AIRCRAFT DESIGN FOR LOW COST GROUND HANDLING - THE FINAL RESULTS OF THE ALOHA PROJECT

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Abstract

A significant reduction in turnaround time and costs can be achieved by changing the conditions of critical turnaround processes through an adapted aircraft design. The consideration of foldable passenger seats together with a continuous cargo compartment yields into a shoulder wing aircraft configuration with engines at the tail. The resulting enhancements in dis/embarking and off/loading yield, under the premise of masses and performance identical to an Airbus A320-like baseline aircraft, a reduction of 1.3 %... 4.0 % in total DOC per seat-kilometer. However, due to the necessary adaptations of the aircraft configuration, overall aircraft masses and fuel consumption increase. The predicted benefits in turnaround time and costs are not able to compensate this impact on the DOC elements, which results into an increase of total DOC per seat-kilometer.

1 Introduction and Motivation

During the past years, the predicted annual growth rate of 5 % in air traffic gained significance due to capacity limitations and environmental considerations [1, 2]. One aspect to include in the judgment of new aircraft concepts, that are able to serve the predicted demand, is the aircraft-airport interface. The Airbus A380-800 is restricted in wing span and length due to current airport terminal limitations [3]. Likewise, ground clearances, turning radii, turn paths and Load Classification Numbers (LCN) must be taken into consideration during aircraft design and assessment. But not only taxiing, maneuvering and parking is crucial for an efficient airport operation, the turnaround itself demands a number of processes and coordination of many parties involved: the airport, the airline and the ground handling company. Experts in the field believe that nowadays turnarounds are already optimized and therefore limited in a further efficiency increase [4]. This might be due to the fact that the aircraft remained as it is and only the ground handling processes together with used ground handling equipment have been adapted to serve for a more efficient turnaround. In this context, the question arises, if there would be a further potential in efficiency increase due to adaptations of the aircraft design itself which is task of the joint research project *Aircraft Design for Low Cost Ground Handling* (ALOHA) among the following partners:

- Hamburg University of Applied Sciences (HAW Hamburg) - acting as project leader
- Airbus Operations GmbH (Future Project Office)
- Airport Research Center GmbH (ARC)
- Hamburg Airport GmbH (Ground Handling Division)

ALOHA aims at identifying technologies and aircraft design adaptations that are exhibiting the potential of an efficient ground handling in terms of costs and time demand. The HAW Hamburg involvement in the ALOHA project is financially supported with a grant of the FHprofUnd programme from the Federal Ministry of Education and Research. The grant is administered by the *Arbeitsgemeinschaft industrieller Forschungsvereinigungen Otto von Guericke e.V.* (AiF). The duration of ALOHA is 3 years and 2 months. It started in November 2007.

2 The Airlines' Perspective

With the rise of fuel costs and fees that are additionally nowadays related to environmental considerations, airlines strive to reduce costs in areas and segments that are, in contrast to afore mentioned ones, being able to get influenced. What remains as an airline authority can be ascertained by summing up the entire operating costs of an aircraft as part of the Direct Operation Costs (DOC).

$$\begin{aligned} C_{DOC} = & C_{DEP} + C_{INT} + C_{INS} + C_F + \\ & C_M + C_C + C_{FEE} \end{aligned} \tag{1}$$

$$C_{FEE} = C_{FEE,LD} + C_{FEE,NAV} + C_{FEE,GND} \tag{2}$$

The costs C incurred due to depreciation C_{DEP} and interest C_{INT} are primarily related to the purchase price of the aircraft. There is also a restricted influence on insurance costs C_{INS} covering hull damage and hull loss. As has been noticed over the past years, fuel costs C_F cannot be influenced at all. Maintenance costs C_M can be lowered by bringing into a play a fleet of homogeneous aircraft types to reduce costs of spare parts (e.g. through quantity discounts) and/or aircraft type trainings. Crew costs C_C must be kept equal to standardized levels because otherwise airlines run the risk of crew strikes [5]. Landing fees $C_{FEE,LD}$ as well as navigation fees $C_{FEE,NAV}$ are depended on aircraft mass, region and airport and are thus subject to the offered destinations. Ground handling fees $C_{FEE,GND}$ are (predominantly) dependent on the actions required during a turnaround and negotiated with local ground handling companies or airports through Service Level Agreements (SLA).

As a consequence, to remain competitive, airlines have nowadays only limited possibilities to reduce their operating costs, which are, by reducing (1) and (2):

$$\Delta C_{DOC} \approx \frac{\delta C_M}{\delta x_1} \cdot \Delta x_1 + \frac{\delta C_{FEE,GND}}{\delta x_2} \cdot \Delta x_2 \tag{3}$$

Although limited, the potential in reducing costs has been successfully exploited by well established Low Cost Airlines (LCA) such as Southwest Airlines and Ryanair. It is therefore likely that the low cost airlines segment will continue to grow, claiming an increasing market share of travel by air. Their success has sprouted a global interest of all airlines and puts them under pressure to catch up and remain competitive. One of the key enablers of LCA are adapted turnarounds [6, p. 22] as can be clearly seen in (3), partially only in combination with secondary airports though [7].

3 Problem Stating

An improvement in ground handling can lead to two principal effects: a reduction in ground handling costs, and an increase in aircraft utilization.

3.1 Ground Handling Cost Reduction

In principal, a cost reduction at one single ground handling process can be noticed on the total ground handling costs and thus, on the total airline related costs. One of the overall issues is the high dependency on other processes, resources and/or stakeholders. Thus, by reducing the interfaces between the aircraft and the airport terminal, a reduction in required Ground Support Equipment (GSE) and ground handling staff can be accomplished that would further reduce associated costs as well as e.g. the potential of delays. This means that the aircraft has to become more autonomous (i.e. getting independent of external GSE) such as including an autonomous push back system and on-board air stairs. On the contrary, such equipment leads to an increase in aircraft weight. Likewise, the aircraft must be designed to accommodate for the new technology.

Therefore, as improvements to ground handling operation always aim at reducing turnaround time and ground handling costs, it needs a close look to find out if improvements to ground handling operations also reduce the total DOC. This has to be done because in some cases, a reduction in ground handling costs increases the aircraft weight and delivery price, which leads to drawbacks in cruise performance and other DOC cost items such as fuel costs and depreciation (1).

3.2 Ground Handling Time Reduction

In contrast to plausible cost reductions, the reduction in time of one single ground handling process might not essentially lead to an overall reduction in turnaround time. This is because only the ground handling processes that are on the critical path are influencing the overall turnaround time. Processes not on the critical path are running simultaneously to critical path processes but do not dependent on predecessors. Secondly, an overall reduction in turnaround is not directly linked to an increase in utilization. This effect might only be noticed if the reduction in turnaround time throughout the day may lead to a possibility of a further flight during the considered daily availability. (4) emphasizes this by showing the parameters involved:

$$U_{d,f} = t_f \cdot \frac{A_d}{t_f + t_a + t_t} = t_f \cdot n_{f,d} \tag{4}$$

where

$U_{d,f}$	daily utilization [h/d]
A_d	daily availability [h]
t_f	flight time [h]
t_a	turnaround time [h]
t_t	taxi time [h]
$n_{f,d}$	number of flights per day [-] *integer*

The utilization U of and aircraft is a parameter with a strong influence on DOC and indicates the efficiency of an airline's operation. Airlines consistently strive after maximizing their utilization in order to distribute their fixed costs (depreciation, interest, insurance) over an increasing number of flights, which is equivalent to a relative cost reduction of each individual flight. To do so, the parameters involved in (4) must be surveyed individually: The flight time t_f is dependent on flight plan and therefore not a parameter to be adapted. Likewise the taxi time t_t which is mainly dependent on the airport layout. The daily availability A_d of an aircraft depends on many external things: flight plan, airport night time restriction, etc. The only parameter remaining for increasing the utilization is the turnaround time t_a. Hence the question arises: How much in turnaround time reduction is needed to increase the daily utilization $U_{d,f}$ and thus the annual utilization $U_{a,f}$ of an aircraft? Since the number of flights per day $n_{f,d}$ is an integer number, (4) must be rewritten to obtain the relative daily utilization $U_{d,f,rel}$ in [%]:

$$U_{d,f,rel} = \frac{t_f \cdot \lfloor n_{f,d} \rfloor}{A_d} = \frac{\left\lfloor \frac{A_d}{t_f + t_a + t_t} \right\rfloor \cdot t_f}{A_d} \tag{5}$$

$$\lfloor n_{f,d} \rfloor = \max \left\{ k \in \mathbb{Z} | k \leq n_{f,d} \right\} \tag{6}$$

Thus, the relative daily utilization increases only if the number of flights increases by one flight. This yields into the following requirement:

$$\frac{A_d}{t_f + t_a + t_t} = \lfloor n_{f,d} \rfloor + 1 \tag{7}$$

Figure 2 depicts the relative daily utilization over the flight time for two different standard turnaround times by applying (5). The relative daily utilization continuously increases with an increasing flight time up to a point where the number of flights suddenly decreases by one due to the fact of another flight in between. This characteristic is more significant at short range flights. Figure 3 depicts the necessary reduction in turnaround time to increase the utilization for different standard turnaround times by applying (5) and (6). Accordingly, the higher the flight time the higher the required turnaround time reduction for increasing the utilization (note that a reduction of turnaround time above 30 min is physically not possible since the standard turnaround time was set at 30 min or 20 min respectively). With shorter turnarounds throughout the day, the absolute impact on the relative utilization is slightly lower but achieved at a lesser (absolute) number of minutes in required turnaround time reduction.

