LANDING GEAR CONCEPTUAL DESIGN AND STRUCTURAL OPTIMIZATION OF A LARGE BLENDED WING BODY CIVIL TRANSPORT AIRCRAFT

Sunpeth Cumnuantip
Institute of Aeroelasticity, German Aerospace Center
Bunsenstrasse 10, 37073 Goettingen, Germany
E-Mail: sunpeth.cumnuantip@dlr.de

ABSTRACT

The landing gear system is one of the largest aircraft systems which contributes a large part to the overall aircraft weight. Landing gear attachment loads are usually design load cases of major airframe parts such as the rear fuselage and the wing center section. As a result, a well-considered conceptual design of the landing gear system plays a significant role in the final design of the aircraft. A The Blended-Wing-Body (BWB) is a revolutionary concept for commercial aircraft. However, there have been only few proposals for BWB landing gear configurations. The state-of-the-art landing gear conceptual design process is based on experience from existing aircrafts. This process thus is not suitable for the application with the BWB, where no data is available for comparison. Because of these reasons the objective of this work is to propose a design process for the conceptual design of the BWB landing gear system. The work focuses on the following design aspects: a BWB ground loads determination, a BWB landing gear weight estimation, the assessment of the ground loads effect on the aircraft structure and finally the proposal of a conceptual landing gear configuration.

This work introduces a new integrated Multidisciplinary Optimization process to investigate these design issues. There are two essential elements proposed in this process. The first element is the determination of the unknown dynamical ground loads for a BWB. The Multi-Body Simulation, MBS, method is selected for this task. The second element is the landing gear weight determination. An analytical conceptual design method is implemented to design each landing gear component individually for the weight determination. The capability of the new process is validated by a conceptual redesign of the landing gear system of an aircraft comparable to the implemented BWB. The process is then implemented for the landing gear conceptual design of a large (MTOW~700t) BWB transport aircraft. Four different configurations of different numbers of main landing gears (MLG) of 4, 6, 8 and 12 are designed, analyzed and optimized.

It could be shown in a validation case that, the introduced design process is able to realistically predict the ground loads of a large passenger aircraft with multiple main landing gears. In the case of the conceptual design of the example BWB landing gear system, it has been found that the lateral ground loads from the asymmetric landing case play a significant role for the landing gear design. The MLGs must be positioned in a triangle-like topology in order to distribute the landing energy from this landing case. Concerning the total system weight result, it has been discovered that the total system weight is reduced with an increase in the number of MLG. The weight reduction comes from the lower ground loads of the high MLG number configurations. However if the number of MLG is too high this advantage will be outstripped by too many MLG components. As the result, the concept with 8 MLGs has an optimum total system weight for the given BWB configuration. This study of the total system weight trend as the function of MLG number and position has not been possible before with the classical conceptual design method where mostly the MTOW is the only parameter which is used for the weight determination.

1 INTRODUCTION

1.1 Motivation: Landing Gear Conceptual Design for an Unconventional Aircraft Configuration

The landing gear is one of the important aircraft systems. Spieck [1] has given different examples of significant roles of the landing gear system and ground-related issues in the design of the aircraft. The two most important examples are:

- Strength: ground loads are usually responsible for dimensioning load cases on major parts of the airframe such as rear fuselage, wing root and center section.
- Weight: the landing gear system can weight up to 8% of the overall aircraft weight.

A well considered landing gear design from the aircraft conceptual design phase on is therefore one of the most fundamental aspects in order to achieve the final overall optimum aircraft design. In the case of the Blended-Wing-Body (BWB) aircraft configuration, its large fuselage space provides a new opportunity for designers to solve a problem known as a 'landing gear location stagnation' problem. Chai [2] has stated, based on an aircraft landing gear industry review, that in the case of the large conventional aircraft with the introduction of multiple-strut configurations, the envelope within which the landing gear has to be located to produce the ideal loading and stability characteristics may no longer be large enough to accommodate the increased number of main assembly struts. The blended fuselage area of the BWB offers more location for the landing gear. A designer can use this opportunity to distribute the landing gear legs in order to reduce a normally concentrated landing gear load. The reduction of this load can lead to a reduction of the aircraft's total weight. However, according to the author's knowledge, there has been little exploration in order to understand and finally use this great opportunity of the BWB configuration.

The objective of this research thus is to make a contribution to the landing gear system design during the conceptual design phase of the BWB. The emphasis is placed on the analysis of the design aspects related to landing gear system and ground loads. These design aspects are:

- A ground loads determination methodology in order to better predict these loads for an unconventional aircraft configuration.
- A landing gear system weight determination methodology in order to better estimate the landing gear system mass where the current statistical method is not applicable to the BWB.
- An investigation of the landing gear ground loads effects on the 'blended' structure of the BWB.
- An analysis of the landing system weight and the aircraft structural weight trend, in relation to the number of the landing gears and their locations.
- A conceptual design proposal of the optimum number of landing gear and the optimum landing gear position for the BWB.

1.2 Solution Proposal: An Integrated Multidisciplinary Optimization Process for the Conceptual Design of the Landing Gear System of an Unconventional Aircraft

The conventional landing gear conceptual design process such as the one explained in Conway [3] and Currey [4] is based on the experience and empirical formulas from existing and mostly conventional aircraft configurations. Thus this process is not appropriate for the design of the landing gear system of a novel aircraft configuration like the one of the BWB for which previous experience is not available. The novel BWB also introduces additional aspects in the aircraft design. It requires a design approach that departs from the usual de-composition of the airplane into distinct pieces and instead integrates wing, fuselage, engines, and tail to achieve a substantial improvement in performance, Wakayama [5]. This new aspect leads to the need for the implementation of a Multidisciplinary Optimization, MDO, approach for the BWB design.

As the result, this research proposes a new integrated MDO process for the conceptual design of the landing gear system of the BWB. The process is comprised of four major elements which are corresponded to the focus design aspects of this work which are mentioned above.

The first essential element of the new MDO process is the calculation of the landing gear ground loads. Modelling and computational simulation capability of a Multi-Body Simulation (MBS) method, a well-proven approach for dynamic analysis of aircraft on the ground, will be applied for the task in this work. The second process element is the landing gear system mass estimation. In the proposed new process the landing gear component is designed analytically using the applied load from the MBS. With this method, the weight can be determined and can be expressed in relation to the landing gear number and the landing gear position. The third important element in the process is the effects from the landing gear attachment loads to the 'blended' aircraft structure. This effect is addressed by a structural optimization of a conceptual BWB landing gear bay finite element model. The last element is the process flow itself. This works proposes a suitable process flow for the integration of the previously mentioned methodologies and tools. It includes the application of suitable optimization algorithm as well as analysis and data management tools to effectively handle an information exchange and execution of various engineering tools.

The new process has been validated by the conceptual redesign of the landing gear system of the closest comparable aircraft, i.e., a reference aircraft which represents the same overall dimensions, the comparable maximum take-off weight and the same landing gear type as the example BWB aircraft. Finally the new process has been applied for the conceptual design of the landing gear system of the next generation large BWB passenger aircraft. The objective of the design is to propose an alternative for an optimum number of main landing gears and their corresponding position for a minimum total aircraft structural and landing gear component weight.

2 AN INTEGRATED MULTIDISCIPLINARY DESIGN AND OPTIMIZATION PROCESS FOR THE CONCEPTUAL DESIGN OF THE LANDING GEAR SYSTEM OF THE BWB

Figure 1 illustrates the new landing gear conceptual design process proposed in this research. In the first step of the process, step A, the MLG positioning topology optimization, the design variables of the MLG x- and y position are passed by the optimizer to the landing gear conceptual design tool in the second step, step B. This tool is based on analytical formulations and certification requirements. The tool determines, for each of the landing gear legs, the appropriate landing gear lay-out overall dimensions that will meet the ground maneuver stability requirements. The landing gear initial mass is also calculated in this step. Finally, the program determines the geometrical constraint of the landing gear overlapping constraint. In the case of a feasible design (design constraints are not violated) landing gear masses and geometry are passed on to the next step, Step C which is the ground loads determination step.

