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Evolution of the SpaceLiner towards a Reusable TSTO-Launcher

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Since a couple of years the DLR launcher systems analysis division is investigating a visionary and extremely fast passenger transportation concept based on rocket propulsion. The fully reusable concept consists of two vertically launched winged stages in parallel arrangement.

The space transportation role of the SpaceLiner concept as a TSTO-launcher is now, for the first time, addressed in technical detail. Different mission options to LEO and beyond are traded and necessary modifications of the passenger stage to an unmanned cargo-carrier are investigated and described in this paper.

Meanwhile, technical progress of the SpaceLiner ultra-high-speed passenger transport is ongoing at Phase A conceptual design level. Iterative sizings of all major subcomponents in nominal and off-nominal flight conditions have been performed. Potential intercontinental flight routes, taking into account range-safety and sonic boom constraints as well as good reachability from major business centers, are evaluated and flight guidance schemes are established. Alternative passenger cabin and rescue capsule options with innovative morphing shapes were also investigated.

The operational and business concept of the SpaceLiner is under definition. The project is on a structured development path and as one key initial step the Mission Requirements Review has been successfully concluded.

Keywords: SpaceLiner, TSTO, trajectory guidance, LOX-LH2-propulsion, cost estimation, MRR

Nomenclature

D	Drag	N
I_{sp}	(mass) specific Impulse	s (N s / kg)
L	Lift	N
M	Mach-number	-
T	Thrust	N
W	weight	N
c*	characteristic velocity of engine	m/s
g	gravity acceleration	m/s^2
m	mass	kg
q	dynamic pressure	Pa
v	velocity	m/s
α	angle of attack	-
γ	flight path angle	-

Subscripts, Abbreviations

AOA	Angle of Attack
ATM	Air Traffic Management
CAD	Computer Aided Design
CEM	Cost Estimation Method
CER	Cost Estimation Relationship
CMC	Ceramic Matrix Composites
DOF	Degree of Freedom
DSMC	Direct Simulation Monte Carlo
GLOW	Gross Lift-Off Mass
IXV	Intermediate Experimental Vehicle
LEO	Low Earth Orbit
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
MECO	Main Engine Cut Off
MR	mixture ratio
MRR	Mission Requirements Review
NPSP	Net Positive Suction Pressure
OTP	Oxidizer Turbo Pump
PEEK	Poly-ether-ether ketone
RCS	Reaction Control System
RLV	Reusable Launch Vehicle
SLME	SpaceLiner Main Engine
SWIM	System Wide Information Management
TAEM	Terminal Area Energy Management
TPS	Thermal Protection System
TRL	Technology Readiness Level
TSTO	Two-Stage-To-Orbit
TVC	Thrust Vector Control
CoG	center of gravity
cop	center of pressure

1 INTRODUCTION

The key premise behind the original concept inception is that the SpaceLiner ultimately has the potential to enable sustainable low-cost space transportation to orbit while at the same time revolutionizing ultra-long distance travel between different points on Earth. The number of launches per year should be strongly raised and hence manufacturing and operating cost of launcher hardware should dramatically shrink.

Ultra-long distance travel from one major business center of the world to another major agglomeration on Earth is a huge and mature market. An interesting alternative to air-breathing hypersonic passenger airliners in the field of future high-speed intercontinental passenger transport vehicles might be a rocket-propelled, suborbital craft. Such a new kind of 'space tourism' based on a two stage RLV has been proposed by DLR under the name **SpaceLiner** [1]. Ultra-long-haul distances like Europe – Australia could be flown in 90 minutes. Another interesting intercontinental destination between Europe and North-West America could be reduced to flight times of slightly more than one hour.

Ultra-fast transportation far in excess of supersonic and even potential hypersonic airplanes is definitely a fundamental new application for launch vehicles. By no more than partially tapping the huge intercontinental travel and tourism market, production rates of RLVs and their rocket engines could increase hundredfold which is out of reach for all other known earth-orbit space transportation. The fast intercontinental travel space tourism, not only attracting the leisure market, would, as a byproduct, also enable to considerably reduce the cost of space transportation to orbit as is demonstrated in this paper.

Figure 1: The SpaceLiner vision of a rocket-propelled intercontinental passenger transport could push spaceflight further than any other credible scenario

2   GENERAL DESCRIPTION OF SPACELINER CONCEPT

2.1   Status of Previous Technical Development

First proposed in 2005 [1], the SpaceLiner is under constant development and descriptions of some major update steps have been published since then [2, 6, 7, 11, 31]. The European Union's 7th Research Framework Programme has supported several important aspects of multidisciplinary and multinational cooperation in the projects FAST20XX [15], CHATT [51], HIKARI [32], and HYPMOCES [37].

