concept on airplane performance and its general characteristics, a computational code was developed and validated.

Suited airplanes to the new concept

Galley areas of main passenger decks were compared with different types of airliners and cabin layouts. The higher galley area-to-cabin-area ratios were found for wide-body airliners, such as the Boeing 777 (Fig. 5). These airplanes feature high-capacity double-aisle passenger cabin and are designed for long-haul flights. The duration of typical flights of such airplanes requires that two or more meals be served to a higher number of passengers. This usually results in a greater area of main decks for food and beverage stowage, approximately 25% for the typical economy class area of a B777-300 airliner (Boeing, 2011a).

Galleys for the business and first classes present a greater volume per seat dedicated for stowage. In this case, items served to passengers are unique and require longer time for their preparation and handling. First and business classes would benefit rather from beverage storage on the lower deck than that for food. It is important to point out that the presence of first and business classes in the cabin makes the allocation of the galley on the lower deck less effective. Smaller density in occupation of the passenger deck implies a smaller total volume of passenger luggage, releasing room in the cargo compartment for automated galleys.

Smaller aircraft that operates with low-cost airlines may also benefit from the lower-deck galley concept. If one

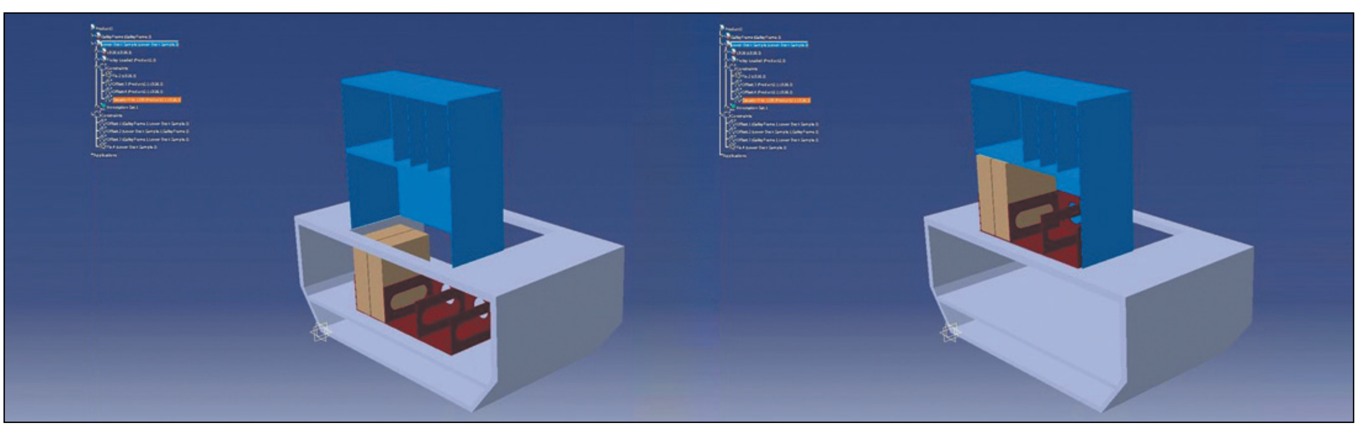

Figure 4. CAD model of the lower-deck galley lift system.

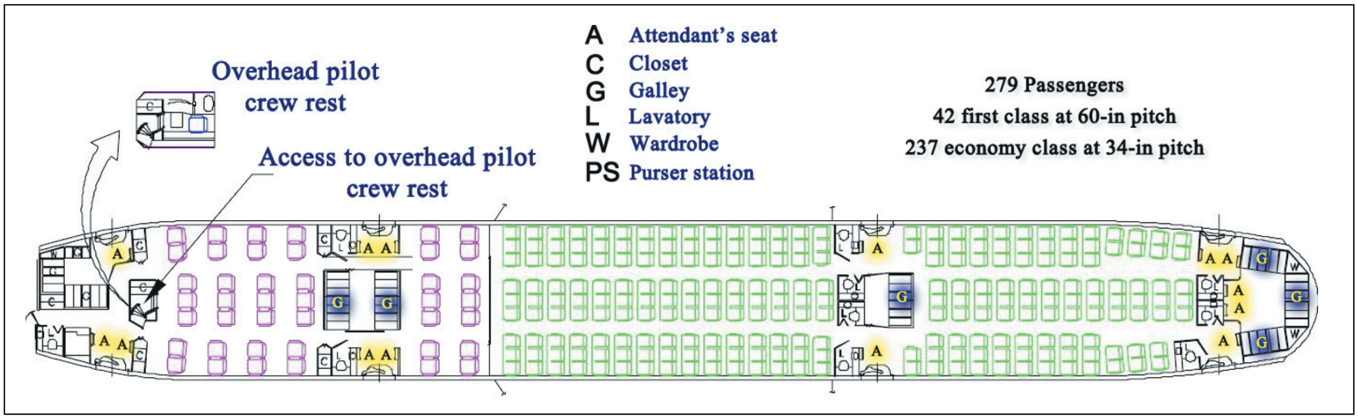

Figure 5. Boeing 777-200 two-class typical cabin layout (Boeing, 2011a).

considers that galleys occupy a smaller portion of the pax cabin area, the high-seat density that they present could eventually support the required investment and pay-off. Low-cost airlines record high-occupation rates, and their policy is marked by very restrictive luggage allowances, allowing the cargo compartment to be easily reconfigured for the automated galley concept. This would also be very simple due to the highly limited service provided by this kind of airline to passengers during the flight. However, due to the size of cargo compartment of mid- and small-size airliners that low-cost airlines operate, the new galley concept does not fit them. Cargo compartments of airplanes, like the Embraer E-190/195, are not able to accommodate the required trolleys and the associated elevator system.