A reduction in turnaround time can be significant and depends primarily on the ratio of flight time to turnaround time. The possibility to achieve a higher utilization is higher for short range flights. With $A_d = 18$ h, $t_f = 1$ h, $t_a = 30$ min, and $t_t = 10$ min, a reduction of about 1.8 min in turnaround time t_a must be achieved to increase the utilization. This value increases to 5.7 min for flights with 2 hours flight time.

4 Analysis of the Current Turnaround Situation

To get a broader perspective of the various issues involved in the daily ground handling of an aircraft, interviews have been conducted with experts in the field. To later judge individual aircraft design proposals in a correct way, data of real turnarounds has been collected and analyzed.

4.1 Expert Interviews

In order to address the real issues that are faced in the daily aircraft ground handling, experts in the field of ground handling procedures, airline business strategies and ground handling equipment have been interviewed. The information collected (out of a total of ten interviews conducted) has been transferred into significant and short statements and separated for each ground handling process [4].

Results emphasize the need of a better door positioning with respect to ground handling equipment dimensions through lowered sill heights and door clearances (e.g. cargo loading and catering processes are often restricted by the engine nacelles. In addition to this, the engine inlet is highly susceptible in the event of secondary damages. The wing root is e.g. interfering with the passenger boarding bridge at the second door of the Airbus A321).

Furthermore, Center of Gravity (CG) limitations decrease the flexibility of cargo loading and enforce many processes that are not optimal: e.g. passing of loose baggage along the cargo hold into the rear end of the cargo compartment; use of cargo nets requires tying of cargo nets which is time consuming and the position of it is decisive for the CG location or cargo loading in a certain sequence (unloading from back to front and loading from front to back).

The process of refueling from the fuel truck ramp is rather often accomplished than in the conventional way with ladder and rolled out fuel hose which needs more time for preparation. Reasons for that are either that the fuel truck cannot park directly under the aircraft wing because of the low wing height (Boeing B737) or, as it is often the case, the fuel truck parking near the cargo holds is interfering with the loading and off loading process.

Experts in the field additionally pointed out that there is a wastage of cargo volume by making use innovative ground handling equipment such as sliding carpets. The pushback must be considered as a critical process since it can lead to delays and the missing of slots. A lower accessibility can be noticed for underwing deicing with wings located close to the ground so that is usually accomplished by hand. Bigger GSE is used for ground handling than it is actual necessary for the type of aircraft at the airport to serve more type of aircraft with the same purchased GSE. Using larger GSE than necessary is often not optimal. Obviously, the capacity and flexibility of ground handling activities is limited by the number of available aircraft doors.

4.2 Turnaround Process Analyses

168 turnarounds of typical single-aisle aircraft in the short to medium range segment at four different airports have been video-tape recorded and analyzed. Collected data has been prepared to undergo mathematical regressions (e.g. number of passengers versus disembarking time) and statistical evaluations of all possible sets of turnaround parameters. Where obvious, outliers have been deleted to get a representative data sample. The evaluation of ground handling processes is thus based on measures of central tendency and dispersion as well as probability den-

sity distributions.

Results showed that only a few processes correlate linearly. A higher order mathematical regression would not deliver better results since collected data is much dispersed. This is due to the fact that ground handling processes necessitate much of activities and are therefore involving and depending on various parameters. Although a total of 96 parameters have been recorded and are thus available in the data sample, a certain number of influences that might even be hard to capture, remain unconsidered. For instance, Figure 1 (top left and right) depicts the number of passengers over disembarking and embarking time. As can be seen, the disembarking time correlates almost linearly with the number of passengers. In contrast to that, the embarking time is much dispersed, prohibiting a successful regression analysis.

Furthermore, in some cases the recorded process times cover more activities than the actual considered one. For instance, as the refueling process has been captured by a time stamp of fuel hose connecting and disconnecting, the definite fuel flow starts a few moments later. In this case, the data sample is representative to calculate total refueling time rather than fuel flow rates.

According to statistical evaluations, most of the processes are exhibiting a log-normal distribution characteristic (9) such as the disembarking process as shown in Figure 1 (middle left). This is because the probability of a value bellow a certain (minimum) time is close to zero due to the fact that the process cannot be carried out in such a relatively short time. The slope of the probability function then rises up very quickly up the mode where it then decreases with a negative but lesser slope than before. This means that the probability of a disembarking time below the mode is very low in contrast to the probability of a disembarking time above the mode. Thus, the mode in this example could be considered as an absolute minimum for later comparisons. For the process of embarking however, the Normal distribution (8) is in better agreement with the data sample (Figure 1 middle right) as the probability distribution shows a symmetrical characteristic about the mode of around 9 min in embarking time. As a result, the probability of achieving an embarking time below or above the mode is similar and emphasizes the hypothesis that the embarking process is dependent on various parameters and cannot be captured solely by the number of passengers.

$$f(x) = \frac{1}{\sigma\sqrt{2\Pi}} \exp\left(-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right) \tag{8}$$

$$f(x) = \begin{cases} \frac{1}{x\sigma\sqrt{2\Pi}} \exp\left(\frac{-(Ln(x)-\mu)^2}{2\sigma^2}\right), & x > 0 \\ 0, & x \leq 0 \end{cases} \tag{9}$$

To evaluate the influence of other (recorded) parameters on e.g. disembarking time, the Pearson product-moment correlation coefficient (PMCC) has been calculated according to [8]:

$$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \cdot \sum (y_i - \bar{y})^2}} \tag{10}$$

with the measured value of x_i of the characteristic X_1 and y_i of the characteristic X_2 at the i-th individual. PMCC values help to identify linear correlations between couples of selected data samples rather than expressing any curve progression other than linear. Figure 1 (bottom) depicts a number of PMCC values of different (preselected) parameters related to the dis/embarking process. What can be noticed is that disembarking time correlates almost linearly ($r > 0.5$) with the aircraft model (A319, A320, A321, B737, B738), the number of aircraft seats, and, as previously mentioned and depicted in Figure 1 (top left), on the number of disembarking passengers. For the embarking process however, no representative linear correlation could be found. Interesting to see however is that the embarking process does not depend on aisle width, seat pitch or stage length. Some pairs show a very good linear correlation e.g. seat pitch versus airline business model where it has to be kept in mind that others are a reason of logic interrelations such as number of aircraft seats versus number of passengers, aircraft type or seat pitch.

5 Aircraft Design Synthesis and Analyses

As can be seen in Figure 2 aircraft that are most affected by turnaround time are short and medium range aircraft, in particular the Boeing B737 and the Airbus A320. The B737 was developed in the 1960's, the A320 in the 1980's. This explains why requirements of nowadays ground handling operations (comparable to that of low cost airlines) were not considered in the design of the B737 and A320. The manufacturers have already announced successors of the B737 and A320. It is therefore of great interest to come up with adapted aircraft design proposals that are additionally featuring enhanced ground handling capabilities.

With this in mind, the twin-engined Airbus A320 has been chosen as the baseline aircraft for later comparisons and analyses with the proposed aircraft designs.

5.1 Aircraft Design Process in PrADO

Basis of aircraft design analysis and multidisciplinary design optimizations is the Preliminary Aircraft Design and Optimisation program PrADO [9, 10], developed by the Institute of Aircraft Design and Lightweight Structures of the Technische Universität Braunschweig. The core of the program reflects a set of design modules, representing each relevant discipline involved in the preliminary aircraft design process that are run until overall aircraft masses are converged. The program can easily be extended by adding new modules to take account for further aspects that are gaining significance [11]. Likewise, modules not necessary for a design analyses can be deactivated to lower computational effort. All modules are communicating with each other only through a data management system which accesses thematically sorted databases. The databases are initialized through data of the transport mission, a basic parametric description of the configuration layout, constraints and design targets. Additionally, different methods for a specific task are available reflecting user-defined requirements such as level of detail, method of analysis, etc.