Different configurations in terms of propellant combinations, staging, aerodynamic shapes, and structural architectures have been analyzed. A subsequent configuration numbering has been established for all those types investigated in sufficient level of detail. The genealogy of the different SpaceLiner versions is shown in Figure 2. The box is marking the configuration trade-offs performed in FAST20XX in 2009/10. These configuration studies supported the definition of the current reference configuration SpaceLiner7. An overview on the interim research configurations 3, 4, 5, and 6 can be found in [6]. At the end of 2012 with conclusion of FAST20XX the SpaceLiner 7 reached a consolidated technical status. Another important milestone has been reached in 2016 with the successful completion of the Mission Requirements Review (MRR, see section 6.1) which allows the concept to mature from research to structured development.
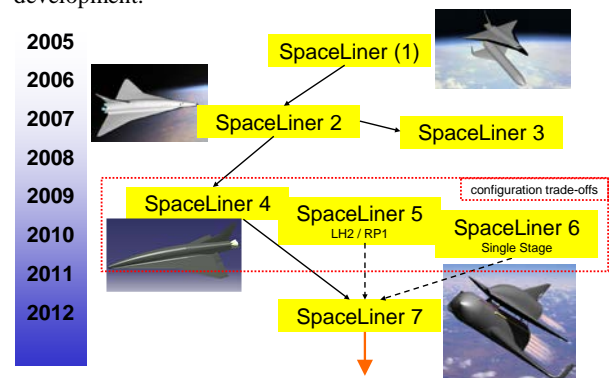

Figure 2: Evolution of the SpaceLiner concept

2.2   Baseline Design Concept

The general baseline design concept consists of a fully reusable booster and passenger stage arranged in parallel. All rocket engines should work from lift-off until MECO. A propellant crossfeed from the booster to the passenger stage (also called orbiter) is foreseen up to separation to reduce the overall size of the configuration.

The current arrangement of the two vehicles at lift-off is presented in Figure 3. Stage attachments are following a classical tripod design. The axial thrust of the booster is introduced through the forward attachment from booster intertank into the nose gear connection structure of the orbiter. The aft attachment takes all side and maneuvering loads.
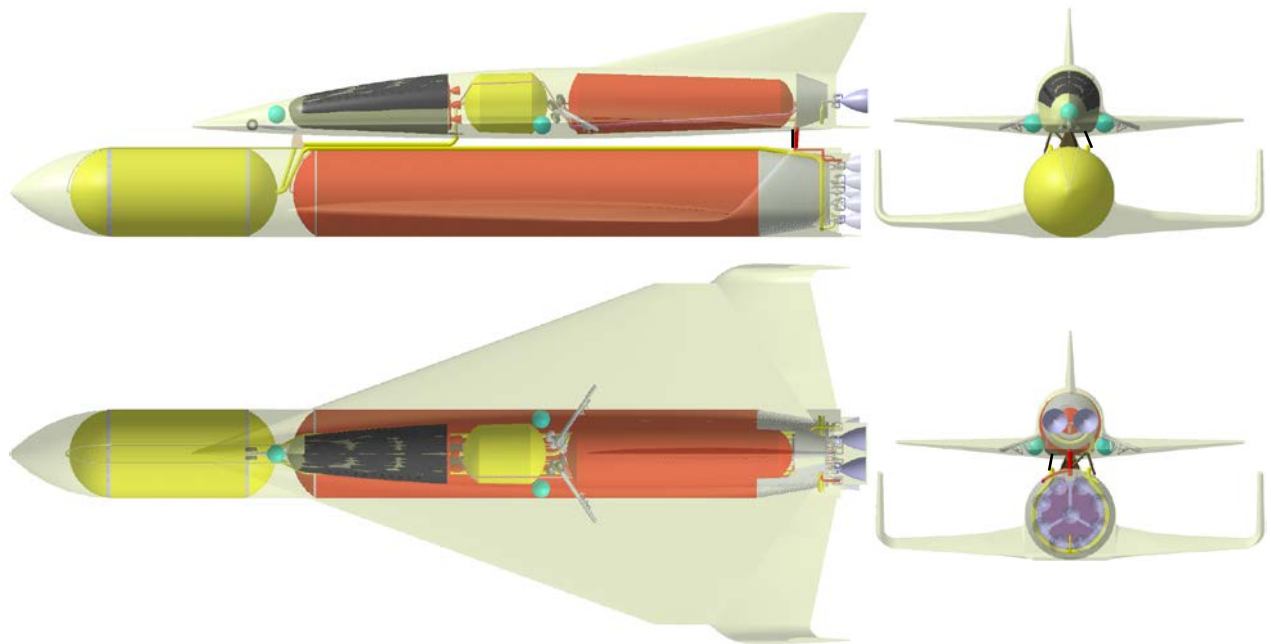
Figure 3: Sketch of SpaceLiner 7-3 launch configuration with passenger stage on top and booster stage at bottom position