General considerations of galley design

Galley configuration also impacts ground operations, as well as in-flight services. The utilization of current trolleys could simplify catering, avoiding longer TAT if new trolley designs are introduced. In addition, the use of current trolley designs would not require any big adaption of cabin crew to new concept. The current equipment used in galleys must also be compatible with the automated galley, in order to reduce installation costs and avoid new certification issues. It would be mandatory that the present galley concept be easily installed and removed from affected airplanes; therefore, increasing their residual value.

The understanding of in-flight service logistics is crucial for the design of any new galley system, which shall provide improved service and reduce the workload of flight attendants. In order to achieve these goals, it is essential to pinpoint the way meals are prepared and served to passengers. The total number of trolleys can be simply calculated by defining how many meals are needed for a flight and the number of meals that one trolley can accommodate. Also, the calculation of the necessary volume of food and beverages requires the knowledge of how galleys are operated when the airplane is airborne, in order to identify parameters that might influence the location of the galleys inside passenger cabins. Factors that may impact TAT must also be taken into account (Fig. 6).

Figure 6. Boeing 777 of KLM prior departure, being catered and supplied with external electric power.

The required number of trolleys is strongly dependent on passenger capacity. The number of trolleys that are needed for a service round at the main deck must be defined. A service round is comprised of attending passengers with snacks, lunch, dinner, drinks and refreshments, and even shopping products. Considering that the majority of the trolleys will not be available in the passenger cabin, according to the new galley concept, the sequence that they must be utilized in the pax cabin is important to their positioning in the lower-deck cargo compartment and to the design of mechanism system, which will bring them to the upper deck.

Usually, a single sandwich or a small snack pack is served to each passenger. Given the relatively low storage space that is necessary to accommodate these items, and the fast distribution procedure, usually one flight attendant can cover one aisle with one trolley. Some airlines serve snacks together with drinks or refreshments. This way, just one trolley will be used per aisle, requiring two flight attendants to do the job. For long-range flights, each passenger will be provided with one pack containing cold items, usually consisting of salad, small juice, and dessert, as well as disposable utensils. These items were prepared by catering companies and arranged inside trolleys, no additional effort is needed by the cabin crew.

Usually, airlines offer two options for hot meals, which are categorized in general terms as “Pasta or Beef” or “Chicken or Fish”. Hot meals are heated in ovens before being offered to the passengers. For this, the meals are covered with protective packing. A single oven is able to heat two batches of food usually consisting of 25 packs for the economy class, or 16 ones for the first or business class. Ideally, a separate and backup oven is used for items, such as bread that are usually served as well. After that, the cabin crew arranges meals on the upper part of trolleys and service starts to passengers.

For wide-body airliners, usually two trolleys with two flight attendants, each one will cover one aisle. In fact, this arrangement is suited to 120 passengers at most. If a passenger asks for a second hot meal, flight crew will usually deny until all passengers were served. However, if a passenger asks again, a second hot meal will be served if available.

After a major meal is provided, usually there is a round of water and beverage service and then cabin crew starts collecting disposables. This is a simple process, it basically consists of stowing garbage and disposables in the trolleys that were employed before for meal distribution. Glasses and cups are kept on the upper surface of the trolley. Further disposables are later collected by using bags and no trolleys, with a single flight attendant covering one aisle.

For the drinks and refreshments service, two trolleys shall be used for a single aisle, with two flight attendants operating them. Some drinkables are kept cold with the use of cold ice. Modern airliners are equipped with chillers, while most of the older airplanes use chillers for items such as dairy products and fruit slices for garnish, which will not hold quality if heated. Many options are usually available for different drinks, and then few or any options within each type of drink. For instance, passengers can choose from a range of up to four sodas, three juices, one red wine, one white wine, two kinds of beer, milk, and water. Each passenger will be served with approximately 200mL – unless additional water or beverage is asked for. Water and beverage service is usually performed before snacks or hot meals are served. Sometimes water and juice are offered together with snacks, and it is also served right after hot meals are distributed among passengers. In average, there are two drink offerings for each hot meal or snack round. Frequently, an additional third round of drinkables is served to passengers.

Galley layout

In this section, the new galley concept will be better described as well as its associated equipment and operation. The main goal of the concept is to provide room for additional passengers in the airplane. It is mandatory that all the necessary food and beverages for servicing passengers be available at the main deck, but not necessarily at the same time. Food for dinner and lunch can be stored on the lower deck while snacks are being served, reducing the size of galleys and providing extra space for revenue passengers.

Using basic cargo containers of known size and small adjustments to fit the machinery used for allocation of the trolleys on the lower deck, a sample, preliminary design of the new galley concept was generated with the CAD package CATIA®. Major geometric design constraints are the width of the galley in the main deck, which is bounded by aisles; and the size of existing cargo containers. Thus, the number of trolleys that can be stored side by side on the passenger deck is limited by the size of galley and the size of the containers placed in the cargo compartment.

PADLAB® (Fig. 7) is a software package used for airplane cabin design modeling that was developed at ILR. PADLAB® is able to deal with different kinds of geometric constraints for any airplane configuration, enabling users to easily customize their designs. Thus, a module to consider the trolley storage in cargo compartments as well as its associated lift system was easily incorporated into the PADLAB® package.