The task in Step C begins with an initial MBS run with common reference oleo parameters of a large passenger aircraft. The information on the static force and the touch down velocity from this first MBS simulation will then be used for the searching of the shock strut parameter from the pre-design database. This use of the parameter from the pre-design database is the most important part in this step. Commonly these parameters shall be locally optimized for each MLG in order to achieve the minimum landing gear attachment load which will finally lead to a minimum structural mass. However in this work the shock absorber parameters came from the pre-designed database instead of optimizing them directly. This is done to improve the computational efficiency of the overall process. Section 3.4 will explain more in detail concerning this pre-designed database.The second MBS run with the parameters from the table will then be performed. The ground attachment loads from this second MBS run will be then sent to the next step. In step D, the MBS ground loads from step C will be used for the final landing gear component design for the landing gear component mass determination. In the last step, Step E, the landing gear aircraft support structure sizing optimization is performed. The FEM conceptual shell model is set up to represent an aircraft structure. A detailed description of this model is given in Section 3.5. Finally, the total system mass, the landing gear component mass and the aircraft support structure mass, will be sent back to the optimizer. The process iteration continues until an optimum MLG position for the minimum total system mass is found.

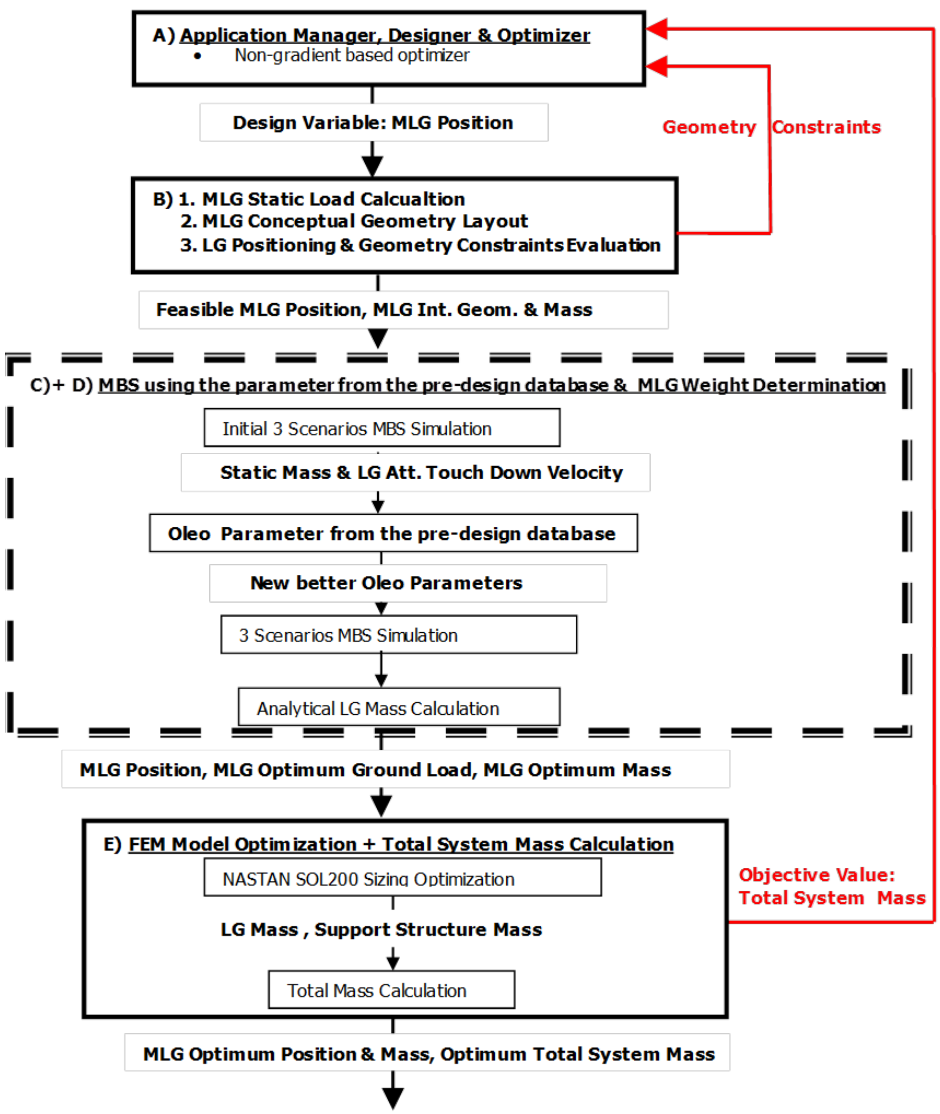


Figure1: A New Proposed Landing Gear Conceptual Design Process

3 SIMULATION MODELS

3.1 Aircraft Modelling for a Multi-Body Simulation

3.1.1 Aircraft as a Multi-Body System

In principle, an MBS system is comprised of various 'bodies' that are connected via different 'joints' and the force between each body is represented by a 'force element'. In the case of an aircraft landing simulation, the MBS system is comprised of the following components:

- The aircraft as the reference body
- The nose landing gear substructure
- The main landing gears substructures
- The aerodynamic force elements
- The force elements within the landing gear substructures

Figure 2 illustrates a topology map of the BWB aircraft multi-body model. The aircraft is connected to the 'global' reference coordinate system via a 6 degree-of-freedom joint. The aerodynamic force is applied to the aircraft body marker. The landing gear substructures are also connected to this reference body via a rigid joint. Each of the landing gear substructures is comprised of various bodies, joints and force elements. The following sections will describe all these elements more in detail. The aircraft and the landing gears are all modelled as rigid bodies. The MBS software package used for this study is the state-of–the art MBS program SIMPACK® [6].

3.1.2 Simulation Scenarios

The simulation scenarios have been selected in order to cover representative examples of possible touch-down scenarios. Three scenarios are selected. These scenarios are based on the reference scenarios described in Spieck [1]. These three cases are:

Scenario 1: Level Landing (Three-Point Touchdown)
The scenario is based on FAR 25.479. The pitch angle is 0.0°. The yaw angle is 0.0°.The roll angle is 0.0°. The landing descent velocity is 10 ft/s. The aircraft is landed with Maximum Landing Weight, MLW.

Scenario 2: Tail-Down Landing
The case is defined according to FAR 25.481. The pitch angle is 10.0°. Both yaw and roll angle are 0.0°. The landing descent velocity is 10 ft/s. The aircraft is landed with MLW.

Scenario 3: Asymmetrical Landing
An asymmetric landing case is added which simulates a hard landing with a lowered wing, for example, to compensate for side wind. The pitch angle is 5.0°. The yaw angle is 7.0°. The roll angle is 5.0°. The landing descent velocity is 10 ft/s. The aircraft is landed with MLW. This scenario is based on the case described by Khapane [7] for a large transport aircraft asymmetrical landing simulation.

3.1.3 Aerodynamic Forces

There are several methods for the application of an aerodynamic force in MBS. The *'Scaled Gravity Method'* is applied in this work. This method assumes a constant lift which is equal to the actual aircraft weight (agreement with FAR 25.473). The aerodynamic forces for the scaled gravity method are calculated based on simple linear aerodynamic theory. The MBS code SIMPACK which is implemented in this work allows the designer to be able to apply this force via a user force routine at the aircraft center of gravity.