Table 1: Geometrical data of SpaceLiner 7-3 booster stage

length [m]	span [m]	height [m]	fuselage diameter [m]	wing leading edge angles [deg]	wing pitch angle [deg]	wing dihedral angle [deg]
82.3	36.0	8.7	8.6	82/61/43	3.5	0

Table 2: Geometrical data of SpaceLiner 7 orbiter and passenger stage

length [m]	span [m]	height [m]	fuselage diameter [m]	wing leading edge angle [deg]	wing pitch angle [deg]	wing dihedral angle [deg]
65.6	33.0	12.1	6.4	70	0.4	2.65

Figure 4: Artists impression of satellite payload release from SpaceLiner 7 Orbiter's open payload bay in LEO

3 SPACELINER AS FULLY REUSABLE SATELLITE LAUNCHER

The SpaceLiner 7 passenger transport is an ideal technical basis for a two-stage fully reusable satellite launch vehicle. The passenger transport is reaching almost orbital speed at MECO during its reference mission (see section 4.6 on p. 14!). The baseline design of the orbital launcher remains unchanged to the passenger version (Figure 3) with a fully reusable booster and passenger stage arranged in parallel and the external shapes will be very similar. The booster should be almost identical to the design described in section 4.2. This approach intends enabling dramatic savings on development cost and moreover by manufacturing the vehicles on the same production line, also significantly lower hardware cost than would result for a dedicated new lay-out.

3.1 Design of Reusable Orbiter Stage

The passenger stage needs to be redesigned for its secondary role as an unmanned satellite launcher. The passenger cabin (see section 4.4.3 below!) is no longer needed and is to be replaced by a large internal payload bay.

Key geometrical constraints and requirements are set that the SpaceLiner 7 passenger stage's outer mold line and aerodynamic configuration including all flaps should be kept unchanged. The internal arrangement of the vehicle could be adapted; however, maximum commonality of internal components (e.g. structure, tanks, gear position, propulsion and feed system) to the passenger version is preferred because of the already mentioned cost reflections. Further, the payload bay should provide sufficient volume for the accommodation of a large satellite and its orbital transfer stage.

In order to fulfil the payload volume requirement, the payload bay has been moved to a location aftward of the now eliminated cabin (shown in Figure 3) benefiting of the larger fuselage diameter at this vehicle station. The LOX-tank is instead moved forward into the nose area with new, amplified conical tank geometry. An iterative sizing analysis revealed that the major constraint of the orbiter stage is the available length of the internal payload bay.

The stage's propellant loading has been reduced by 24 Mg to 190 Mg with a smaller LOX-tank to allow for a payload bay length of 12.1 m and at least 4.75 m diameter. These dimensions are close to the Space Shuttle (18.3 m x 5.18 m x 3.96 m) and should accommodate even super-heavy GTO satellites of more than 8 m in length and their respective storable upper stage (Figure 5). Large doors open on the upper side to enable easy and fast release of the satellite payload in orbit as illustrated in Figure 4. A movable and rotatable mounting mechanism for the payload similar to the Shuttle's support systems [48] is installed in the bay. The LH2-tank, the landing gear positions, as well as the full aft section are identical to the passenger variant.

The orbiter stage mass has been estimated based on the SpaceLiner 7-3 passenger stage budget (see Table 4 on p. 13). Adaptations include the complete removal of all

cabin related masses. Instead a mass provision for the payload bay and its mechanisms including doors, the mounting structure, and also a radiator system for on-orbit heat-control is added. The resulting orbiter dry mass is about 102 Mg and the budget is listed in Table 6.
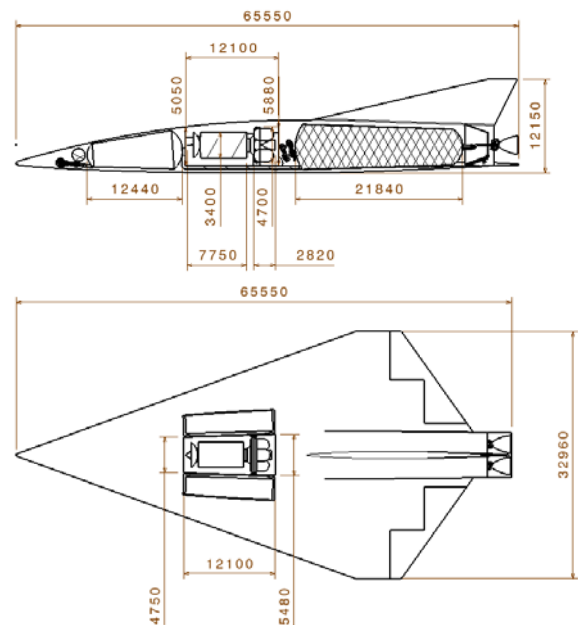