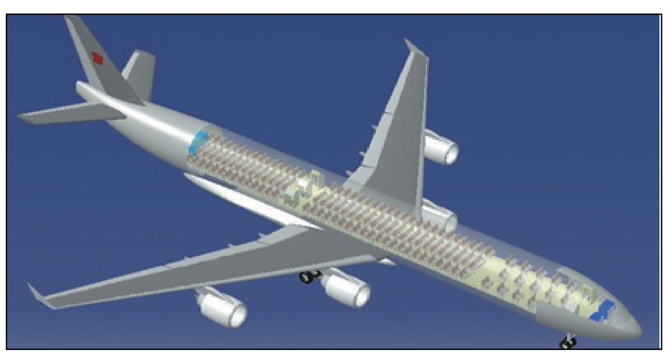

Figure 7. A340-300 modeled with PADLAB®.

The lower deck geometry and its sizing are tailored to accommodate standard cargo containers. There are many containers of different sizes and shapes. Our concept chose the LD-26 one (Fig. 8). This container presents a suitable capacity and it would be the safest option for housing the necessary machinery, which will operate on the lower deck.

Figure 8. View of LD-26 container (Driessen Cargo Equipment).

The LD-6 container shall suffer some modifications to accommodate the trolleys in organized storing positions: an opening on its upper surface is necessary to allow trolley to be lifted to the main deck; an important aspect that has to be considered is the required structural reinforcements to support elevator operations; the incorporation of a system to lock the trolleys into their storage positions; and the incorporation of a movement mechanism to allow trolleys to reach the elevator in an appropriate fashion.

Trolleys are kept in special stowage hub, so that they can be easily handled by a feeding mechanism system in the lower deck. As can be seen in Fig. 9, there is a space below the floor that supports the trolleys. This area will house the necessary equipment to move the trolleys from their parked positions to the elevator, and vice versa.

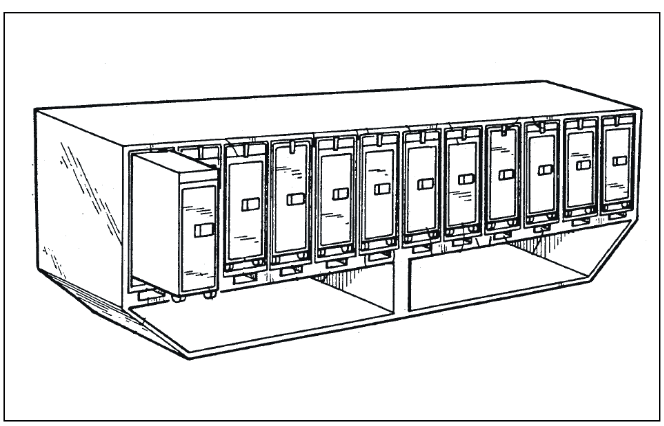

Figure 8. View of LD-26 container (Driessen Cargo Equipment).

Figure 10 shows the shared area between the lower and main passenger decks and Fig. 4 provides an idea of how trolleys can be brought to galleys on the main deck. In Fig. 10, the area dedicated to the elevator is displayed. If a single elevator is employed, it would be necessary to control the position of the trolleys on the lower deck using a bi-axial system, which would compromise the level of service and would increase the workload of the cabin crew. The optimal configuration consists of the same basic layout, but using a multi-lift system to cover the full extension of the lower deck area, so that trolleys are moved in a single direction inside the cargo compartment.

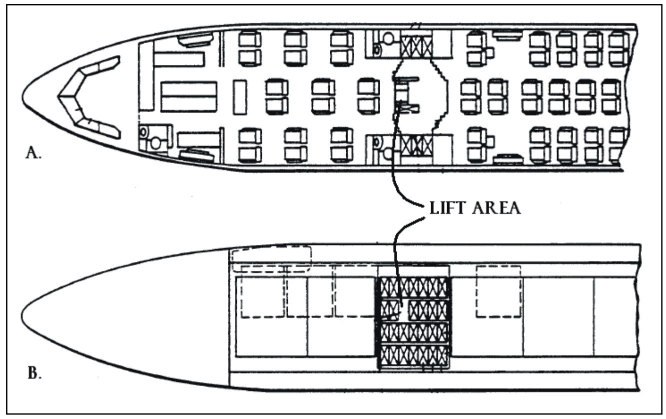

Figure 10. Main passenger deck and lower deck area of a modified airplane that incorporated the new galley concept.

Structural considerations

In order to keep development and manufacturing costs as low as possible, it would be highly convenient that the new galley structural layout in the main passenger deck does not depart significantly from current designs. The frame is built using aeronautical aluminum and low-density polymers in order to reduce structural weight. The structural design is usually modular, based on the dimension of the equipment that the galley should enclose. According to the quantity of the specific equipment of the galley and taking into account geometric constraints imposed by the cabin sizing and geometry, the galley structure is possible to be defined. Taking this into account, a design tool for the frame structure of the galley was developed. The basic dimensions of the galley are input and calculations that provide specific coordinates for the galley assembly using a CAD tool. The designed frame is very simple, composed basically of the bottom area for trolley storage and the main working surface for the in-flight service. To the extent, the design becomes more complex; items are to be added to the frame structure.

Preliminary design of aircraft interiors could greatly benefit from such tool. Based on that demand, a MATLAB® Graphic User Interface was developed and could represent a good further development for the ILR's PADLAB® tool.

Basic galley equipment design was based upon Driessen Aircraft System galley equipment. The company has agreed to provide basic information regarding its models' geometry and technical specifications. That information has been used as a background for the CATIA® models, so that the design can be consistent in terms of dimensions.

Elevator system

The necessary technology for the elevator system that was envisaged has been already employed with Boeing 747. The main deck of this airliner is used to store trolleys to be employed for servicing the upper deck. This takes place when airplane is on ground. If the airplane becomes airborne, trolleys shall be in the deck where they will be utilized. This procedure poses no major effort of the cabin crew. Similar concept is used for the Airbus A380 double-deck airliner. The operation procedure is the same as that for the Boeing plane, where two trolleys are placed in the elevator. Yet, on the A380, the ground service team can reach the upper and lower decks through service doors on the fuselage, making the re-stocking process simpler to use (Stilp, 2006). Yet, there remains the high occupation of both decks by the galley kitchen, since all trolleys are still on the deck even when they are not being used.