In context of the ALOHA project, the module *DOC* becomes significant. The PrADO method selected for DOC computation is the DOC method according to Association of European Airlines (AEA) [12] due to its completeness and public availability. The method of AEA was established in 1989. For later comparison and analysis with available cost indices, a compensation for inflation must be provided to account for the predominantly financial condition of all the years in between:

$$k_{INF} = \prod_{n_{method}}^{n_{year}} (1 + p_{INF}) \qquad (11)$$

According to the U.S. Department of Labor k_{INF} amounts to 1.79 for the period of 1989 to 2010 with average consumer price indexes as a calculation basis [18].

The design method in PrADO has been validated (Table 1) through a re-design of the baseline aircraft (Figure 6). Overall aircraft masses are in good agreement with data out of [14]. Take-off field and landing-field length according to FAR requirements as well as the approach speed are subject to flight mission simulations off landing and take-off and predicted with a deviation of about 13 %. However, on this basis, the requirements of further adapted aircraft designs have been set to values of Table 2, compensating the deviations subject to flight mission simulations.

5.2 Aircraft Design Proposals and Analysis

The aircraft design under investigation is an Airbus A320 aircraft adapted for ground handling operations. The analysis of the current turnaround situation (Chapter 4) showed, that a shoulder wing aircraft could exhibit the capability of time-reduced and cost-reduced turnarounds. The configuration to be investigated is therefore an Airbus A320-like configuration with a shoulder wing instead of a conventional low wing.

In the case of a shoulder wing, the landing gear integration becomes challenging. On the contrary, the wing can be designed without a kink which yields into a simple (and single) tapered wing design. To lower the length of the landing gear, the fuselage should be kept close to the ground which additionally eases ground handling operations due to lowered sill heights. With this in mind the tail clearance for appropriate take-off rotation becomes decisive. A remedy can be found be additionally locating the engines at the tail of the fuselage, shifting the aircraft CG and thus the wing position and landing gear adjustment (relative to the fuselage) backwards. The free area obtained below the aircraft wings additionally eases ground handling processes such as refueling or loading and offloading because there will be no interferences with the engine nacelles anymore. The calculation of the wing position towards an optimum overall CG has been implemented in PrADO, by solving an equilibrium of momentum around the leading edge of the Mean Aerodynamic Chord (MAC) of the wing group (WG) and the fuselage group (FG):

$$\tilde{x} = x_{FG} - \Delta\tilde{x}_{CG} + \frac{m_{WG}}{m_{FG}} \left(\Delta\tilde{x}_{CG,WG} - \Delta\tilde{x}_{CG}\right) \tag{12}$$

with

x	longitudinal axis
$\tilde{x}$	x coordinate of leading edge at MAC
$\Delta\tilde{x}_{CG,..}$	distance between CG and $\tilde{x}$
$\Delta\tilde{x}_{CG}$	e.g. set to $0.25 \cdot c_{MAC}$
$m_{..}$	mass of wing or fuselage group

Although optimized in wing positioning, the stretched fuselage of the shoulder wing configuration will get heavier. However, the question can be raised, if the shoulder wing configuration is able of compensating its structural and aerodynamic penalties through a simple tapered wing design. Figure 4 summarizes and visualizes the results of an calculated Pareto-optimal boundary with design variables $\mathbf{x}$ of aspect ratio (AR), wing reference area (S_{ref}) and taper ratio (λ):

$$\min_{\mathbf{x}\in\Re^n} = \left\{ \begin{vmatrix} \mathbf{f}_{\mathrm{m}_W}(\mathbf{x}) \\ \mathbf{f}_{\mathrm{m}_F}(\mathbf{x}) \end{vmatrix} g(\mathbf{x}) \leq 0 \right\} [13] \tag{13}$$

with the objective functions of minimum wing mass $\mathbf{f}_{\mathrm{m}_W}(\mathbf{x})$ and minimum fuel mass $\mathbf{f}_{\mathrm{m}_F}(\mathbf{x})$ (calculated for the selected reference mission). The overall tendency of the selected objective functions is depicted according to the theory: the better the aerodynamic quality – the higher the aspect ratio or wing span – the higher the wing bending moment and thus the structural weight of the wing. In contrast to that is the wing - very short in span - that is very light in weight but exhibits a poor aerodynamic quality. What can be seen is that the fuel mass is not decreasing anymore after a certain point (around the wing mass of 13 t) which means that any further increase in wing span is not favorable. This is due to the structural penalty of the wing which is - after this point - higher than the aerodynamic improvement.

Figure 4 shows additionally where the wing of the baseline aircraft would be located in terms of wing and fuel mass for the same flight mission. The point is situated below the Pareto-optimal boundary due to the fact of lower operating empty mass which mainly results out of a lower fuselage mass (11.7 t versus 9.3 t of fuselage mass). This leads to the conclusion that the shoulder wing configuration is not able of compensating its structural and aerodynamic penalties through a simple tapered and optimized wing design.

When it comes to optimizations with DOC as a target function, the wing design point is moving along the Pareto-optimal boundary according to the cost parameters selected. To come up with a final wing design, the shoulder wing configuration has been optimized towards minimum DOC per seat and per kilometer with cost parameters selected and listed in Figure 8. The resulting point is slightly above the Pareto-optimal boundary (Figure 4). This is because of the fact that the fuselage mass dependency on wing mass has been neglected during calculations. What can additionally be noticed is that the wing has been optimized towards a more aerodynamic efficient design compared to the baseline aircraft. This is due to the fact that the DOC parameters selected for optimization do incorporate higher fuel prices which was obviously not the case when the Airbus A320 was designed back in the 1980's.

The proposed aircraft designs additionally feature foldable passenger seats [15] next to the aisle for a faster dis/embarking. The increase in fuselage mass can therefore additionally be blamed on the heavier foldable passenger seats (40.0 kg instead of 29.9 kg of a triple economy seat bench).

The idea of reducing the time of processes on the critical path of the turnaround, has been further extended by designing a six abreast, twin-aisle shoulder wing aircraft (Figure 6). The empennage of the shoulder wing configuration could be adapted towards an *H-tail* to allow for engine noise shielding effects (compare [16]). This is however not a primary task of the ALOHA project.

6 Ground Handling Analyses of Proposed Aircraft Designs

In order to assess the aircraft design proposals in terms of ground handling operations, ground handling scenarios have been developed that have been reproduced in the simulation environment CAST Ground Handling. The process oriented cost calculation has been chosen to accurately predict the difference in ground handling costs.

6.1 Ground Handling Scenarios

All collected data from turnaround analyses (Chapter 4.2) has been fed into turnaround Gantt charts that are thus based on realistic turnaround parameters. It has been noticed, that turnaround processes are primarily dependent on the airline business model (conventional versus low cost) and the parking position (terminal or remote apron). In order not to loose this information through a rough averaging of the real-time turnaround parameters, four ground handling scenarios have been defined as depicted in Table 4. Scenarios at the terminal (I and III) reflect a *full service* turnaround including a cleaning of the cabin, potable water refilling and waste water service as it would occur at every third or fourth turnaround on short-haul flights. A further differentiation is made between conventional and low cost airlines (I and II vs. III and IV): use of containers (transfer baggage) vs. bulk cargo, full catering vs. limited catering, towbarless push back vs. towbar pusback (less GSE costs), etc. Also, a different passenger load factor between low cost and conventional airlines is taken into consideration.

An example of the derived Gantt chart is depicted in Figure 5. The length of each bar has been scaled according to the results of the regression analysis of each turnaround process where the lines indicate the process time with respect to the standard deviation of each turnaround process. All scenarios and derived Gantt charts are thus based on realistic turnaround data and represent the basis of evaluation of adapted aircraft designs. Furthermore, all derived Gantt charts do not take into consideration a refueling parallel to dis/embarking as this is not the case in the 168 turnarounds video-tape recorded.

6.2 CAST Ground Handling

Results from spreadsheet (Gantt chart) analysis have a disadvantage: they will not be able to cover requirements resulting from geometry based component interaction. Simulations allow to bring the different complex views together in one model by the use of layered modeling, each of these layers reflecting thus simulation and analysis of the individual reality. In addition to the layered structure of the simulation engine, it was necessary to remain flexible during the development as well as in the modeling process. Using simulations off-the-shelf, the user will usually either not be able to realize specific needs coming from the analysis or the simulation will – because it only provides general building blocks – need quite much user effort to generate sophisticated yet understandable results.