3.2 Landing Gear Modelling for a Multi-Body Simulation

3.2.1 Modelling of a Rigid Landing Gear Model

In Figure 2, an example of an MBS schematic for a tri-twin tandem (4 MLGs concept) which is one of the three MLG concepts that are investigated in this thesis has already been illustrated. The model is comprised of a shock absorber main fitting, shock strut, bogie, axle and wheels. These landing gear components are modeled as rigid bodies. The attachments to the aircraft are also modelled to be rigid. The important rigid body properties for the MBS modelling are the body mass and mass moment of inertia. These properties for the landing gear model in this work are obtained from the analytical landing gear conceptual design tool that will be described in Section 3.3. The force elements applied in the landing gear model will be described in the following section.

The landing gear modelling approach described above is simplified, but remains complex enough to represent the dynamical behavior of the actual landing gear during the conceptual design phase. An example of the use of this modelling approach is the design and analysis of control parameters for semi-active landing gear in Krueger [8].

3.2.2 Force Elements in the Landing Gear Model

A force element describes interactions such as the force or moment between different bodies in the MBS simulation to represent realistic characteristics of the multi-body system. Since the analysis is done for the conceptual design of the landing gear and only the vertical motion is a major concern, three major force elements are sufficient to represent the characteristics of the landing gear. These three forces are: the oleo gas spring force, the oleo damper force and the tire force. The tire force which is implemented in this work are described and applied in the same way as in Cumnuantip [9]. Within this work, a great effort although has been invested in the setting of the oleo forces. The following paragraph will explain this force element more in detail.

Oleo Force: Gas Spring

The gas spring is represented by the law of polytropic expansion, Krueger [8]

$$F_f = F_0(1-(\frac{s}{s_m}))^{-n \cdot c_k} \tag{1}$$

with spring force F_f , pre-stress force, F_0 , oleo stroke, s, oleo gas length, s_m, polytropic coefficient n, and a correction factor, c_k. The correction factor, c_k, typically has a value between 0.9 and 1.1. The oleo gas length, s_m, is set to 0.6m for the application aircraft according to Loerke [10]. The value of $n*c_k$ is assumed to be 1.4, which is a common value for a commercial aircraft with the same range of static load on each landing gear. The F_0 is the function of the static load which can be calculated using Equation 1, using already obtained s_m, F_f for static case and s for static case. The value of s is equal to the possible maximum stroke of the shock absorber in the case of static load. The possible maximum stroke applied in this work is based on the aircraft characteristics described in Section 4. The oleo stroke is measured internally in SIMPACK. Finally, the force element is applied between the main fitting body and the shock strut body as expressed in Figure 2.

Oleo Force: Passive Damper

The properties of the passive damper are determined by the laws describing the flow of a hydraulic oil through an orifice. Bernoulli's equation solves for the force on the oleo piston yields, Krueger [8],

$$F_d = \mathrm{sgn}(\dot{s}) \cdot d \cdot \dot{s}^2 \qquad (2)$$

with oleo stroke velocity $\dot{s}$, oleo damping force F_d and damping coefficient *d*. The damping coefficient can be adjusted for touchdown or for rolling of the aircraft. The oleo stroke velocity is measured internally in SIMPACK. Finally, the force element is applied between the main fitting body and the shock strut body as expressed in Figure 2. A major effort is invested in this work for the setup of the damping coefficient, *d*. In order to minimize the first landing impact load, a pre-designed database which contains different optimized damping coefficients for the MLG types which are implemented in this work has been generated. The detailed description of this database is described in Section 3.4.

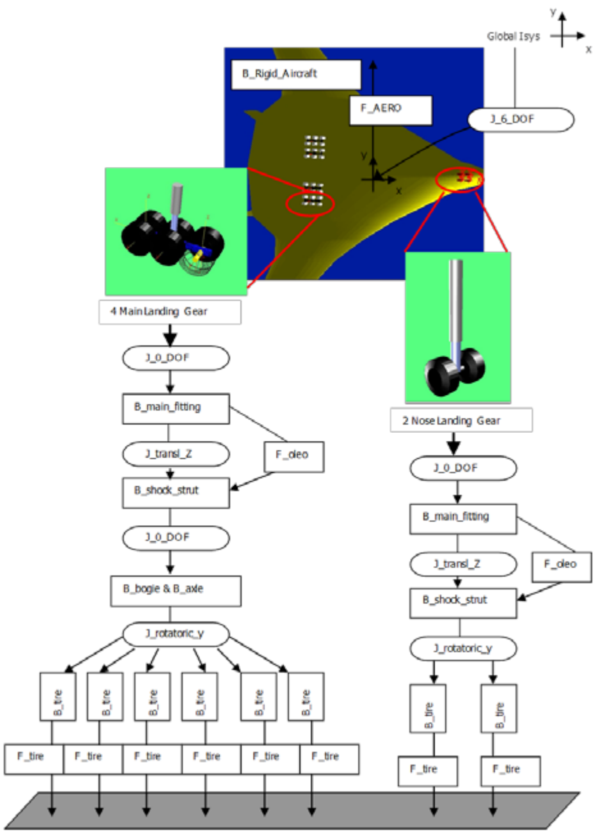


Figure 2: An MBS topology of the BWB with 4 MLGs

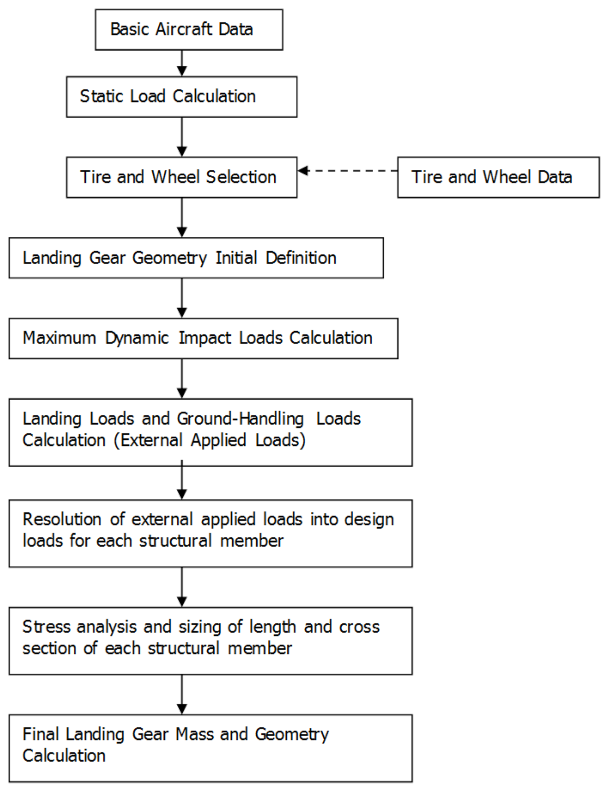


Figure 3: A diagram of an Analytical Landing Gear Conceptual Structure Weight Estimation Method of Kraus [11]

3.3 Analytical Landing Gear Conceptual Design and Weight Estimation

An analytical weight estimation method designs each landing gear component individually for the weight determination. It is thus capable of estimating the landing gear system mass as a function of the number of landing gears and their corresponding positions. This capability is one of the important focuses of this work. As the result, it has been decided to implement an analytical approach instead of the statistical approach for the landing gear weight estimation. The analytical method used in this work is based on the method described in Kraus [11]. The procedure is comprised of five basic steps:

1.) Definition of landing gear geometry
2.) Calculation of applied external loads
3.) Resolution of external loads into loads for each structural part
4.) Sizing of landing gear structural member length and cross sectional areas
5.) Calculation of final real weight of the landing gear

In addition to these steps a tire selection procedure is introduced as part of the final weight estimation. Figure 3 gives an overview of this process. The aircraft basic input data of the process in Figure 3 is the aircraft parameters such as design gross landing and take off weights, gear stroke, landing angle, take off angle, center of gravity position and positions of the landing gear relative to the center of gravity. In this work, this tool is used to conceptually design and estimate the weight of five landing gear components: main fitting cylinder, piston, bogie, axle, wheel and tire. These components are corresponded with the landing gear MBS fidelity level described above. Figure 4 illustrates these landing gear components.