According to the new concept proposed by the authors, trolleys shall be brought from the lower deck to the pax cabin during flight, before and after their used. All this must be accomplished in a reasonable period. However, the existence of trolleys that are already employed in similar tasks contributes to reduce costs and time of development.

Based on the technical data available for the current dual-trolley elevator (Jenoptik, 2007), it is possible to estimate the weight and capacity of the new equipment. The estimation was carried out considering a parametric approach, evaluating the impact of the number of trolleys on the engineering features in order to keep operational conditions. Table 1 displays the results of this estimation.

The critical factor for the weight estimation is the load capacity of the elevator. It must be taken into account that all trolleys will be fully loaded to their maximum capacity, when they are being moved to the main deck. The tare weight of the trolley is about 25kg, resulting in a total 125kg for five trolleys. Hence, elevator capacity can be estimated as 475kg.

Table 1. Weight estimation for the system of the elevator.

	Data for the dual-Trolley Elevator	5 Trolley Lift Estimation
Weight (elevator)	< 320kg	< 800kg
Weight (trunk)	< 60kg	< 150kg
Speed	0.2 to 0.4m/s	0.2 to 0.4m/s
Load	240kg during flight 480kg on ground	600kg during flight 1,200kg on ground

Handling mechanism

The mechanism system for the lower deck is the only item that is not currently under aeronautical operation in commercial aircraft. However, there are similar applications under operation for freighter jets.

Once it has been defined that the lower deck machinery system should allow movement in a single direction, the axis of the airplane, the ideal solution is one that can move the group of trolleys as a whole. A simple solution is a revolving chain to be attached to the trolley groups in order to hold their position and allow their movement on the container platform.

This system will operate in a horizontal direction, so it can be assumed that it will have a smaller impact on weight than the trolley elevator system. Motors and required structure will be considerably lighter, since they are stable on top of a surface and must not hold the total weight of the trolleys.

It is hard to pinpoint the weight of such a system. This would require the full development of the material, and such task is beyond the purpose of a preliminary design of the lower deck galley. However, estimations are to be considered as well as a sensitivity analysis regarding the estimation parameters.

A good estimation can be achieved by determining the weight of the total lower deck equipment as the sum of the tare weight of the container and items belonging to the mechanism system. Equipment weight can be estimated co-relating it to the elevator weight, considering that the operation is restricted to horizontal displacement, as described. The tare weight of the container, however, is already known.

By varying the fraction of weight of the lift that is assumed to represent the horizontal positioning control system, it is possible to determine the total increase of weight produced by each occurrence of the lower deck equipment. Based on these estimations, the total weight of the lower deck system may vary from 400 to 900kg (Table 2).

Table 2. Estimation of equipment weight (kg).

	Percentage of elevator weight			
	80%	60%	40%	20%
Equipment weight	640	480	320	160
Equipment + Container	890	730	570	410

System operation

Initially, it was thought to introduce a fully automated new galley system. This includes automated use of ovens for heating meals and of automated system to displace items in lower deck, such as cold drinks from the refrigerator to the trolleys. This approach could contribute to lower DOCs, considering that it would require fewer flight attendants. For instance, a fully automated system would require considerable knowledge of Robotics and Control Theory. In addition, any new system has to comply with aeronautical certification rules, besides presenting low weight and extreme high reliability. For these reasons, a simpler concept was chosen, which attains the same basic goal of allowing extra room for passenger allocation on the main deck.

The approach that was adopted consists of keeping trolleys in the cargo compartment, while equipment such as ovens, water heaters and others remain in the pax cabin. Cabin crew will manually put meals inside the ovens for their heating. Garnishing would be carried out by the flight attendants, as well as cold drink distribution using trolleys. Thus, lower deck equipment will be substantially reduced. Basically equipment that is needed consists of an elevator to move trolleys from the lower to the main deck, and of a horizontal controller, or, maybe, a matrix oriented controller, to move the trolleys inside the lower deck. Also, there would be more considerations regarding special stowage needs for the lower deck, which would also have to be fully automated and highly reliable to comply with safety requirements. For this option, the main factor to determine the operation of the galley is the elevators that will transport the trolleys between the lower deck and the main cabin. Current elevators that operate with Boeing 747, between the main deck and the upper cabin in the forward part of the airplane, and also the ones that operate on A340 with lower deck galleys with access to flight attendants operate lifting two trolleys at a time. This number is not the optimum possible, as most of the trolleys will have to be lifted, moving two at a time would take a long time, both during flight service and in ground preparation, impacting turnaround time. Lower deck positioning of the trolleys would also have to be much more complex, since there would be only one place where all the trolleys could go in order to be taken to the upper deck. One possibility is to employ from two to three elevators for each galley. This would decrease the time that is needed to bring trolleys up and down, and simplify the moving criteria on the lower deck, due to the multiple positions of elevators. Yet, it would cause a significant increase in weight to the project, and, more importantly, in necessary equipment. This would lead to a less efficient occupation of the galley area on the lower deck and also in the container.