By using the Comprehensive Airport Simulation Tool (CAST), an in-house development of the Airport Research Center [17], as a basis for a new ground handling module, software classes can be quickly and flexibly adapted while, at the same time, being powerful enough in fulfilling the needs raising from discussed requirements. As a result, the ground handling part of the simulation engine CAST *Ground Handling* has been developed within ALOHA and allows for simulation of different service arrangements of different aircraft models.

From a *user's point of view*, different aspects of the simulation itself and the simulation results can be realized by quite detailed modeling abilities and powerful object filters which only report relevant model and analysis details. By quick object instantiation, the user can handle the base components such as aircraft models, vehicles and lane segments to quickly reflect the turnaround scenario that shall be analyzed. Because every single object can be configured individually including the definition of properties, methods and processes, the simulation scenario can be developed and tested step-by-step, providing interim simulation results and thus evaluation and validation in every stage of the modeling, increasing the reliability and thus the efficiency.

From the *developer's point of view*, CAST provides an object oriented simulation core, which allows a capsulated and safe development. In addition, CAST contains a sophisticated state-of-the-art 3D rendering engine including abilities to model textured, detailed and precise geometry details. As an example, it was possible to implement an importing component to provide the detailed aircraft geometry out of PrADO, acting as an autonomous agent in the CAST engine (Figure 7). This conversion of the 3D PrADO geometry into the 3D CAST Ground Handling environment allows for ground handling simulation of different aircraft designs that have been designed and pre-evaluated with PrADO. Finally, the time and process based simulation run itself allows to define complex object interactions in advance, that is, during the modeling process itself, the user can describe what shall happen when the participating object is led into a certain state during the simulation run.

During the modeling process, CAST allows the user to instantiate objects of the developed classes in a simulation model, which aggregated reflects the desired scenario. Once connected and configured, the simulation runs will modify the objects' properties based on the natural classes' behavior as well as the user's configuration. This includes realistic behavior of the participating objects – for instance, the vehicles will move along the defined lanes, reflecting tow curve behavior and loader modification (platform lifting, cargo transport, fuselage docking at predefined connection points, etc.).

Once the different simulation scenarios have been performed, CAST allows to extract the simulation results as well as process times and their detailed cost structure efficiently by the use of spreadsheet software.

6.3 Process Cost Calculation in Ground Handling

Process cost calculation uses an approach that allows for a better assignment and control of indirect divisions or e.g. service provider costs. This means that the costs can be imposed to their actual product or service. Relating to each single company processes, a first orientation can be found at the value chain. The company cost centers are splitting general tasks into process oriented activities. Process cost rates will then be calculated by assigning costs (that are subject to the so called cost drivers) to the process activities. The process oriented overheads (burden costs) are then imposed on the products and services with the help of the derived process cost rates [19, Chapter 5].

The process cost calculation (which is a full cost pricing method) takes only into account processes with a repetitive character. This is because the cost drivers can only be imposed on such processes. In contrast, processes with a non-repetitive character cannot be evaluated analytically. Processes with repetitive character are further subdivided into activity quantity induced and activity quantity neutral processes. The latter ones are in general calculated by being drawn up to a budget. Process cost rates (of processes with a repetitive character that are activity quantity induced) are calculated by means of the cost driver p_{CD} i.e. per definition: process costs divided by process quantity. For processes with a repetitive character that are activity quantity neutral, a fixed amount allocation p_{const} has to be evaluated i.e. the ratio of costs of activity quantity induced and activity quantity neutral processes which is additionally multiplied by the cost driver p_{CD} [19, Chapter 5]. The total cost driver p is then the sum of both (14).

$$p = p_{CD} + p_{const} \tag{14}$$

$$C_{FEE,GND} = \sum_{i=1}^{n_p} \sum_{j=1}^{n_A} \left[t_{i,j} \left(x_{ops}, \overline{k} \right) \cdot p_{i,j,CD} \cdot n_{i,j,RES} + p_{i,j,const} \right] \tag{15}$$

where

n_p	no. of individual ground handling processes involved
n_A	no. of activities of the individual ground handling process i
t_i	process time of an individual ground handling activity j within the ground handling process i that is, if applicable, a function of x_{ops} and k
x_{ops}	operational parameter such as no. of seats, no. of baggage, volume of fuel refueled, etc.
k	average rate of the operational parameter x_{ops}
$p_{i,j,CD}$	cost driver of activity j within the ground handling process i
$n_{i,j,RES}$	number of resources necessary for activity j within the ground handling process i
$p_{i,j,const}$	fixed amount allocation for activity j within the ground handling process i

The process cost calculation of ground handling has been successfully applied and demonstrated by [20]. In principal, on every process that takes part in the ground handling of aircraft, actual costs can be imposed. This means that the ground handling fee is the sum of all process and activity related costs involved in the ground handling. Thus, (15) can be stated in general for estimating the ground handling costs. The parameters x_{ops} and k can be found for the main ground handling processes out of the regression and statistical analysis of collected turnaround data (compare Chapter 4.2). For the cost drivers, a further data analysis becomes necessary. Some data can be found in [20], other might be possible to gather from webpage's of ground support equipment manufacturers, ground handling companies, and airports.

7 Aircraft Design Assessment and Discussion

At the time of writing, the analyses of the proposed aircraft design with the help of CAST Ground Handling have not been finished (Figure 7). The method of analysis is therefore restricted to Gantt chart analysis and process oriented cost calculation according to (15).

The reduction in turnaround time has been predicted by adapting the processes of dis/embarking and off/loading of derived Gantt charts of each individual ground handling scenario. According to preliminary dis/embarking simulation results, the foldable passenger seat yields a reduction in disembarking time of 44.9 % and in embarking time of 16.6 %, both considered for a one door operation (scenario I and III due to the use of a passenger boarding bridge). The difference in embarking and disembarking is in agreement with the results obtained from the real data turnaround analysis (Figure 1). It is estimated that for a two door operation (scenario II and IV) the same percentages in reduction apply (further simulations pending). Furthermore, the cleaning time has been reduced by 1/3 due to a better accessibility. Due to simultaneous offloading and loading of cargo, the GSE does not have to be changed from the aft to the forward cargo door and vice versa. For low cost airlines, the loose baggage has to be loaded into containers, before the container is loaded into the aircraft. This is considered as more time efficient and easier in operation (alternatively, a *container-like box* inside the cargo hold could be loaded with loose baggage either by hand due to the reduced cargo sill height or with the help of a belt loader). After loading, the container can than be slid to the correct CG position. As a consequence, no weight and balance calculations have to be accomplished (optimal CG position could be located by weight sensors at landing gear struts) and no proportioning of baggage and freight into forward and aft cargo holds is disarranging the ground handling process. For all this reasons, it is believed that the off/loading processes are not decisive for the overall turnaround time anymore and in non of the cases part of the critical turnaround path. The reductions in turnaround time are depicted in Figure 8. The high percentage in turnaround time reduction in scenario II is because of the switching of the critical path processes. Obviously, a further reduction in turnaround time could be possible for scenarios II and IV by making use of a three-door operation (not considered to the lack of empirical data).

The reduction in turnaround costs has been predicted with the help of cost parameters to be found in [20]. Due to a turnaround time-depended amount of the total turnaround related costs ($\approx$ 70 %) an overall reduction in costs is depicted in all scenarios (Figure 8). Scenarios I and III require crew and passenger transports from the remote apron to the terminal which rises the absolute value. For all scenarios a container loader instead of a belt loader is needed. This gives two container loaders for scenarios I and II and only one for scenarios III and IV. Due to the easier operation, only two instead of three aircraft loaders of the ground staff are necessary. For scenarios III and IV, the ground staff remains as it is due to off/loading of loose baggage into the container boxes. Although the container loaders are more expensive than the belt loaders, the overall reduction in turnaround costs is depicted due to the reduction in the number of ground handling personnel needed and their active time (e.g. cleaning).

With predicted reductions in turnaround time and costs, DOC calculations have been performed for different DOC flight missions (DOC range = 300 nm, 500 nm, and 700 nm). With an assumed daily availability of about $A_d = 16$ h, and annual availability of $A_a = 3750$ h according to [12], and *under the premise of overall aircraft masses and performance identical to the baseline aircraft*, a total reduction of 1.3 %... 4.0 % in total DOC per seat-kilometer can be noticed. However, by implementing the concepts of foldable passenger seats and simultaneous loading and offloading into the aircraft design, the overall benefit in DOC gets lost. This is due to the higher overall aircraft masses of the proposed aircraft design which rises almost all DOC elements in (1) and (2), but primarily as a result of a higher fuel consumption of about 9.5 %. A higher purchase price of the aircraft is also taken into consideration which is however not crucial. The relative annual utilization yields into discrete values according to (5) and (6) and is also subject to performance calculations and therefore the flight time. It can be seen that although the relative annual utilization increases by up to 19.7 %, the DOC per seat-kilometer value increases. Thus, the advantage of a better turnaround disappears due to the mass penalties of the proposed aircraft design.