It should be noted that the applied ground loads of the original method of Kraus are still based on the empirical formula. This fact is the major limitation of the Kraus method for the application to the landing gear conceptual design of the new aircraft configuration. In this work, the applied ground loads instead come from the MBS simulation. This enables the process to be able to be used for the landing gear system mass estimation of the BWB.

3.4 Generation of the Shock Absorber Parameter Pre-Designed Database

3.4.1 Two-Mass Model Application

One of the major functions of the landing gear is the landing kinetic energy absorption. This kinetic energy is the function of the aircraft static mass applied to each landing gear and the vertical (touch down) velocity at each landing gear. The most important landing gear component for this task is the shock absorber. Various research works on the shock absorber in the past are often performed using reduced landing gear model called a drop test ‘Two-Mass’ model. This model is used, for example, in Krueger [8] for the design and optimization of a semi-active landing gear shock strut control parameter.

The two-mass model example for the twin tandem main landing gear which is used in this work is shown in Figure 5. A two-mass model consists of a single full suspension, including shock absorber, tire and suspension mass, the so-called “unsprung mass”, supporting a substitution point mass, the so-called “sprung mass”. The sprung mass is equivalent to part of the total vehicle body mass which, in this case for the landing simulation, will be equal to the static mass acting on a single main landing gear leg. The main advantage of the two-mass model is its simple set-up. The model is reduced to the essential suspension design. Its usage is justified when the excitations are mainly vertical, no pitch and roll motion has to be considered, and as long as only rigid body motion is concerned. Due to the advantage of the two-mass model, it will be implemented for the generation of the optimum shock absorber pre-designed database. This parameter optimization task will be explained in the next section.

3.4.2 Shock Absorber Parameter Optimization

The following points summarize the specific set up of the model for the application in this work:

- The equivalent mass is equal to the static mass resting on each landing gear leg.
- The equivalent mass and the landing gear component properties (mass, mass moment of inertia) are obtained from the analytical landing gear design code which is described in Section 3.3.
- The oleo force and the tire force formula are the same as the formula in Section 3.2.
- There is no aerodynamic force and 1g gravitational acceleration is applied.
- The drop test velocity (vertical impact velocity) is part of the design study. It is varied for 8 touchdown velocities between 2.5-6.0 m/s. These velocities are used according to authority requirements and the possible touchdown velocity variation during the real landing.

It should be noted that the equivalent mass that each landing gear can carry is limited to the capability of the implemented tire of each landing gear. As the result, in this work, the oleo parameter database is built for a selection of different tires. Nineteen different tire types are applied. All of them are common tires that are used in today civil transport aircraft. In this work, the database is generated for each of the three MLG types. In each of these database sets there are in total 152 optimum oleo parameters. This is the result of the implemented 19 tires and 8 touchdown velocities.

For each of the 152 values in each database set mentioned above, a parameter optimization is performed in order to find the optimum oleo damping coefficient value. The optimization objective is the minimization of the vertical ground impact force at the main fitting joint to the equivalent mass. The shock absorber parameter optimization is performed under the commercial MDO platform of ModelCenter® [12]. A SQP optimization algorithm is chosen for the optimizer. Table 1 shows an example result for the twin tandem main landing gear with a 37x14.0-14 tire. The usage of the optimum damping coefficient from the pre-designed database tables in the global process has been shortly described previously in Section 2. Detail of this pre-designed database usage can be found in Cumnuantip [13].

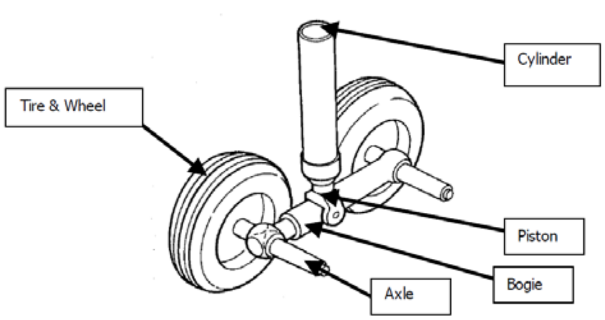


Figure 4: Major landing gear components designed by the analytical landing gear design tool

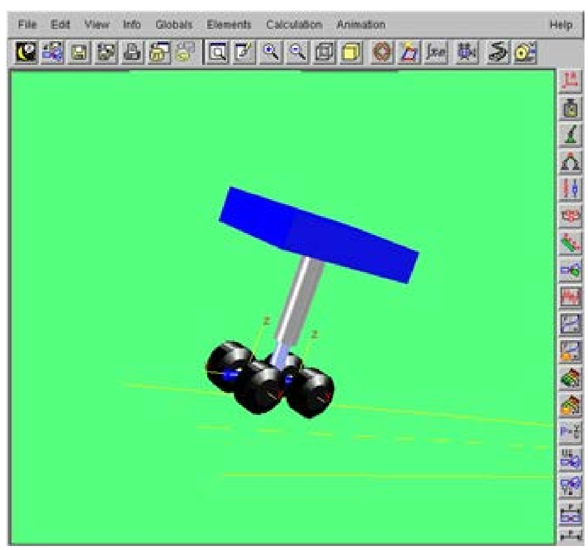


Figure 5: A Two-Mass model of a twin-tandem landing gear

Table 1: Optimum shock strut damping coefficients for a twin tandem configuration with a 37x14.0-14 tire (static mass of 45,360 kg)

Touchdown Velocity [m/s]	**Optimum Damping Coefficient [N/(m/s)^2]**	**Attachment Force, F_z [N]**
-2.5	132,692	406,458
-3.0	153,285	521,020
-3.5	174,114	647,487
-4.0	187,542	787,915
-4.5	203,701	946,247
-5.0	218,422	1,116,891
-5.5	239,837	1,308,881
-6.0	260,269	1,531,988

3.5 Landing Gear Bay Aircraft Structure Modelling for Conceptual Weight Estimation

The structural topology of the reference BWB aircraft in this work is based on the concept in Loerke [10]. However, as the focus is only on the landing gear ground related issues only the landing gear bay section of the BWB is modelled. The landing gear bay structural concept is similar to the BWB landing gear bay structural concept in Hansen [14]. Figure 6 shows the BWB MLG bay FEM implemented in this work. The following points describe the major properties and characteristics of the model.

- The MLG bay is modelled as a flat pressure bulkhead with an I-bar re-enforce. This structural topology is commonly used in a civil transport aircraft at points of introduction of concentrated forces such as those from the wings, tail surfaces and landing gear, Niu [15].
- The implemented material is Aluminium 2024.
- The model is a half model and 6 DOF supported at the major I-bar column.
- The RBE3 rigid body elements are used to transfer the ground loads to the I-bar primary structure. These RBE3s can be automatically moved according to the modification of the landing gear position.
- Cabin pressure is applied to the MLG bay wall. A distributed pressure load of 8.85 psi is applid. This assumption is based on the common value applied for the commercial transport aircraft.
- The fidelity of the model is comparable to the BWB MLG bay FEM used in Hansen [14]. It offers a compromise between complexity and computational efficiency during a preliminary design phase.