An optimal configuration can be achieved by developing a new elevator, which is capable of transporting six trolleys to the main deck. This way, the required time to move all necessary trolleys is reduced as well as the complexity of the moving mechanism on the lower deck, since all six trolleys could be moved as a group, removing the necessity for a matrix oriented allocation system, replaced by a single direction operator. The drawback lies in the necessity of the development of a new tool, yet, due to its simplicity, it would probably not represent a high demand on research. Using this configuration, each galley could provide service to 150 passengers, which is considerably more than the typical figure of 120. This could boost efficiency for the overall cabin crew service. Slots of up to six trolleys could be prepared by the ground operation team to accommodate each round or service. At each round, the galley would send to the main deck only the trolleys required, keeping the others on the lower deck, meanwhile moving them to accommodate the upcoming disposals, when the current service is completed.

A door to allow ground personal to load and unload trolleys without entering the airplane is fully feasible, but it was not considered. Deeper structural calculations are required for its design and integration into the airplane configuration. These issues are beyond the scope of the present work.

MTOW AND BOW ESTIMATION

Besides the equipment related to the new galley concept, structural reinforcements are required to accommodate the increased payload. Payload increase could top three tones for airplanes like the Boeing 777. Thus, MTOW will vary if payload is increased and/or structural weight is added to the configuration. The lift and drag coefficients will also vary and they will impact range, takeoff, and climb performance. All this will lead to additional fuel to fulfill the mission. Furthermore, everything changes and the new airplane parameters must be computed. For this purpose, a computational code was developed in MATLAB® language. The code was Christianized WEST, which iteratively calculates the MTOW and other core weight figures. Airplane component weights are calculated according to Roskam's Class II methodology (Roskam, 1985). Calculation of aerodynamic coefficients also fits into a Class II approach (Roskam, 1985). Some component weight calculations were carried out using methods developed by Torenbeek (1982). Figure 11 presents the workflow utilized for WEST. In the present work, engine was modeled into a simpler way, with the specific fuel consumption being provided for some flight phases. Thus, no sophisticated engine deck was elaborated. Vertical and horizontal tail stabilizers areas were obtained using the tail volume coefficient approach (Roskam, 1985).

WEST was employed for weight estimation of the following airliners: Airbus A340-300; Boeing 777-200 and Boeing 767-200.

A module was added to WEST in order to incorporate the impact on component weights caused by the incorporation of the new galley concept. An extra 2.5 tones accounted for the systems and structural modifications. This represents an overestimation of the galley components total weight, and it also encompasses two lower deck galley installations in the same aircraft, if necessary.

Airbus A340-300

The Airbus A340-300 is a long-range four-engine wide-body commercial passenger airliner designed and manufactured by Airbus, a subsidiary of EADS (Fig. 12). It seats up to 335 passengers in a two-class layout (the stretched 600 series carries 440), and it has a range between 12,400 and 16,600 km. It is very similar in configuration and systems to the twin-engine A330 with which it was concurrently designed. Initial A340 versions share the fuselage and wing of the A330, while later models are longer and have larger wings. Over 370 A340s are in operation worldwide as of September, 2010.