Figure 5: Sketch of SpaceLiner 7 as orbital space transportation with internal cargo bay for satellites

Successful accommodation of the payload inside the given SpaceLiner 7 geometry is for itself not sufficient to prove the technical feasibility of the concept as reusable TSTO launcher. Without the heavy passenger compartment and with an empty payload bay during atmospheric reentry, the CoG position is moving backward by 4 to 5 m (up to 7.5%) compared to the reference passenger transport. This significant shift raises the question of aerodynamic trimability and hence flyability of the orbiter stage. The aerodynamic trimming with the existing trailing edge flaps and the bodyflap has been preliminarily checked in numerical simulation under hypersonic flow conditions and is found feasible within the constraints of the present lay-out. This promising outcome is a result of the robust SpaceLiner design philosophy which is also taking into account off-nominal abort flights. The calculated maximum L/D is reduced approximately 15% by the significant flap deflections compared to the L/D achievable for the nominal passenger mission with almost no deflection. Pre-trimmed aerodynamic data sets have been generated and were used for reentry trajectory simulations of the orbiter.

3.2 Reference GTO satellite mission

Launch of the SpaceLiner 7 TSTO has been simulated from the Kourou space center into a low 30 km × 250 km transfer orbit. Actually, this trajectory allows at least for the GTO mission that the orbiter stage becomes a once-around-Earth-vehicle capable of reaching its own launch site after a single circle around the planet. As a consequence, the achievable payload mass increases and overall complexity is reduced; e.g. an active deorbiting is not needed. Trajectory optimizations show that the orbiter is able to deliver internally more than 26150 kg of separable payload to the very low and unstable orbit.

Subsequently, an orbital transfer is necessary from LEO to GTO. Reusable space tugs are under discussion and especially for the SpaceLiner with its potentially increased market volume due to significantly lower transportation cost (see section 5.3!) similar transfer stages for multiple uses could be an interesting option of the future. Such networks using fuel depots in space have already been investigated in the 1980s [49] and these papers could serve as an inspiration for future research. However, the recent SpaceLiner 7 TSTO investigations focus on more conventional transfer- or upper stages using high-thrust chemical propulsion. Several options exist from the Space Shuttle experience [48, 50], however, not all of them had been realized as an operational system.

A generic storable propellant upper stage has been selected for payload transfer from 30 km × 250 km to the 250 km × 35786 km GTO. The main reason for this choice is the restricted volume inside the payload bay which does not allow accommodating both the larger size cryogenic fuel stage and the also probably longer satellite related to a heavier payload enabled by better performing LOX-LH2 propulsion. A second, less important reason is the expectation of a more complicated operation of cryogenic tanks inside a cargo bay. These issues have already been investigated during development of the Centaur G/G' in the early 1980s and the principal feasibility had been demonstrated at high TRL [48]. Nevertheless, the Centaur G was cancelled after the Challenger accident due to safety considerations of the manned system and overall re-orientation of the Space Shuttle operations.

The duration of the ballistic phase available for upper stage and payload release starting after Orbiter MECO up to stage ignition in a safe distance is approximately 1600 s. The maneuvers can occur in a favorable position with ground visibility from the Malindi station. The optimum upper stage propellant loading (combination not yet selected but I_{sp} set to realistic 324 s) is slightly above 16 tons which permits a separated satellite mass in GTO of 8250 kg.

Return of the two reusable stages to the launch site is to be assured for any feasible option. The separation Mach number of the booster stage is approximately 12.5 which is already too high for any powered fly-back with acceptable amount of on-board fuel. A down-range landing site is not available in the Atlantic Ocean. Therefore, the patented in-air-capturing method [16, 17] should be used. The empty stage is to be captured during subsonic descent and subsequently towed back by an airplane and finally released for an autonomous gliding landing on a runway. Simulations of the SpaceLiner booster's reentry show that sufficient time for the in-air-capturing maneuver is available.

The SpaceLiner Orbiter reentry has been simulated with an entry interface speed of approximately 7.37 km/s. Reaching its once-around destination CSG in Kourou is without problem for the orbiter due to its still very good hypersonic L/D well above 2. The vehicle crosses Central America at high altitude and turns to the South over the Caribbean Sea (Figure 6). Almost no sonic boom should be audible on ground. The maximum heatloads remain slightly lower than for the reference

passenger concept because of a different AoA-profile and lower vehicle mass. The preliminary assumption of a common TPS with the passenger stage is confirmed.