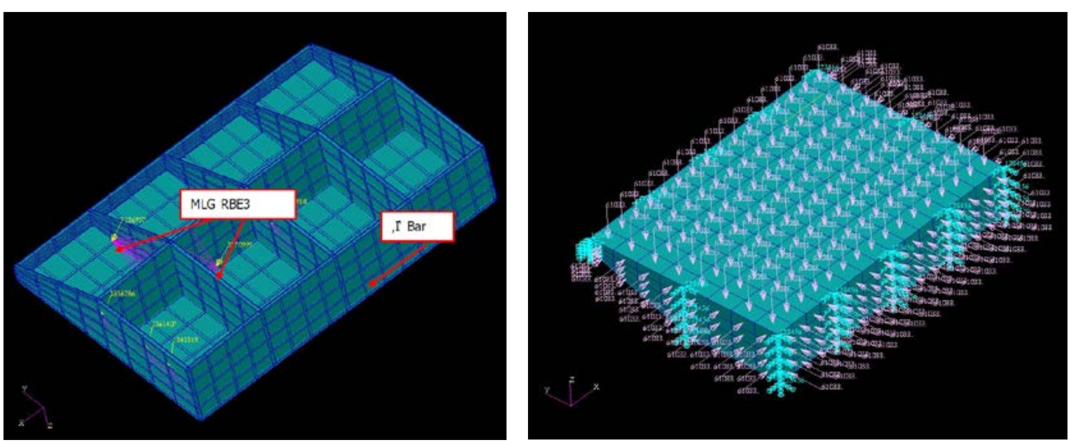


Figure 6: The MLG bay FEM with MLG RBE3s and cabin pressures

4 APPLICATION AND RESULTS

4.1 Validation of the New Landing Gear System Conceptual Design Process

4.1.1 Verification Design Case: Conceptual Re-Design of the Future Mass Transport Aircraft, FMTA, Landing Gear

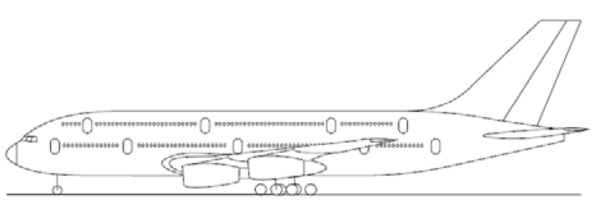
A commercial MDO platform, ModelCenter®, is chosen for the integration of different tools of the proposed new design process. Information on ModelCenter® and its capability can be found in [12].

The FMTA was a preliminary design project during the 1990's of the current largest civil transport aircraft. In this project, DLR was responsible for the conceptual analysis of the landing gear system. The aircraft is a double-deck, low wing civil transport aircraft with an MTOW of 580 tons with 650 passenger seats. It is a four engine aircraft with a wing span of 77m. The landing gear system consists of one nose landing gear, NLG, two wing-mounted main landing gears, WLG, and two fuselage-mounted body landing gears, BLG. The main gears are equipped with bogies, each of them carrying 6 wheels. Figure 7 shows this reference aircraft. It should be noted that the FMTA is chosen as a references aircraft due to two reasons. First, it represents the current largest civil aircraft with MTOW>550 tons and it represents the large civil transport aircraft with 24-Wheel MLGs. This characteristic of the FMTA landing gear layout is currently the closest example when compared the BWB requirements. The second reason is its landing gear data. It is a verified data from the industry partner during a realistic preliminary design process. This data is thus suitable to be the reference data for the validation.

The new design process is used for the re-design of the FMTA landing gear system. The major result to be verified is the landing gear system component weight. The focus is on the Wing Landing Gear, WLG. Two design test cases are performed:

Test Case 1: The MLG is designed by the new proposed design process. However, the ground loads are based on the conventional empirical formula.
Test Case 2: The MLG is designed by the new proposed design process with the MBS ground loads. The oleo parameters are based on the pre-design database

Table 2 shows the comparison of the MLG component geometry and weight of the actual FMTA data with the result from the test case 1 and the test case 2. It should be noted that exact FMTA actual values cannot be published.



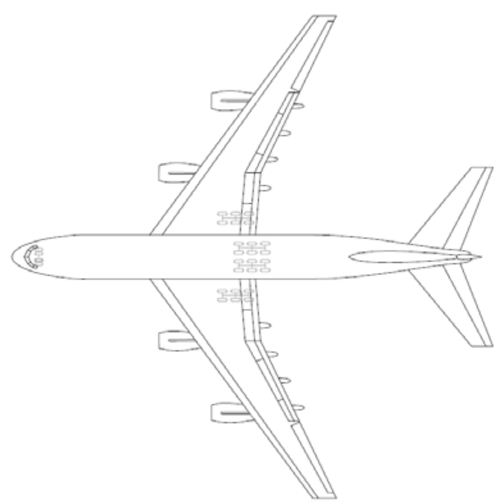


Figure 7: The reference FMTA aircraft

Table 2: Comparison of the actual FMTA component weight with the result from test case 1 & 2

Items	Test Case 1 (/Actual Data)	Test Case 2 (/Actual Data)
Main Fitting Length, [m]	2.44 (~0.94)	2.44 (~0.94)
Piston Length, [m]	1.17 (˜0.99)	1.17 (~0.99)
Bogie Length, [m]	2.95 (~0.98)	2.95 (~0.98)
Main Fitting Weight, [kg]	1,001.0 (~0.87)	1270.0 (~1.11)
Piston Weight, [m]	390.00 (~0.75)	590.5 (~1.14)
Bogie Weight, [kg]	560.35 (~0.75)	836.0 (~1.11)
Tire & Wheel Weight, [kg]	227.00 (~0.91)	227.0 (~0.91)

Concerning the component geometry result in Table 2, the results from both test cases are comparable to the actual data. However, for the component weight, the test case 1 result has the tendency to underestimate the component weight when compared to the actual data. It has been demonstrated that the proposed design process with the implementation of the oleo parameter from the pre-designed database, test case 2, delivers a result that is comparable to the actual data. According to this satisfactory validation, the new design process with the pre-design database is applied for the conceptual landing gear system design of a novel BWB configuration that is explained in the following section.

4.2 Process Application: Conceptual Design of the Landing Gear System of a Blended Wing Body Aircraft

4.2.1 Application Aircraft

The example aircraft is a large BWB configuration designed within the European consortium project, NACRE-New Aircraft Concepts Research, Loerke [10]. Figure 8 illustrates the aircraft with its initial 4 MLGS configuration. The aircraft has the following major characteristics:

MTOW	700 t
Passengers	750
Range	7,650 NM
Cruise Mach Number	0.85 at 35,000 ft
Max. Wing Span	100 m

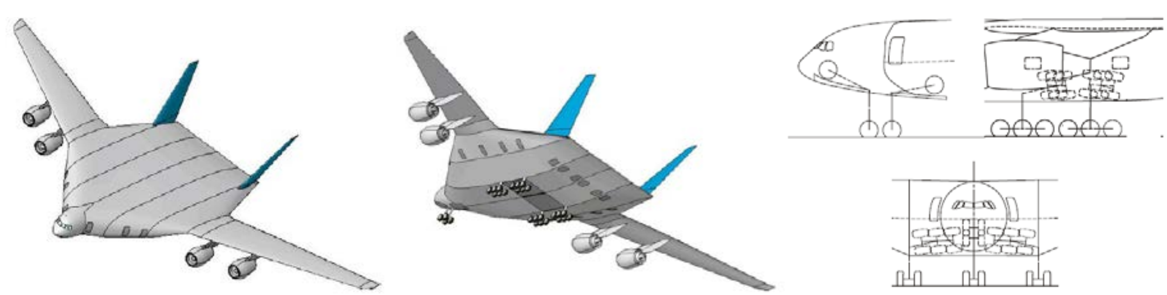


Figure 8: The application BWB aircraft with its initial landing gear positions

4.2.2 Simulation Models and Optimization Definition

A number of BWB landing gear configurations have been proposed in the past. Some proposals suggest a multiple landing gear configuration with a low number (<4) of main landing gears, with the argument that this decreases the weight of the overall landing gear system. On the other hand, landing gear configurations with higher numbers of main landing gear legs (>6) may allow the reduction of the structural mass of the airframe, as they distribute ground loads more efficiently. The latter design may finally lead to a reduction of the overall aircraft weight. There has been little investigation, to the author's knowledge, performed towards gaining more insight into this problem. As a result, it is the objective of this work to propose the number of MLGs and their locations for the large BWB civil transport aircraft.