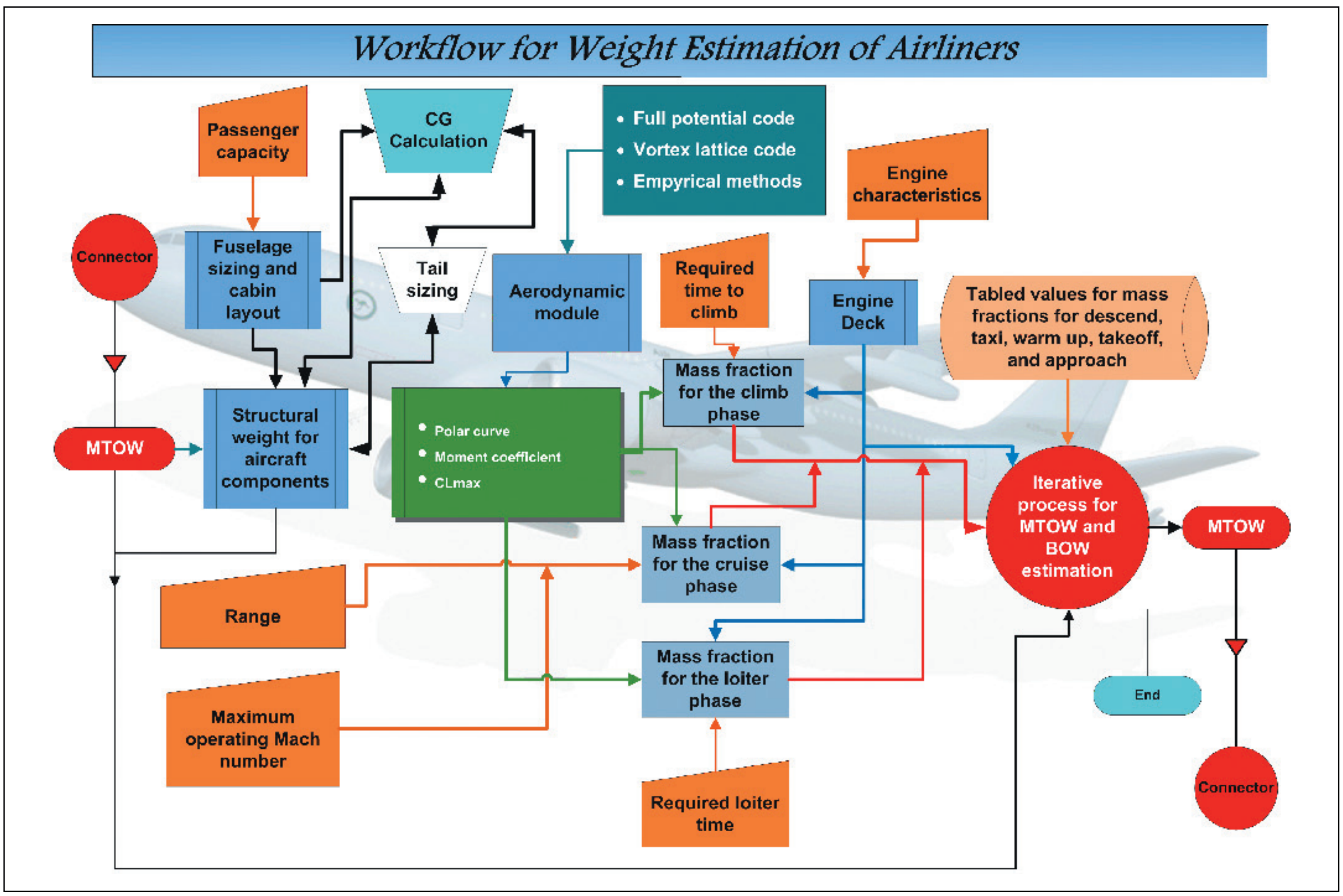

Figure 11. WEST code workflow for MTOW and OEW estimation.

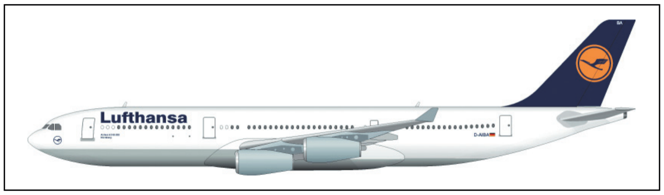

Figure 12. Airbus A340-300 profile.

Table 3 displays the estimation carried out for weight estimation for the A340-300 with the WEST code. Table 4 contains the results of a sensitivity study of passenger capacity for the A340-300 series. The extra weight due to the lower deck galley concept was considered in the model.

Table 3. A340-300 weight estimation with WEST code (all values in tones).

	Airbus data	WEST results	Error (%)
Empty weight	126	123.8	-1.8
MTOW	251.7	246.1	-2.2
Mission fuel	72.5	70.0	-3.4

The increase in the required fuel to fulfill the mission falls close to the error margin as seen in Table 4. The increase observed for MTOW and OEW values takes into account the structural modifications to accommodate the increased payload and new galley concept.

Boeing 767-200

Launched in July, 1978, the Boeing 767 (Fig. 13) was developed in tandem with the narrow body 757 with which it shares a common two crew EFIS flight deck (with six color CRT displays) and many systems. The 767 also features a unique width fuselage typically seating seven abreast in economy, and a new wing design with greater sweepback than that of the 757 wing. The 767 first flew on September 26, 1981, and entered service with United on September 26, 1982. Certification with Pratt & Whitney engines was awarded on July 30, 1982.

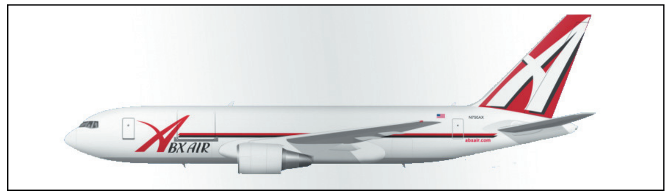

Figure 13. Boeing 767-200 side view.

Table 5 displays the validation effort carried out for the Boeing 767-200 MTOW estimation. Error margins are acceptable, considering that Class II methodology was employed for the present calculations. The estimated empty weight is now slightly higher than that for the actual airplane (Boeing, 2011b). Table 6 shows the results of the sensitivity study carried out for Boeing 767-200. The increase in the required fuel is now higher than that calculated for the A340-300, especially for the 20% passenger increase. If both airliners are able to transport 20% more passengers thanks to the new galley concept, the Boeing 767-200 will require 6.5% more fuel while the Airbus aircraft will consume 9% more kerosene. However, considering that the Boeing aircraft carries typically 200 passengers and the Airbus airplane about 300, the impact of payload increase on DOC could reveal another trend. The results signalize potential DOC reduction, provided that the increase in passenger capacity is always higher than the associated increase in the mass of the components. The results of the DOC analysis will be later presented.

Table 5. Boeing 767-200 weight estimation (all figures in tones).

	Boeing data	WEST results	Error (%)
Empty weight	80.1	81.5	-1.8
MTOW	142.9	138.9	-2.8
Mission fuel	29.9	28.8	-3.9

Table 4. Sensitivity analysis for increasing the passenger capacity of Airbus A340-300 (values in tones).

	5%		10%		15%		20%	
	Total	Increase	Total	Increase	Total	Increase	Total	Increase
Passenger capacity	305	15	319	29	334	44	348	58
OEW	128.1	3.5%	128.4	3.8%	128.5	3.9%	128.7	4.0%
MTOW	252.8	2.7%	255.2	3.7%	256.7	4.3%	258.6	5.1%
Mission fuel	72.4	3.5%	73.4	4.9%	73.9	5.5%	74.6	6.5%

Table 6. Sensitivity analysis for increasing the passenger capacity of Boeing 767-200.

	5%		10%		15%		20%	
	Total	Increase	Total	Increase	Total	Increase	Total	Increase
Passenger number	210	10	220	20	230	30	240	40
Empty weight (t)	85.3	4.6%	85.6	4.9%	86.1	5.5%	86.1	5.5%
MTOW (t)	142.9	2.9%	144.4	4.0%	146.8	5.7%	147.3	6.1%
Mission fuel (t)	29.4	2.4%	29.8	3.7%	30.5	6.1%	31.3	9.0%

Boeing 777-200

Boeing 777 (Fig. 14) is the world's largest twinjet. The airplane offers seating for over 300 passengers and has a range from 5,235 to 9,380 nautical miles (9,695 to 17,370 km), depending on the model. It isable to accommodate 550 passengers in a single-class cabin layout. Its distinguishing features include the largest diameter turbofan engines of any aircraft, six wheels on each main landing gear, a circular fuselage cross-section, and blade-shaped tail cone. Developed in consultation with eight major airlines, the 777 was designed to replace older wide-body airliners and bridge the capacity gap between the 767 and 747. The 777 was Boeing's first fly-by-wire airliner.