Figure 6: SpaceLiner 7 Orbiter final phase of reentry ground track

3.3 Alternate and high performance missions

The SpaceLiner 7 two-stage fully reusable satellite launch vehicle should serve different types of missions. Those to lower energetic orbits could be directly reached without the need of an additional transfer stage reducing the expendable parts to a minimum. The ISS resupply mission has been investigated as the first such example of a typical LEO application.

The LEO-launch of the SpaceLiner 7 TSTO has been simulated once more from the Kourou space center into an initial 70 km × 410 km transfer orbit with inclination of 51.6°. Separation of the booster stage occurs at slightly higher velocity and almost the same altitude as for the GTO-mission. The orbiter's circularization burn is preliminarily assumed to be executed by re-ignition of the main propulsion system. Overall propellant consumption is not negligible and the estimated inside-bay payload performance is around 12.4 Mg. Any maneuvering propellants for RCS and for de-orbit are not yet considered. Thus, the actually delivered payload to the ISS is probably further reduced. Despite the relatively large lift-off mass of the SpaceLiner TSTO configuration, the cargo performance is not better than one achievable for medium size launchers. This sobering outcome is resulting from the relatively large portion of orbiter dry mass on total circularized mass. De-orbiting and reentry of the Orbiter has been simulated with an approach from the South Pacific, crossing Central America similar to the low-inclination return and finally looming its launch site from the Atlantic. The overall feasibility of the LEO-mission is confirmed.

The growth potential of the SpaceLiner TSTO to transport very large and heavy payloads for high performance missions is to be further assessed. An interesting option is the external mounting of a large upper compartment with integrated high performance (e.g. LOX-LH2) upper stage. This allows overcoming the volume restrictions of the internal cargo bay and making even better use of the actually high lift capability of the configuration. On the downside, the reusable

orbiter stage would require additional structural changes to the passenger stage and a large external fairing will be necessary. More detailed investigations of this option are part of future work on the SpaceLiner.

4   STATUS OF SPACELINER 7 PASSENGER CONFIGURATION

Since the last IAC2013-overview paper on the Space-Liner [7] significant technical progress related to the overall launch configuration as well as to both stages, the reusable booster and the passenger stage, has been achieved. The arrangement of the two vehicles at lift-off shown in Figure 3 is the current baseline, however, still subject to trade-offs and optimization and hence might be changed in the future.

4.1   Mission Definition

The ambitious, originally west-bound, Australia – Europe mission has been used as the reference case since the beginning of the SpaceLiner investigations. This flight distance should be served for 50 passengers on a daily basis in each direction. Several other, shorter intercontinental missions exist, which potentially generate a larger market demand. For this reason a SpaceLiner configuration derivative has been studied, which could transport up to 100 passengers [23]. In order to keep the number of different stage configurations at the lowest possible level, the potentially interesting flight destinations have been divided into three classes:

- Class 1: Reference mission (up to 17000 km) Australia – Europe with 50 passengers orbiter and large reference booster
- Class 2: Mission (up to 12500 km) with increased 100 passengers orbiter and large reference booster
- Class 3: Mission (up to 9200 km) e.g. Trans-Pacific with increased 100 passengers orbiter and reduced size booster

These three mission classes could be flexibly served by a suitable combination of four different vehicles (however with a lot of commonality in subcomponents like engines): 50 and 100 passenger orbiter stage and large and shortened booster.

4.2   Definition of reusable booster stage

The current SpaceLiner 7 booster geometry is relatively conventional with two large integral tanks with separate bulkheads for LOX and LH2 which resembles the Space Shuttle External tank lay-out. The major additions to the ET are an ogive nose for aerodynamic reasons and for housing subsystems, the propulsion system, and the wing structure with landing gear. The overall size of the booster is reaching significant dimensions of more than 80 m in length, if the ambitious reference mission is to be served. The current configuration of the booster has been defined based on extensive analyses of the propellant crossfeed system, pre-design of major structural parts like tanks, intertank and the thrust frame. Further, the size of the body flap and the geometry of the large wing were optimized. Major geometrical data of this configuration 7-3 are listed in Table 1.

The booster wing (and winglet) airfoils have been adapted from the previous version 7-2. The original 4-digit NACA wing airfoils have been altered to modified NPL-EC/ECH cut at trailing edge thickness of 75 mm [36]. The maximum thickness position on the chord line is moved backwards which is beneficial for drag reduction in the supersonic and hypersonic flow (thus improved L/D) and at the same time allows for larger frame heights in those regions where the largest amount of the aerodynamic lift forces are introduced. The wing modifications also resulted in a constant trailing edge sweep.