The optimization task is to find a feasible configuration (position) of the MLG to obtain minimum total system weight which is the sum of the aircraft support structure weight and the landing gear system weight. In this work, four different configurations of different MLG number of 4, 6, 8 and 12 are analysed and optimized. However, each concept has the same total wheel number of 24 wheels. The following list briefly summarises the optimization task:

- Objective: Minimization of the total system weight
- Constraints:
  1. Overlapping of each MLG is not allowed.
  2. Maximum static load on each NLG of 15 % MTOW, Currey [4].
  3. Ground Maneuver Stability/ Operational Requirement Constraints
- Design variables: Each MLG position in aircraft global co-ordinate system.
- Optimization Algorithm: Genetic Algorithm

It should be noted that the design variables are a finite set of allowed discrete positions. This is due to the nature of the landing gear bay geometry and of the FEM aircraft support structure that is illustrated in Figure 6. As the result, a non-gradient based optimization algorithm of the Genetic Algorithm is implemented in order to handle these discrete design variables.

Concerning the landing gear bay structural optimization task, it is performed by using the commercial software, MSC NASTRAN® SOL200 [16]. The structure optimization task is aimed at minimizing the mass of MLG bay, W_{bay}, with the applied load of the landing gear attachment loads and the cabin pressure loads. The design variables are each primary 'I' beam geometry, $t_{ib1...ib4}$ and each MLG bay wall shell thickness, t_{ys}. The constraints implemented are each element geometrical constraints and Von Misses allowable stress constraints. The following list briefly summarises the optimization task. Figure 9 shows the MLG bay design variables and the geometrical constraints.

- Minimize $W_{bay}(\mathbf{x})$
- Design Variable $\mathbf{x} = [t_{ib1}, t_{ib2}, t_{ib3}, t_{ib4}, t_{ys}$: i = 1,..,956 and y = 1,...,480]
- Constraints:
  1. $g1(\mathbf{x}) \leq 0$, $g1(\mathbf{x}) = \sigma_{max,Mises(\mathbf{x})} - \sigma_{allow}$
  2. Geometrical constraints (See Figure 12)
- Optimization Algorithm: Full Stress Design and Modified Feasible Direction

4.3 Application Results

4.3.1 MLG Position Topology Result

Figure 10 shows an optimum MLG position result. The following points summarize the major characteristics of the MLG position topology results:

1. *Positioning of one MLG at the most backward corner*: In all cases, it can be observed that there is at least one MLG at the most backward corner of X=39.441 and Y = 8.567.
2. *Positioning of MLGs at the last primary spar*: In all cases, when possible, the MLG is positioned at the last primary spar (X=39.441), although at least one or two MLGs are positioned at the next forward spar (X<39.441).
3. *Positioning of 'Bogie-MLG' at the aircraft center line*: In the case of 8 MLGs concept, which is a configuration with the combination of MLG with and without bogie configuration, the bogie MLG is positioned as closely as possible to the aircraft centreline.
4. *A 'Triangle'-like MLG positioning*: The last important observation is that from the global top view perspective, MLGs are positioned in a 'triangle'-like pattern (see Figure 13 for 4, 6 and 12 MLGs).

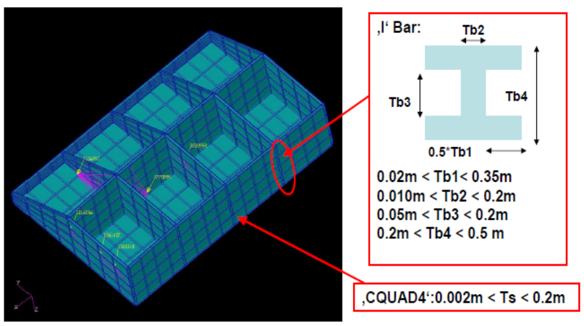
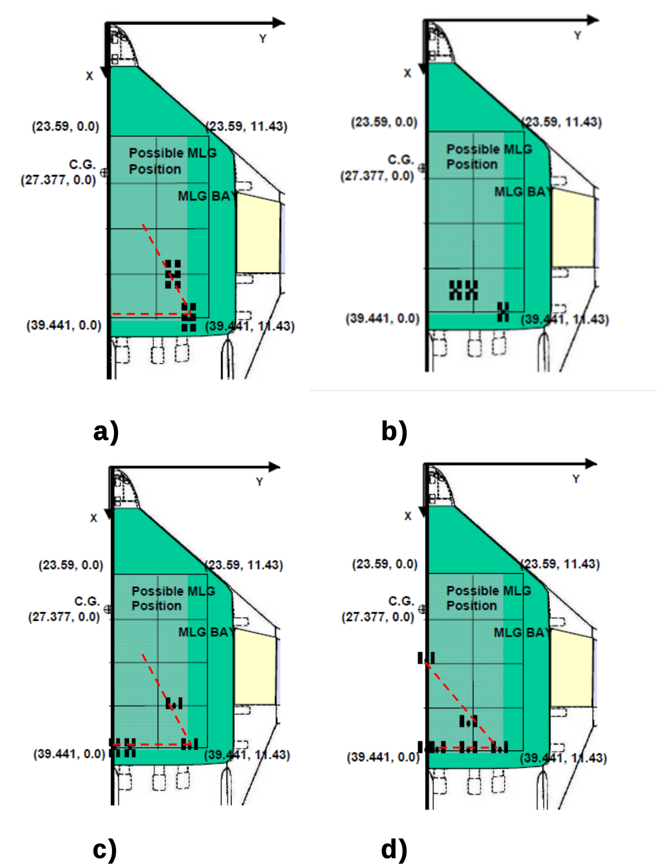


Figure 9: The BWB MLG bay FEM optimization design variable constraints



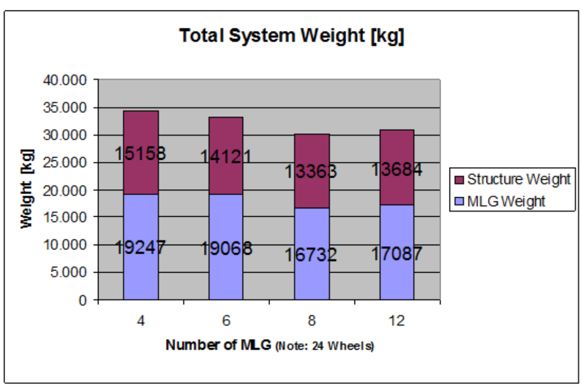


Figure 11: The total system mass result

Figure 10: MLG position topology results **a)** 4 MLG **b)** 6 MLG **c)** 8 MLG **d)** 12 MLG (MLGs are symmetric around x-axis)

The following points discuss the major characters of the MLG topology position results described above:

1. *Positioning of one MLG at the most backward corner*: This characteristic can be explained by the role of the landing gear as the landing energy absorption mechanism. This most backward corner MLG is vital in the role of the first possible position to locate an MLG to absorb the first landing impact energy.