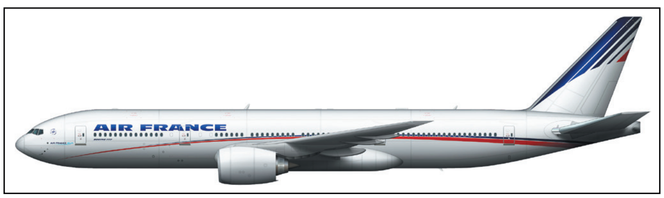

Figure 14. Boeing 777-200ER in Air France livery.

For the 777, the WEST code slightly underestimated MTOW, OEW, and the required fuel mass (Table 7). However, the accuracy is very satisfactory considering the low fidelity approach of the modeling; all errors fall below 3% for the three airliners studied here.

Table 7. Boeing 777-200 weight validation with the WEST code.

	Boeing data	WEST results	Error (%)
Empty weight	139.2	136	-2.3
MTOW	247.2	240	-2.9
Mission fuel	71.2	69.7	-2.0

Once the model has been pre-qualified for the analysis, the lower deck galley is implemented on the design, and then the tests are made considering the possible results in terms of passenger capacity increase. Table 7 illustrates the results obtained. The additional fuel for B-777 if payload is increased is considered when compared to the remained models studied here (Table 8). This can be credited to its higher capacity and range.

PASSENGER CAPACITY INCREASE AND DOC CALCULATION

Figure 15 displays the rear portion of Airbus A340-300 passenger cabin, modeled with PADLAB®. Outer airplane skin was set transparent in order to generate a cutaway of the airplane interior. This is an example of the PADLAB® output file for CATIA. The program generates a complete aircraft layout for the entire cabin. Specifications, such as economy

Table 8. Results from the B777-200 weight impact analysis.

	5%		10%		15%		20%	
	Total	Increase	Total	Increase	Total	Increase	Total	Increase
Passenger number	383	18	402	37	420	55	438	73
Empty weight (t)	141.2	3.8%	142.6	4.9%	143.2	5.3%	144.0	5.9%
MTOW (t)	248.4	3.5%	255.0	6.2%	255.5	6.5%	262.6	9.4%
Mission fuel (t)	72.6	4.1%	75.5	8.3%	76.8	10.1%	78.6	12.8%

class seats, seating pitch, and the number of seats abreast, can be defined by users using a user-friendly graphical interface. The code generates an output file, which is read by a CATIA® macro code, producing the CAD surfaces as shown in Fig. 15.

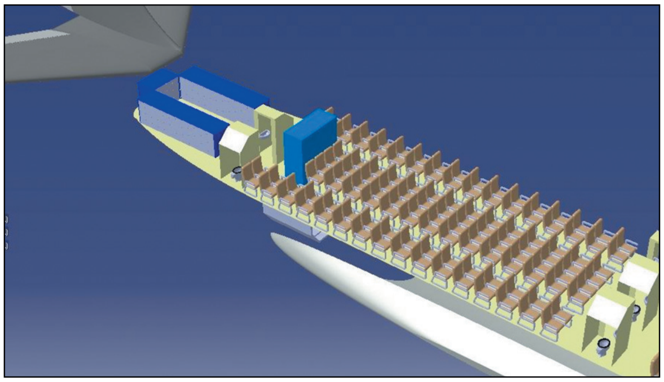

Figure 15. A340-300 aft pax cabin as modeled by PADLAB®.

New cabin layouts were elaborated incorporating the proposed galley concept. They were useful for the evaluation of the increase in passenger capacity thanks to the new concept.

Figures 16 to 18 show the original cabin layout compared to its reconfiguration after the new galley concept is incorporated into the airplane configurations, which were studied here. Table 9 shows how many additional passengers can be transported in the main cabin of the three airliners studied in the present work after changing the galley configuration. The galley concept described in the present work proved to be advantageous for the three airliners that were studied here (Table 10). DOC was calculated using the methodology suggested by Roskam (1985).

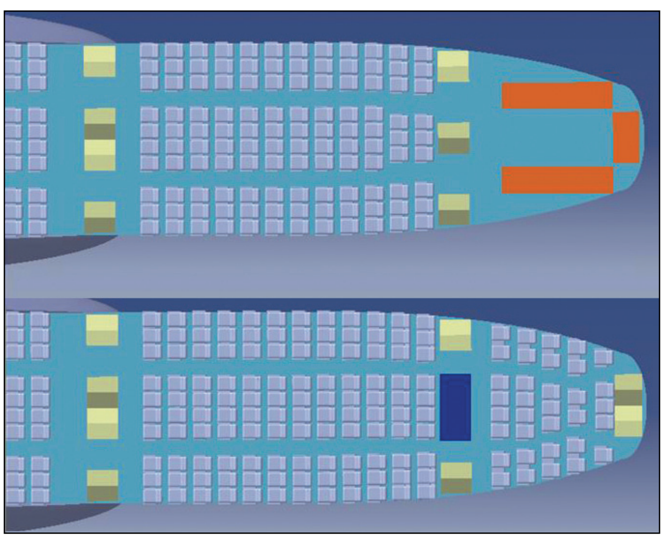

Figure 16. Original cabin layout of the Boeing 777 airliner (top) and the additional seats that were added after the incorporation of the new galley concept (bottom).