The 7-3 configuration of the booster not only includes an improved wing but also a considerably updated mechanical architecture. Overall propellant loading is reduced by 13.5 tons compared to the previous 7-2 due to volumetric constraints. The integral tanks have been positioned slightly upward of the centerline which allows attachment of TPS with increased thickness on the lower side of the vehicle without impacting the outer mold line. The bodyflap length is reduced with the more compact arrangement of the aft section and total stage length is slightly shortened (see Table 1 and compare to [7]). The huge winglets remain in their original 7-2-position at the wing tips.
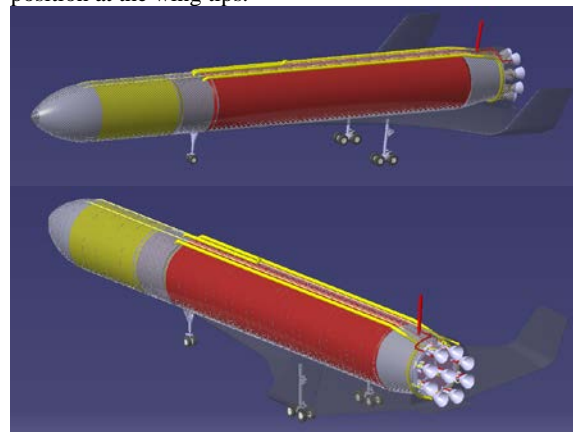

Figure 7: CAD-model of SpaceLiner 7-3 booster with semi-transparent outer surface showing internal arrangement of tanks and propellant feed- and pressurization-lines

Both tanks with an external structural diameter of 8.5 m carry all major loads and interface thrust to the passenger stage is going through the intertank right in front of the very large LH2 tank with a total internal volume of 2577 m^3. Engine thrust and the ground support loads at the launch pad are directed through the conical thrust frame shown in Figure 8 which is connected to the aft-Y-ring of the hydrogen tank.
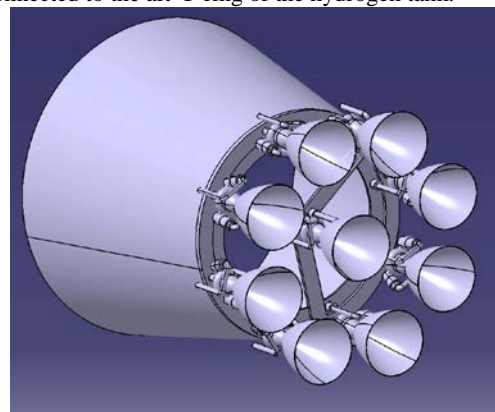

Figure 8: Thrust cone of SpaceLiner 7-3 booster with SLME attached

The main primary structure elements of the fuselage have been sized for dimensioning loads during powered ascent. The thrust frame is a conical structure strongly supported by frames and stringers and a center star segment. Both tanks are metallic aluminum-lithium structures, integrally stiffened by stringers and internally attached frames. The external loads, mainly those of the wing, are to be introduced in dedicated main frames of the hydrogen tank. The optimum connection between pressurized and unpressurized elements as well as cold cryogenic tanks and continuously warm construction is under study. A potentially interesting option could be a strut element design which has been investigated [31].

Meanwhile, also the booster structure has been modelled using the commercial ANSYS FE-element program (Figure 9). The ANSYS based structural analysis system HySAP developed at DLR-SART has been used, which iteratively adapts the structural dimensions in order to minimize the vehicle mass. Detailed tool descriptions can be found in [22]. Several design trade-offs are performed to identify the driving tendencies.
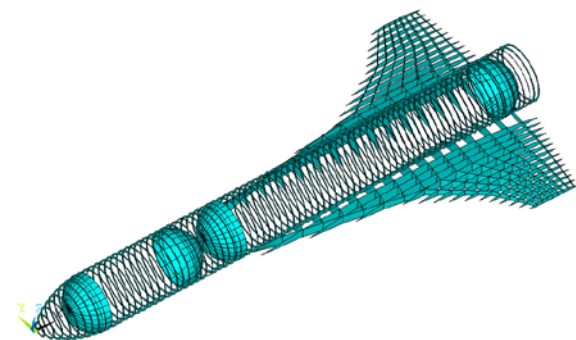

Figure 9: ANSYS FE-model of SpaceLiner 7-3 booster

The hydrostatic pressure loads acting on the large integral tanks are shown in Figure 10 at the launch pad conditions. The effect of the high-density liquid oxygen is clearly visible in the forward tank. A critical point is the connection between cold tanks at cryogenic temperatures and the warm wing structure. A conventional aircraft-like design would result in excessive wall thicknesses in the cylindrical section of the hydrogen tank with non-acceptable structural weight for the vehicle. Suitable decoupling of these major elements is systematically investigated. Strut-connections with flexible joints or non-integral tanks are technical options.