Although the presented method of turnaround analyses takes a number of parameters into consideration, not all improvements could have been assessed with respect their financial impact. An example of that are possibilities of delays due to turnaround issues which could lead into the missing of departure slots. Such situations are becoming increasingly the case at highly optimized and increased capacity airports. It is believed that by simplifying operational turnaround processes the possibility of delays subject to ground handling activities is reduced, putting the proposed shoulder wing aircraft into another spotlight. Furthermore, the potential of optimizing e.g. the fuselage has not been exhausted. Weight reductions would therefore be possible.

Due to the high influence of overall aircraft mass on the total DOC, the concept of the twin-aisle shoulder wing aircraft as depicted in Figure 6 has not been followed. A second problem that might occur with this concept is the bottleneck of the passenger boarding bridge what could nullify the benefit of the second aisle during dis/embarking for scenarios I and II. Furthermore, as the turnaround time could be reduced already by a remarkable extend, a further reduction would be problematic in other areas than ground handling. As an example, the pilots itself demand some time to work off all required preflight checks.

8 Summary

A short turnaround time of an aircraft is nowadays essential for an efficient and economic operation of an aircraft. Although nowadays ground handling processes are already optimized to a certain extend, new possibilities evolve by adapting the aircraft design itself, providing new conditions for turnaround processes. In principal, an improvement in ground handling can lead to an increase in aircraft utilization and/or a reduction in ground handling costs. The increase in aircraft utilization can only be noticed if the total time reduction of all turnarounds of the considered day enables the possibility of conducting another flight. A significant reduction in turnaround time can only be accomplished by adapting the processes of dis/embarking and off/loading. This is because the adaption of only one process could shift the other process onto the critical path of the turnaround. A significant reduction in dis/embarking time can be achieved by incorporating foldable passenger seats next to the aisle, which reduces the aisle interference. For off/loading of cargo and baggage, a continuous cargo compartment is suggested that enables a simultaneous offloading or loading as well as an optimum aircraft CG positioning by an optimum container positioning in the cargo hold. Incorporating these two enhancements in an aircraft yields into a shoulder wing aircraft configuration with the engines located at the tail of the aircraft. Under the premise of masses and performance identical to an Airbus A320-like baseline aircraft a total reduction of 1.3 %... 4.0 % in total DOC per seat-kilometer can be noticed. The necessary adaptations of the aircraft yield however into an increase of overall aircraft masses due to an increase in fuselage length and the engines at the tail. The resulting higher fuel consumption rises the fuel costs which are in relation to the increase in aircraft utilization and decrease in ground handling costs of a greater extend. For these reasons, the proposed shoulder wing aircraft design featuring a time and cost reduced turnaround results in a higher total DOC per seat-kilometer in comparison to the unchanged baseline aircraft with poor turnaround time capabilities. However, the proposed shoulder-wing aircraft configuration could reduce the possibility of delays caused by ground handling operations which has not been taken into consideration in the analysis presented.

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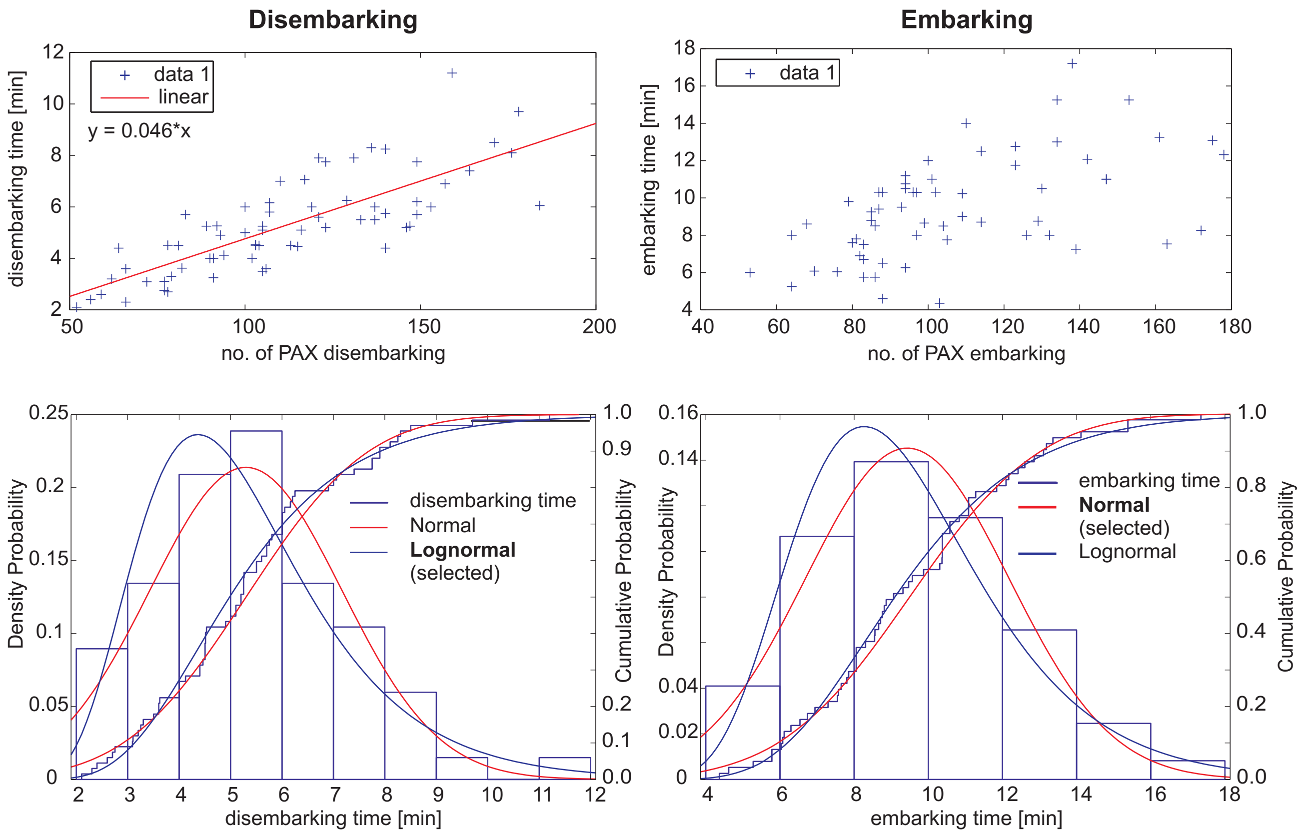


Pearson product-moment correlation coefficients (PMCC):

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
airline business model	1	1.000	0.163	-0.177	-0.175	-0.494	0.242	0.828	-0.082	-0.348	-0.286	-0.485	-0.153	-0.072	-0.078	0.047
A/C model	2		1.000	0.170	0.286	0.627	0.423	0.211	-0.063	0.319	0.326	-0.424	0.039	0.146	0.527	0.397
previous stage length	3			1.000	0.689	0.348	-0.059	-0.269	0.351	0.317	0.221	0.112	-0.109	-0.045	0.340	N/A
subsequent stage length	4				1.000	0.425	-0.009	-0.246	0.404	0.306	0.364	0.034	-0.161	-0.068	N/A	-0.075
no. of A/C seats	5					1.000	-0.163	-0.541	0.301	0.749	0.666	0.185	-0.054	0.053	0.512	0.222
aisle width	6						1.000	0.349	-0.419	-0.404	-0.448	-0.575	0.332	0.233	0.083	0.130
seat pitch	7							1.000	-0.382	-0.447	-0.356	-0.478	-0.097	-0.070	-0.111	0.085
cabin class layout	8								1.000	0.335	0.262	0.293	-0.297	-0.159	-0.033	-0.283
no. of disembarking PAX	9									1.000	0.593	0.408	-0.274	-0.250	0.568	N/A
no. of embarking PAX	10										1.000	0.237	-0.221	-0.120	N/A	0.296
dis/embarking thr. 1/2 doors	11											1.000	-0.414	-0.544	-0.238	-0.354
time for positioning GSE	12												1.000	0.588	0.115	N/A
time for removing GSE	13													1.000	N/A	0.265
disembarking time	14														1.000	0.308
embarking time	15															1.000