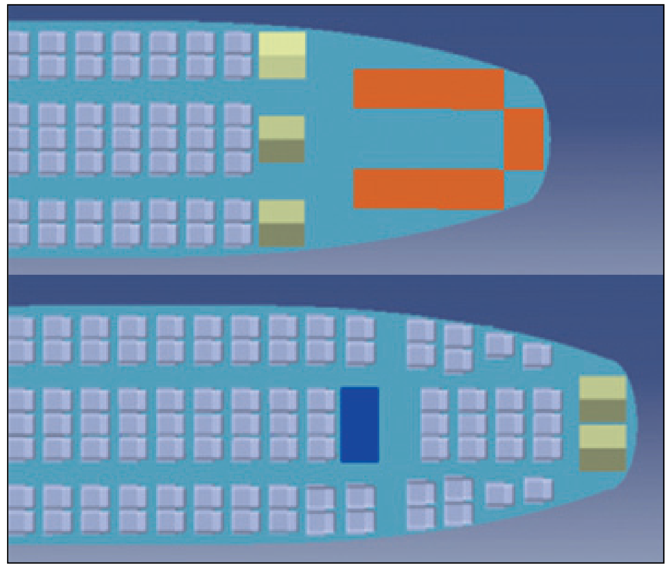

Figure 17. Original cabin layout of the Airbus A340-300 airliner (top) and the additional seats that were added after the incorporation of the new galley concept (bottom).

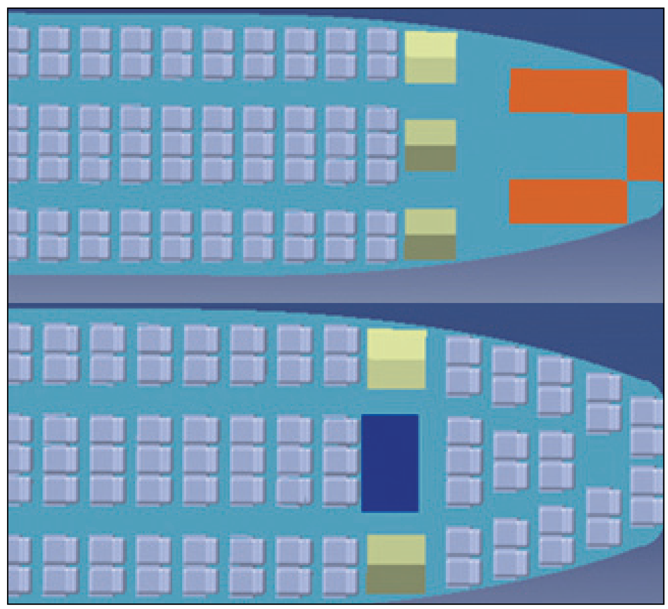

Figure 18. Original cabin layout of the Airbus Boeing 767-200 airliner (top) and the additional seats that were added after the incorporation of the new galley concept (bottom).

The new galley concept can provide a significant increase in passenger's capacity for the three long-haul airliners studied. The payload increase and its associated structural reinforcements are largely justified by the associated DOC reductions that were obtained. In addition, there will be a more healthy work environment in the passenger cabin. Airplane ownership cost will increase with the incorporation of the new galley system, but the lower DOC per seat mile will overcome this. DOC per seat mile improvement ranged from 11.8 to 15.4%.

Table 9. The present concept enables increasing the number of passengers that can be transported in the main cabin of three major airliners.

	A340-300	Boeing 767-200	Boeing 777-200
Typical Economy class capacity	238	175	280
Additional seats in the economy class	28	27	34
Seating capacity variation	+11.8%	+15.4%	+12.1%

Table 10. The galley concept described in the present work proved to be advantageous for the three airliners that were studied.

	A340-300	Boeing 767-200	Boeing 777-200
DOC per seat mile improvement	-4.17%	-5.42%	-3.25%
Variation ofSeating capacity	+11.8%	+15.4%	+12.1%

CONCLUDING REMARKS

The new galley concept can provide a significant increase in passenger's capacity for the three long-haul airliners studied. The payload increase and its associated structural reinforcements are largely justified by the associated DOC reductions that were obtained. In addition, there will be a more healthy work environment in the passenger cabin. Airplane ownership cost will increase with the incorporation of the new galley system, but the lower DOC per seat mile will overcome this. DOC per seat mile improvement ranged from 11.8 to 15.4%.

In order to reduce development and manufacturing costs, the present work was restricted to the conceptual design and it used available equipment of existing galleys. However, there is room for improving the concept by the incorporation of new technologies and smarter designs. Further development of the lower-deck trolley allocation is the utilization of modern galley products for future airliners. Airbus SPICE innovative catering equipment (Airbus, 2012) can be utilized in the design of trolley, and galley equipment and structure enable an additional reduction of the system overall weight, enabling yet better DOC figures.

Detailed design of the mechanism system for the trolley displacement inside the cargo compartment is needed to enable a better weight estimation of the new system and its impact on the overall airplane weight, performance, and operating costs. This is a hard task, considering that the concept is new. Certification issues may require additional reinforcements to the airplane structure as well as its systems. It is likely that this would be the critical stage of the design and creation of a prototype, once all the other necessary equipment is available on the market.

Another area that could be very sensitive for the success of the concept presented on this report is that of safety regulations, especially the evacuation requirements. FAR 25 regulations require that all passengers must be able to evacuate the cabin within 90 seconds. Santos (2004) utilizes software simulation to evaluate the possibility of evacuation from wide-bodied aircraft equipped with a lower deck passenger seating area. It is possible that the same routine can be adapted for the calculation of the evacuation time for the models described, providing important data to support further research on this subject, or indicating problems that must be solved.

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