The booster separation Mach number of the passenger version's reference mission Australia to Europe is approximately 12.5, too high for any powered fly-back with acceptable amount of on-board fuel. A down-range landing site, if available at all, is not attractive for logistical reasons. Therefore, the patented in-air-capturing method [16, 17] as described previously in section 3.2 should be used.

ESA has recently been calculating the SpaceLiner 7-3 booster stage with Euler CFD (Figure 11). An unstructured grid with several million elements has been generated. Figure 12 shows the atmospheric entry condition of the booster stage after separation close to its maximum load condition. A critical shock-shock interaction at the outboard leading edge has been

revealed. Studies are ongoing on how to improve the aerodynamic design of future SpaceLiner booster variants.
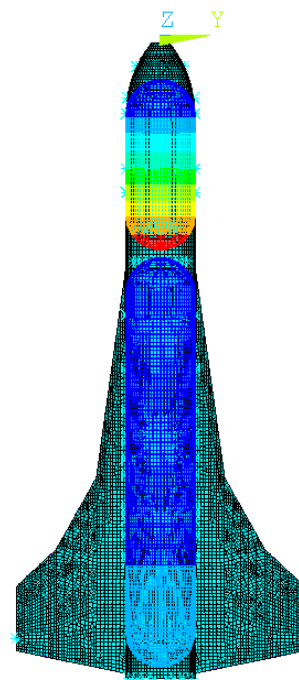

Figure 10: Hydrostatic pressure of launch pad load case in ANSYS FE-model of SpaceLiner 7-3 booster
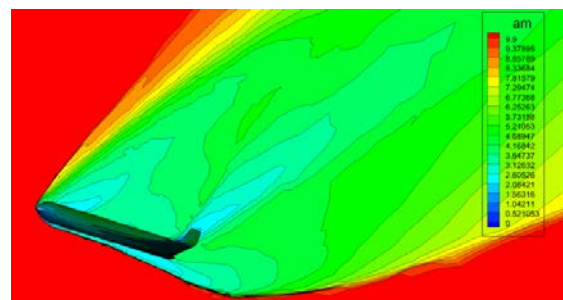

Figure 11: Mach contours of SpaceLiner 7-3 booster stage at M= 10, α= 35° from ESA-ESTEC Euler CFD- calculation

4.3 Definition of reusable passenger stage

The SpaceLiner7 is the first SpaceLiner configuration characterized by an aerodynamic shape arisen from a fully automated optimization process. The final result of the optimizations, a trade-off between the optima of the three trajectory points, showed considerable improvements in glide ratio and heat loads and pointed out the clear advantages of a single delta wing [10, 18]. Major geometry data of the SpaceLiner 7-3 passenger and orbiter stage are summarized in Table 2.

The SpaceLiner upper stage's wing airfoils were slightly adapted for the latest 7-3 configuration to keep a finite minimum thickness at the trailing edges. For operational considerations and for practical TPS integration a 50 mm constant thickness is chosen. At the wing's root a modified NACA 66-003.5 is implemented which is cut when the trailing edge thickness reaches 50 mm. At the wing tip a modified NACA 66-005.5 is cut at the same trailing edge thickness. Although the changes in trailing edge thickness are minor, having almost no impact on

calculated aerodynamic performances, the fuselage-wing interface surface geometry with complicated 3D-shapes needed a redesign. The local curvature is carefully designed to avoid any potential hot spot areas. The SpaceLiner passenger stage's shape is shown in Figure 12.

Safe controllability of the vehicle in all flight conditions has to be assured including during abort cases. To define the wing flaps of the SpaceLiner, knowledge on the most extreme flight maneuvers is needed. This has been assumed to be an abort scenario starting at the time of booster separation with the passenger stage's propulsion system inoperative. A re-entry trajectory for this case is simulated with the constraint of maximal allowed loads [12].

Figure 12: SpaceLiner 7-3 passenger stage

Aerodynamic data sets have been generated with different numerical tools and an aerodynamic database for preliminary engineering design work has been established [24, 36] for all four SpaceLiner flight configurations: The mated launch vehicle, the booster stage, the passenger stage, and the rescue capsule.