Fig. 1 Example results of turnaround process analyses [21]: disembarking (left) versus embarking (right) with analyses of linear regression (top), probability density distribution (middle) and PMCC (bottom)

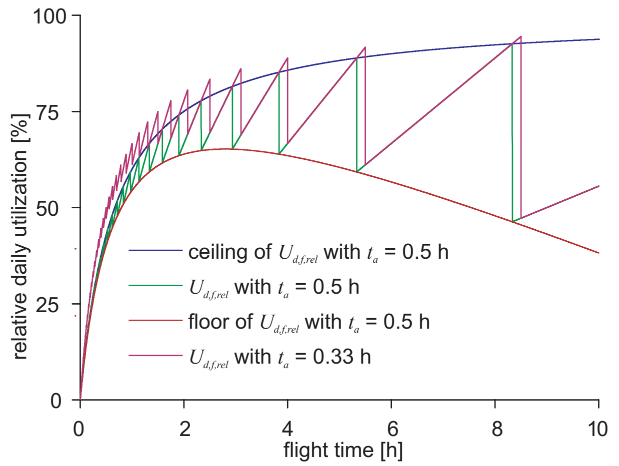


Fig. 2 $U_{d,f,rel}$ over t_f at different t_a with $A_d = 18$ h, $t_t = 10$ min

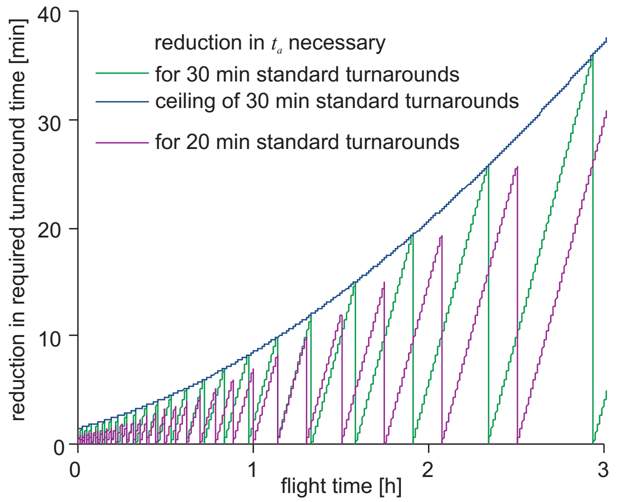


Fig. 3 Necessary reduction in t_a as a function of t_f to increase $U_{d,f}$ with $A_d = 18$ h, $t_t = 10$ min

Table 1 Results of A320 redesign to validate the design method of PrADO

Parameter	Airbus[14]	PrADO	Dev.
operating empty mass	41244 kg	41966 kg	2%
fuel mass (design range = 3273 km)	13157 kg	13401 kg	2%
max. take-off mass	73500 kg	74466 kg	1%
cruise lift-to-drag ratio	-	18.1	-
required take-off field length FAR	2090 m	2371 m	13%
required landing field length FAR	1750 m	1603 m	-8%
approach speed	72 m/s	82 m/s	13%

Table 2 Requirements for aircraft design proposals (including chosen values that are subject to the validation of the baseline aircraft)

Parameter	Value
transport mission	
- design range	3273 km
- payload :	19099 kg
- passenger (BC / EC)	12 / 138
- cargo mass	5674 kg
range for flight with max. fuel	5277 km
max. acceptable take-off field length (MTOW, 0 km, ISA)	< 2400 m
max. acceptable landing field length(MLW, 0 km, ISA)	< 1650 m
max. acceptable approach speed (MLW, 0 km, ISA)	< 82 m/s
fuel reserves	
- range for diversion (reserve fuel) FAR Part 121 (domestic)	370.4 km
- loiter FAR Part 121 (domestic)	0.5 h
freight density	
- baggage	200 kg/m^3
- cargo	180 kg/m^3

Table 3 Results of investigated aircraft designs

Parameter	Shoulder Wing - single aisle	Shoulder Wing - twin aisle
fuselage geometry		
- length	40.6 m	40.6 m
- max. width/height	3.95 m/4.14 m	4.43 m/4.14 m
wing geometry		
- reference area	130 m^2	133 m^2
- aspect ratio	10.04	10.04
static thrust	2 x 121 kN	2 x 121 kN
cruise (begin)		
- altitude	11.28 km	11.28 km
- Mach number	0.75	0.75
- trim angle	-9.5°…1.6°	-10.7°…0.6°
- L/D (trimmed)	18.37	18.73
oper. empty mass	48295 kg	50009 kg
- fuselage	11746 kg	12516 kg
- wing	10153 kg	10561 kg
- propulsion	7955 kg	7955 kg
fuel mass (reference mission: 3273 km), incl. reserves	13401 kg	13401 kg
max. take-off mass	80795 kg	82509 kg
max. landing mass	71011 kg	72725 kg
max. loadable fuel mass	21212 kg	24897 kg
FAR take-off field length	2356 m	2400 m
FAR landing field length	1627 m	1631 m
approach speed	81.00 m/s	81.88 m/s

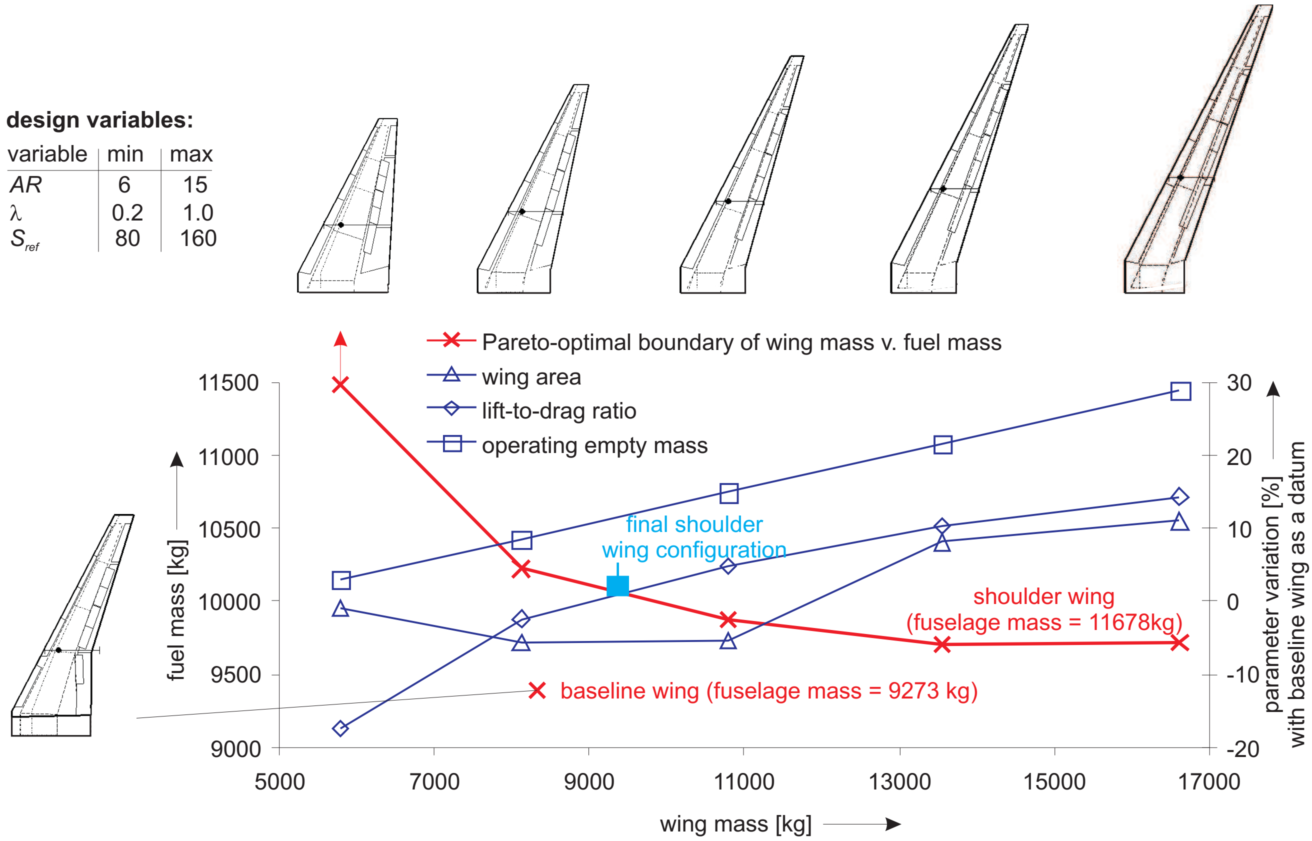


Fig. 4 Pareto optimal boundary of min. wing mass v. min. fuel mass of the shoulder wing (red curve) vs. the baseline wing (red cross); note that the top left point could even be at higher fuel masses because the optimization at this point was restricted by the preselected aspect ratio lower limit of $AR = 6$.