2. *Positioning of MLGs at the last primary spar*: Concerning other MLGs, they are located at the last spar, which comes from the fact that at this position the landing gear can be designed as short as possible, if the operational requirements are satisfied. With the shortest shock strut the landing gear weight is also minimized. In addition, at the last spar position the static load on each MLG is minimum which leads to a selection of a smaller tire and wheel.
3. *Positioning of 'Bogie-MLG' at the aircraft center line*: This is the consequence of the effect from the asymmetrical landing case. The lateral side load from this landing case generates additional torsional moment around z-axis of the landing gear. It plays a significant role in the design of the MLG, especially for the bogie component. As a result, in order to minimize the effect of these lateral loads on the bogie, the optimizer has located the MLG with bogie as closely as possible to the aircraft center line. The evidence of this effort is shown in the case of 8 MLGs configuration where both bogie MLGs are located near the aircraft centreline.
4. *A 'Triangle'-like MLG positioning*: This characteristic is also the result of the asymmetrical landing case. In order to optimally distribute the landing impact energy, the optimizer put an effort to locate the MLG in the 'triangle' like topology. The shape of the triangle reflects the roll and yaw angle of the aircraft of the asymmetrical landing case. This triangle like topology offers a possibility to locate the MLG to absorb the kinetic energy where the aircraft would touch down with the asymmetrical position.

4.3.2 Total Mass Result

The MLG system mass, the MLG bay mass and the total mass result are shown in Table 3 and Figure 11. The result shows that with an increasing number of MLGs, the MLG system mass is reduced until 8 MLGs and it increases again when the number of MLGs rises further (12 MLG). In the case of the aircraft structure weight, the MLG bay mass is reduced until 8 MLGs and it increases again when the number of MLGs rises further (12 MLG). Finally, the 8 MLGs configuration delivers the optimum total system weight. Following points discuss the major characteristics observed from the MLG system mass and aircraft structure mass results:

1. *Relationship between the MLG system mass and the number of MLG*: In the current investigation, a trend can be observed that a reduction of the MLG system weight is observed with the increased number of MLG until 8 MLG. This is due to the fact that with more landing gear the reaction ground load acting on the landing gear is less, which finally leads to the lighter structure. In addition, with the more distributed load, smaller tires can be implemented. However, when the number of MLGs further increase, 12 MLGs in this investigation, the MLG weight fraction also further increases. This will be discussed in the following point.
2. *Disadvantage of the redundant MLGs*: In the case of the 12 MLGs concept, there is no bogie. However the total number of MLG struts is high (12 struts) and has finally outstripped the advantage of less reaction ground load and lower combined load.
3. *Effect of the bogie design to the MLG system mass*: The smaller tire and fewer tires of the 8 MLG concept allows the use of a smaller bogie, which results in a lower combined load on the structural members and finally leads to a lighter structure. This argument also supports the topology trend described above in which the optimizer has located the landing gear with bogie near the aircraft center line in order to reduce the effect of the combined loads.
4. *Relationship between the MLG bay mass and the number of MLG*: Comparing between the results of different MLG configurations, in the case of the comparison between 4 MLG, 6 MLG and 8 MLG, it can be observed that the 8 MLG has a better load distribution. This leads to less reinforcement of the aircraft structure which finally leads to the reduced aircraft structure weight. If the 8 MLG is compared to the 12 MLG, the 12 MLG has a better ground load distribution. However, the

reinforcement locations of the 12 MLGs concept are more and outstrip the lower ground load advantage. Finally, the 8 MLG concepts has the minimum MLG bay weight.

5. *Effect of the bogie on the primary structure reinforcement*: Concerning the effect of the bogie, the effect can be clearly observed from the result of the most extreme corner beam at the position of X=39.4441 m, Y = 8.567 m. Table 4 compares the optimum geometry of this beam between the 4 MLG (Tri-Twin Tandem MLG with the longest bogie), 6 MLG (Twin Tandem MLG with the middle length bogie) and 12 MLG (Twin MLG without bogie). It can be derived from Table 4 that at the same first landing impact position, the MLG with the longest bogie has the highest combined ground load and results in the heaviest beam.

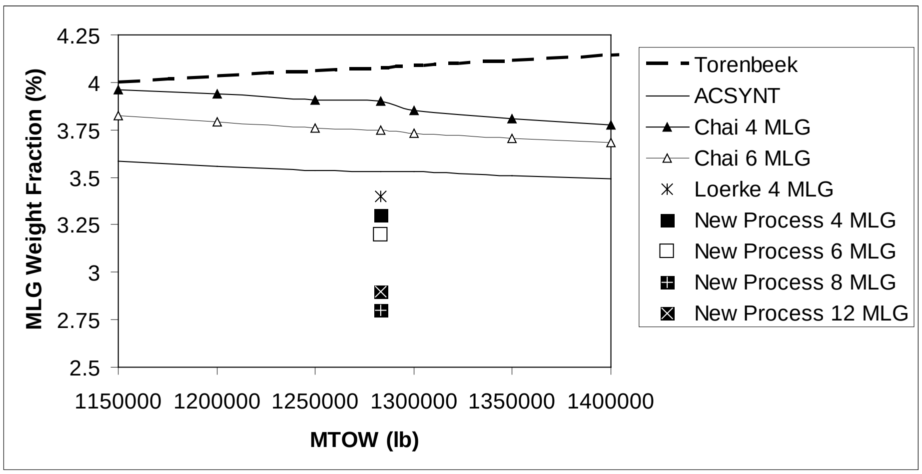


Figure 12: MLG weight fraction result

Table 3: MLG system mass, MLG bay (aircraft structure) and total system mass result

Configuration	MLG System Mass [kg]	MLG Bay Mass [kg]	Total Mass [kg]
4 MLG	19,247	15,158	34,405
6 MLG	19,068	14,121	33,189
8 MLG	16,732	13,363	30,095
12 MLG	17,087	13,684	30,771

Table 4: Optimum MLG bay beam at the position of X= 39.441 m, Y = 8.567 m

MLG Concept	t_{b1} [m]	t_{b2} [m]	t_{b3} [m]	t_{b4} [m]
4 MLG	0.1506	0.0540	0.1096	0.2517
6 MLG	0.1500	0.0520	0.1305	0.2491
12 MLG	0.1392	0.0293	0.1238	0.2335

4.3.3 MLG System Mass Trend Result

One of the objectives of this work is the study of the MLG system weight fraction in relation to the aircraft MTOW. The current state-of-the-art methods for the MLG system weight prediction are the empirical and analytical method. In this work, the MLG system mass trend result from the new proposed process is compared with the result from the current state-of-the-art methods.

MLG System Mass Trend: The State-of-the-Art Methods vs. the New-Proposed Process

Table 5 summarizes the comparison of the MLG weight fraction between the results from the current state-of-the-art methods and the results from the new process presented in this work. Both empirical approaches, Torenbeek [17] and ACSYNT (Jayaram [18]), make no assumptions about relationship between the number of MLGs and the MLG system weight. The new design process, however, is able to give the information on this relationship. According to the result from the new approach, the MLG weight fraction will decrease when the number of MLG increase up to 8 MLGs and the weight fraction will increase when the number of MLG further increases.

In the case of the analytical approach from Chai [2], the method can predict the MLG weight trend in relationship with the MLG numbers. However, Chai only performed the parametric study of the MLG system mass only for the aircraft with 4, 5 and 6 MLGs. Chai method predicts the decreasing trend for an increasing number of MLGs.

Concerning the comparison to the actual data, as for example for the case of 4 MLGs configuration, the actual data approximates the MLG system weight to be 3.4% of the MTOW. The new approach predicts the MLG weight fraction of 3.3% of the MTOW for the reference aircraft. Torenbeek, ACSYNT and Chai predict the value to be 4.1%, 3.6% and 3.9%, respectively. The new approach shows its capability of a better prediction of the MLG weight fraction to the industry value than the state-of-the-art methods. Figure 12 shows the MLG system weight fraction results from the state-of-the-art approaches and from the new process. The values given in Figure 12 for the MLG weight fractions for ACSYNT and the method of Chai have been interpolated from graphs given in Chai [2]. The values for the approach of Torenbeek have been calculated by the author.