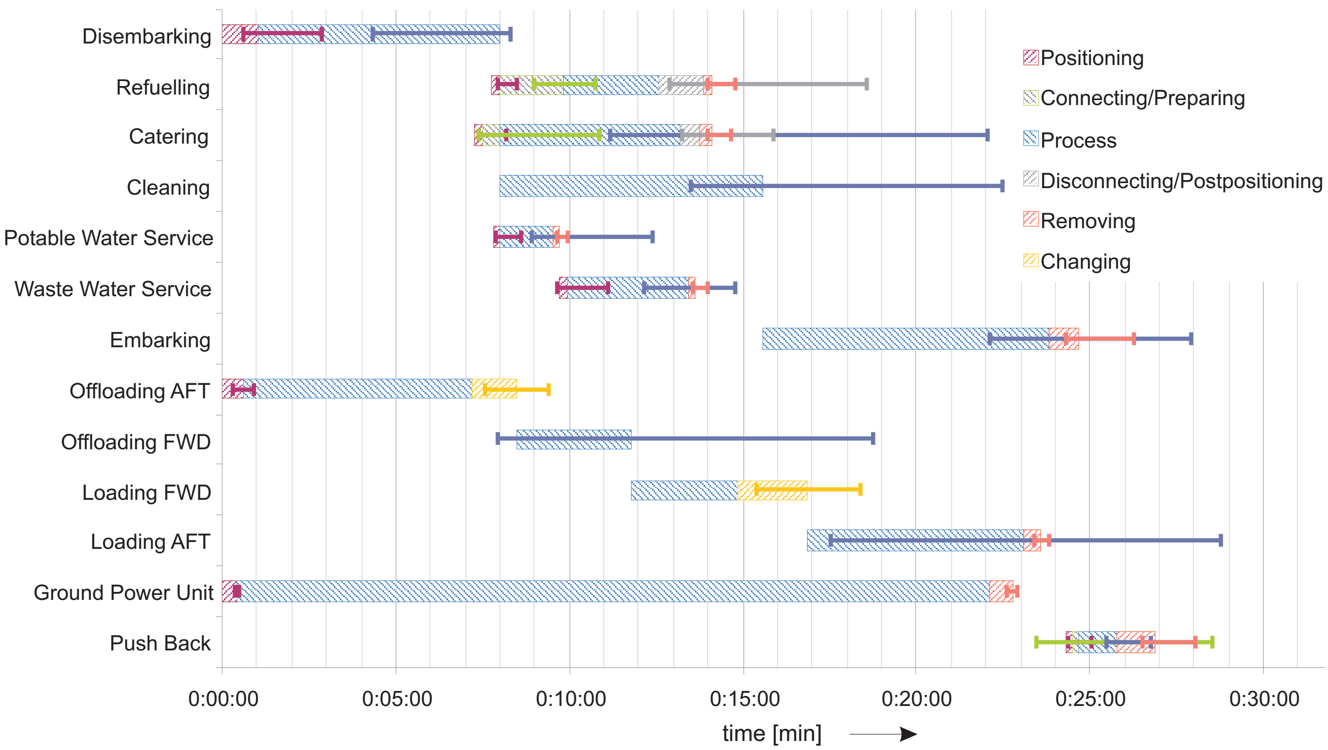


Fig. 5 Turnaround Gantt chart of ground handling scenario I of the baseline aircraft [22]: process bars scaled according to regression analyses, lines represent standard deviations out of statistical evaluations

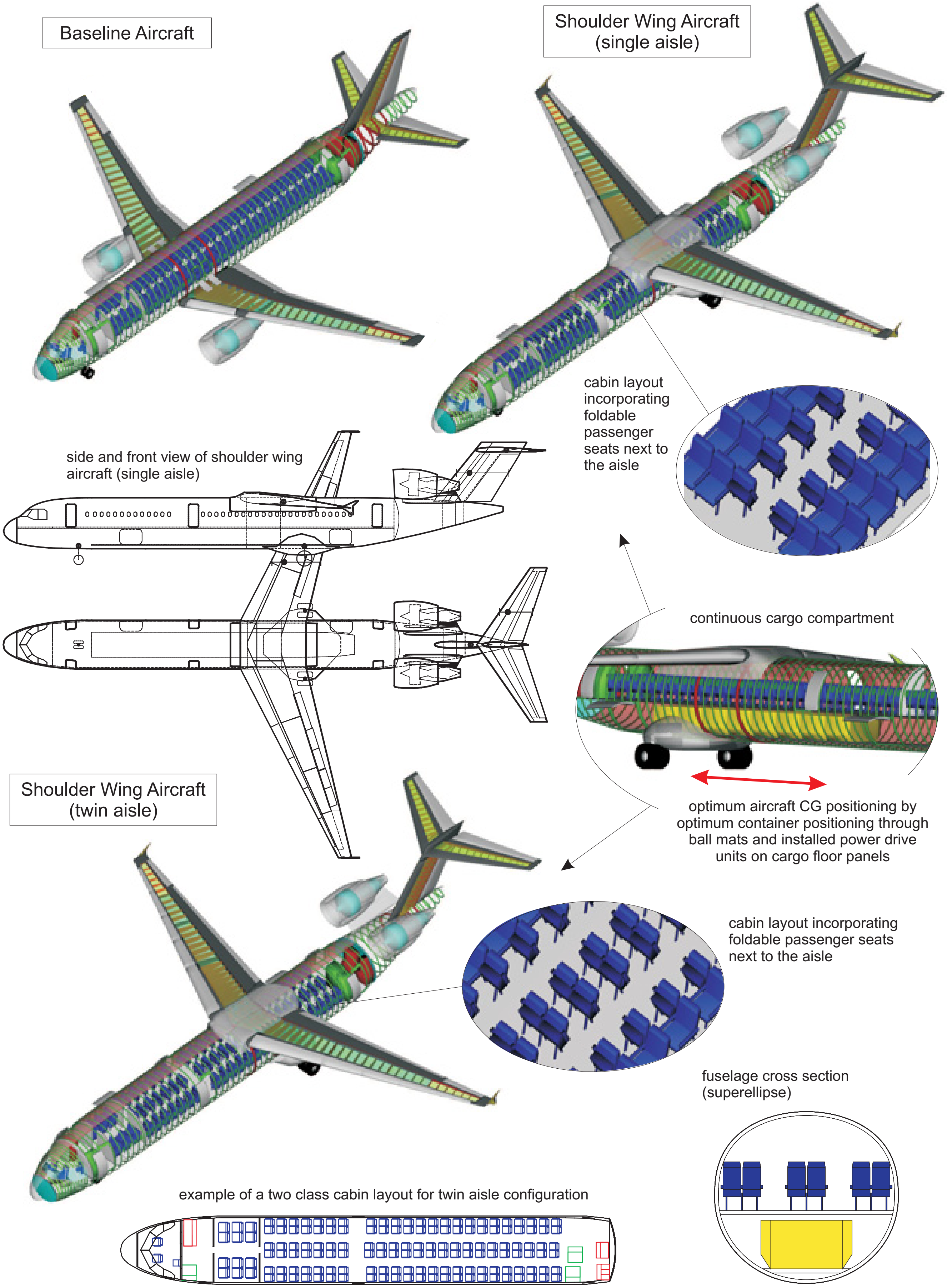


Fig. 6 PrADO 3D visualization using Tecplot of baseline aircraft (top left), single aisle shoulder wing aircraft (top right), and twin aisle shoulder wing aircraft (not further investigated in terms of ground handling).

Table 4 Definition of ground handling scenarios: conventional vs. low cost airline business model / terminal vs. remote apron position

Scenario	**I**	**II**	**III**	**IV**
airline business model	conventional		low cost	
no. of passengers	67 % passenger load factor		83 % passenger load factor	
fuel	according to DOC mission (range = 500 nm)			
catering	two catering trucks: 1 AFT, 1 FWD		one catering truck: 1 AFT	
potable water service	100 l	n/a	100 l	n/a
waster water service	80 l	n/a	80 l	n/a
parking position	terminal	remote apron	terminal	remote apron
cargo (type and amount)	4 ULDs (3 AFT, 1 FWD)	4 ULDs (3 AFT, 1 FWD)	100 bags (bulk cargo)	100 bags (bulk cargo)
ground power	from PBB[1]	from GPU	from PBB[1]	from GPU
cleaning	yes	no	yes	no
push back	towbarless	n/a (remote apron)	towbar	n/a (remote apron)

[1] PBB = passenger boarding bridge

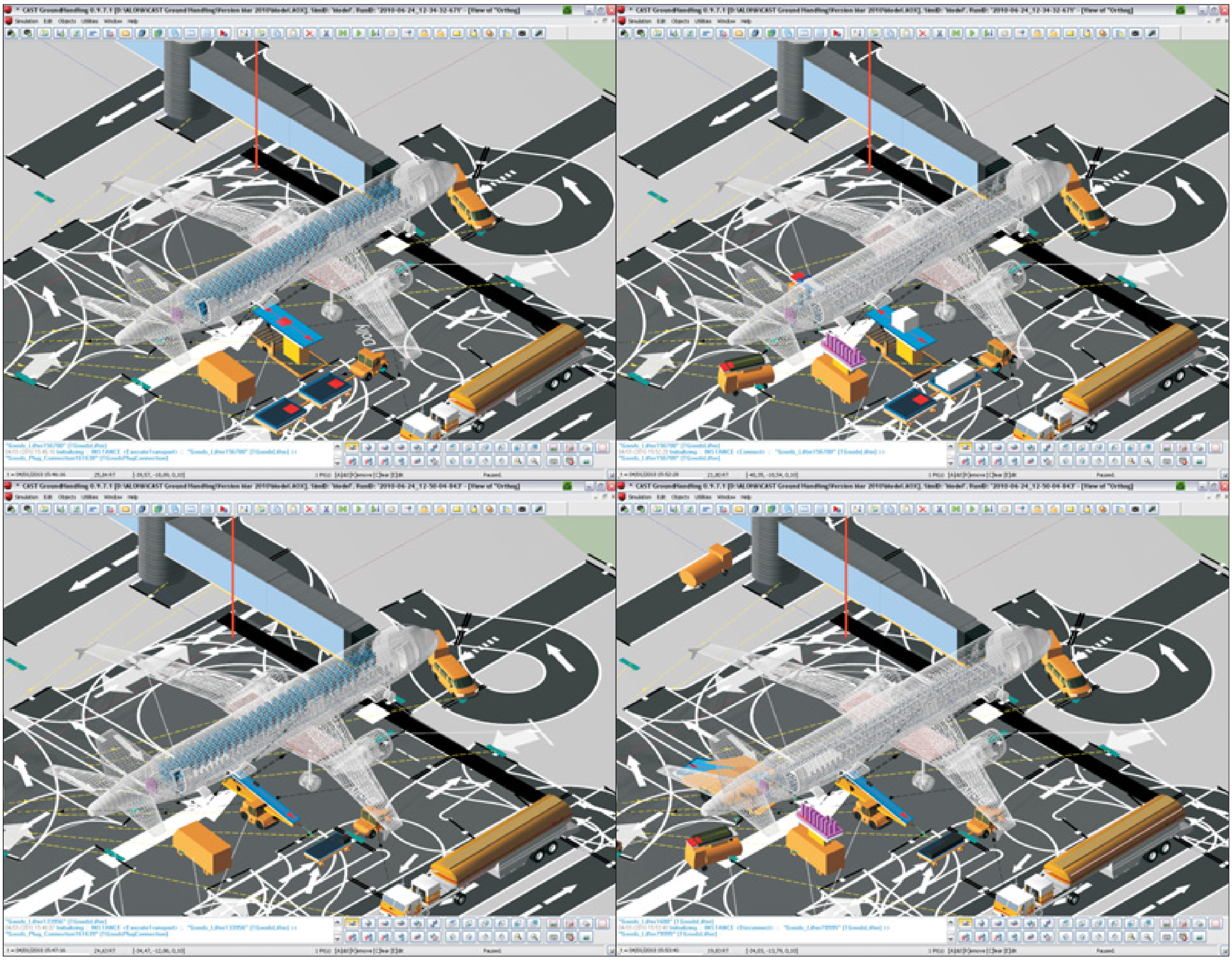
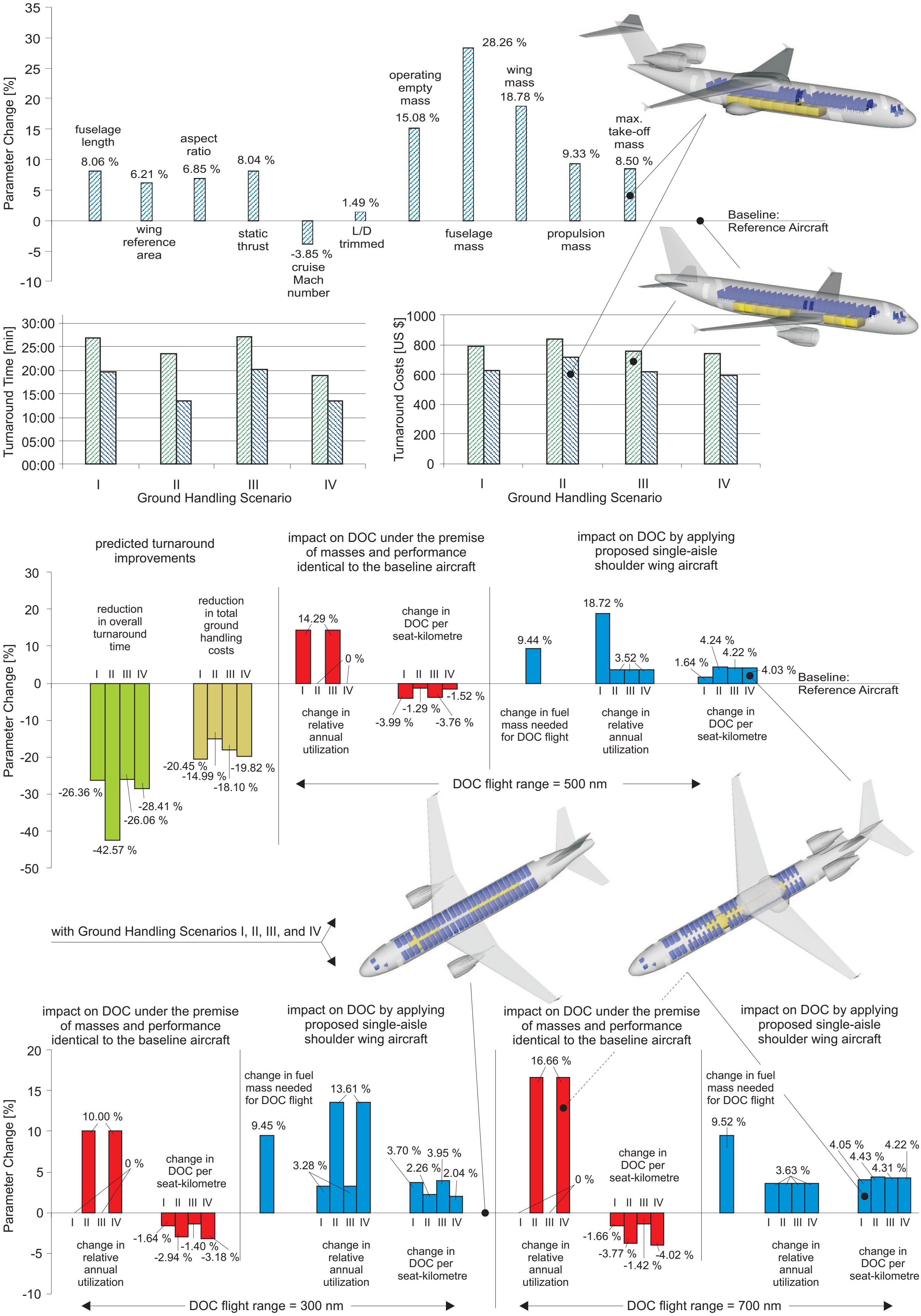


Fig. 7 Turnaround simulation with CAST Ground Handling at different time stamps of the baseline aircraft (3D geometry out of PrADO): ground handling scenario I at the top (left 04:45, right 10:57), scenario III at the bottom (left 05:45, right 12:09); left: PAX disembarking; right: all PAX disembarked. Turnaround simulation of adapted aircraft designs is still in progress.



with basic DOC values of fuel: 0.68 US $ / kg, landing fee: 2463 US $, navigation fee: 781 US $, daily availability 16 h, annual availability 3750 h for all calculations

Fig. 8 Assessment of turnaround improvements in general and by applying the proposed aircraft design