Table 5: MLG weight fraction to aircraft MTOW of the BWB application aircraft

	New Process Result [kg] (%MTOW)	**ACSYNT [kg] (%MTOW)**	**Torenbeek [kg] (%MTOW)**	**Chai [kg] (%MTOW)**
4 MLG	19,247 (3.3%)	21,119 (3.6%)	23,626 (4.1%)	~22,746 (3.9%)
6 MLG	19,068 (3.2%)	21,119 (3.6%)	23,626 (4.1%)	~22,345 (3.75%)
8 MLG	16,732 (2.8%)	21,119 (3.6%)	23,626 (4.1%)	N.A. (N.A.)
12 MLG	17,087 (2.9%)	21,119 (3.6%)	23,626 (4.1%)	N.A. (N.A.)

*N.A.= Not Available

5 SUMMARY AND OUTLOOK

A BWB aircraft with its 'blended fuselage' provides a large fuselage space for a higher possible number of landing gears and for more landing gear locations. This opportunity allows a designer to better distribute the normally concentrated landing gear ground loads. This opportunity can finally lead to a reduction of the aircraft total weight. This motivated the research of this work.

A current state-art-of landing gear conceptual design process is based on the knowledge of the conventional aircraft configuration. It is not suitable to use this process for the BWB. In this work, a new integrated MDO process for the BWB landing gear conceptual design has been proposed. Different crucial elements are proposed in this new process. The following list summarizes these important elements:

- The Multi-Body Simulation, MBS, method with a pre-optimized landing gear shock strut parameters database is applied for the determination of the ground.

- An analytical approach for the landing gear system mass estimation
- The conceptual aircraft landing gear bay structural finite element model for the study of the effect of the ground loads to the ‘blended’ structure of the BWB
- The generation of an effective process flow of the new proposed design process.

The capability of the new process has been validated by the conceptual re-design of the MLG of the current largest civil passenger aircraft. The verified process is then implemented for the conceptual design of the landing gear system of a next generation large civil BWB transport aircraft with the MTOW of 700 tons. Four MLG concepts of 4, 6, 8 and 12 MLG configurations are investigated. Different new knowledge has been obtained from the implementation of the new design process.

In the case of the MLG topology result, it is vital to locate a landing gear at the first touchdown position at the most backward corner in order to absorb the first landing impact energy. The second learned aspect is that, in order to absorb the landing impact energy of the asymmetrical landing case, a ‘triangle’ like landing gear position topology is recommended. The last recommendation is that, in the case of the design configuration with a bogie landing gear, it is proposed to locate this landing gear near the aircraft center line in order to reduce the applied torque effect from the bogie.

Concerning the ground loads determination aspect, the MBS method with the pre-determined shock strut parameter database application has shown its capability to perform a more precise ground load prediction than the classical method. This is verified by a comparable landing gear component mass result of the FMTA design case. An application of this pre-design database offers an inexpensive approach for the setting up of the landing gear parameter for the optimum ground loads. Concerning the ground loads itself, the result shows the significant influence of the lateral landing load from the asymmetrical landing case.

From the point of view of the total system mass prediction, the 8 MLGs concept has the optimum total system mass. The result also shows that the mass will decrease when the number of MLG increase until 8 MLGs. This is due to a better load distribution. However the mass will increase when the number of MLG further increases. This is due to too high number of MLGs leads to too many MLG components and too many aircraft structure reinforcement locations which finally outstrip the advantage of the lower ground loads. From the aircraft conceptual design perspective, the new process is able to predict the MLG system mass as a function of the MLG number. It has also been shown that the MLG weight fraction to the MTOW is lower than the one predicted by the conventional approach.

Knowledge in different perspectives of the BWB landing gear system has been obtained by the application of the new design process. However, certain issues are still open for the future detailed investigations. These points are highlighted in the following list.

- Optimization Problem: The large dimension of the BWB requires a high lift-off pitching moment. This requirement finally influences the final landing gear position. As the result the flight mechanical constraints shall be integrated into the new process in the future.
- Simulation Cases: The ground operational maneuver cases of e.g. braking, taxing, and turning can affect the landing gear positions and the total system masses. These simulation cases shall be integrated into the new design process when the definitions for these maneuvers are defined.
- Landing Gear and Aircraft Structure Model: It has been shown that the lateral forces play a significant role to the design. Further investigation in the landing gear secondary structure including the corresponded aircraft structure to deal with this problem shall be performed in the future.

6 REFERENCES

[1] Spieck, M.: Ground Dynamics of Flexible Aircraft in Consideration of Aerodynamic Effects. PhD Thesis. Technical University of Munich, Germany, 2003.

[2] Chai, S.T. and Mason, H. W.: Landing Gear Interaction in Aircraft Conceptual Design. Technical Report MAD 96-09-01. Virginia Polytechnics and State University, Blacksburg, VA, 1996.

[3] Conway, H.G.: Landing Gear Design. Chapman & Hall, London, 1958.

[4] Currey, S. N.: Aircraft Landing Gear Design: Principles and Practices. AIAA Education Series, Washington, 1988.

[5] Wakayama, S.: Multidisciplinary Design Optimization of the Blended-Wing-Body. AIAA Paper 98-4938, September 1998.

[6] SIMPACK: Dassault Systemes Company, Gilching, Germany.

[7] Khapane, P.D: Simulation of asymmetric landing and typical ground maneuvers for large transport aircraft. Aerospace Science and Technology 7 (2003) 611–619, July 2003.

[8] Krüger, W.: Integrated Design Process of the Development of Semi-Active Landing Gear for Transport Aircraft. DLR Forschungsbericht 2001-27, Deutsches Zentrum für Luft-und Raumfahrt, Germany, 2000.

[9] Cumnuantip, S., Krüger, W. and Spieck, M.: Conceptual Configuration of a Blended Wing Body Landing Gear System. In: Proceedings of IFASD 2005. IFASD 2005 - International Forum on Aeroelasticity and Structural Dynamics, 28 June - 01 July 2005, Munich, Germany.

[10] Loerke, J.: NACRE D1.2-5 Publication of Flying Baseline Configuration. Technical Report, NACRE – New Aircraft Concepts Research Consortium, 2006.

[11] Kraus, P.R.: An Analytical Approach to Landing Gear Weight Estimation. SAWE, 829, May 1970.

[12] ModelCenter: Phoenix Integration Corp., Blackberg, Virginia

[13] Cumnuantip, S.: Landing Gear Positioning and Structural Mass Optimization for a Large Blended Wing Body Aircraft. DLR Forschungsbericht 2014-20, Deutsches Zentrum für Luft-und Raumfahrt, Germany, 2014.

[14] Hansen, U. L., Heinze W. and Horst, P.: Representation of Structural Solutions in Blended Wing Body Preliminary Design. In: 25th ICAS International Congress of the Aeronautical Sciences, CA, 2006.

[15] Niu, M.: Airframe Structural Design: Practical Design Information and Data on Aircraft Structure. Conmilit Press Ltd., Hong Kong, 1995.

[16] MSC NASTRAN: MSC Software Corp., Santa Ana, California.

[17] Torenbeek, E.: Synthesis of Subsonic Airplane Design. Delft University Press, The Netherlands, 1982.

[18] Jayaram, S., Myklebust, A., and Gelhausen, P.: ACSYNT - A Standards-Based System for Parametric Computer Aided Conceptual Design of Aircraft. AIAA Paper 92-1268, February 1992.