In the context of FAST20XX, ESA in parallel with ELECNOR Deimos contributed CFD analyses to support the maturity of the SpaceLiner concept by calculating the shape of the SpaceLiner 7-1 passenger stage [36, 38]. The analyses performed spanned the entire Mach range (0.4 – 18) and consisted of perfect gas Euler simulations. An unstructured grid with several million elements had been generated. Obtained coefficients have been used for establishing the aerodynamic data base. [24]

The appraisal of the results obtained included the acknowledgement of deficiencies in the Euler subsonic-transonic modelling, whilst the level of accuracy of the supersonic and hypersonic regime was deemed appropriate. After the end of FAST20XX, subsonic-/transonic modelling has been improved by mesh refinement resulting in better convergence behavior. Supersonic flow modelling is aiming at sonic boom prediction and efficiency increase for hypersonic modelling. All topics involve an improved control of the mesh refinement procedures. Surface streamlines confirm the presence of a strong vortex (Figure 13). Flowfield anisotropic refinement enhances the capture of such features.
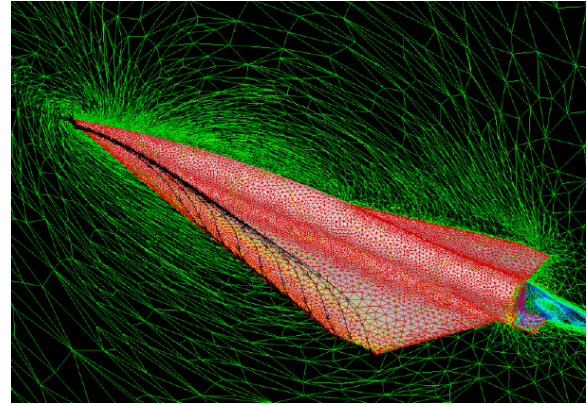

Figure 13: Strong vortex at SpaceLiner 7-3 passenger stage leading edge in subsonics obtained from ESA-ESTEC Euler CFD- calculation with anisotropic mesh refined flowfield

The SpaceLiner 7 passenger stage achieves without flap deflection an excellent hypersonic L/D of 3.5 up to M=14 assuming a fully turbulent boundary layer. The laminar-turbulent transition is assumed occurring at an altitude of 58 km which is around Mach 18 [36]. Impact of the finite trailing edge introduced in version 7-3 on aerodynamic efficiency is negligible.

The range of SpaceLiner altitudes in which rarefactions effects are expected is 75÷85 km. The inviscid conditions are based on the continuum aerodatabase [24], while the free molecular flow data have been computed by means of DSMC. In between bridging functions are applied which deliver the altitude dependence of longitudinal aerodynamic coefficients for the 7-1 configuration [30, 52].

Preliminary structural analyses have been conducted for the SpaceLiner passenger stage. The ANSYS based structural analysis system HySAP developed at DLR-SART has been used, which iteratively adapts the structural dimensions in order to minimize the vehicle mass [22]. The considered load cases include +2.5 g and -1.0 g normal acceleration maneuvers with flap deflection, rocket powered ascent where the orbiter is still attached to the booster, and landing loads at main gear touch-down.

The vehicle structure is an all honeycomb-sandwich design. Stringer stiffening has been investigated as well, but found to be not competitive due to the dominance of bi-axial stress systems in many panels. Several structural materials have been compared with each other. Thermal effects in terms of material property degradation and thermal stresses have been included in the analysis. Thereby, the wing and fuselage skins operate at elevated temperatures, which correspond to the structural temperature limits for which the particular TPS was designed. As a worst case scenario, the internal members (ribs, spars, frames) are assumed to remain at room temperature (293 K) resulting in temperature gradients which induce significant thermal stresses. This reflects the strong transient heating environment due to rapid heat flux build-up in the first part of the trajectory.

The cut-out in the fuselage necessary for passenger cabin integration are included in the vehicle's FE-model. Figure 14 exemplarily shows stress resultants in

x- and y-direction in the local panel coordinate systems for the landing load case. The vehicle deflections are exaggerated in the figure. Severe local loads in the cut-out area are obvious, which explains the structural mass increase. Stress resultant peaks can also be observed at the landing gear positions in the wing due to touch down load introduction.
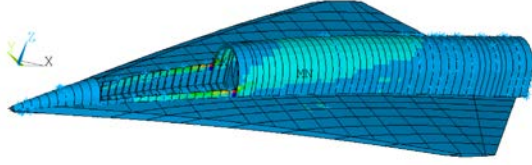

Figure 14: Stress resultants in x-direction in SpaceLiner 7-3 primary structure for landing load case

A structural mass comparison for different materials has been performed and preliminary results are presented in comparison to a statistically based estimation (red dashed line *STSM* in Figure 15). Structural skin temperature levels of 293 K, 400 K, 480 K, and 530 K have been investigated which reflects the temperature levels for which different TPS designs have been generated. Investigated materials include the standard aluminium alloys 2014 and 2024, aluminium-lithium 2195, titanium, beryllium based LockAlloy. The PETI-based high-temperature composite IM7/PETI-5 delivers the lightest solution. Note that this material's temperature range has been slightly extended to 520 K in the calculation beyond tested range. An interesting trend is observable for the titanium vehicle structure, which – in contrast to the results for the simplified model – does not anymore exhibit a structural mass increase with increasing temperature. This is presumably a result of load-redistributions due to the strong coupling between wing and fuselage.
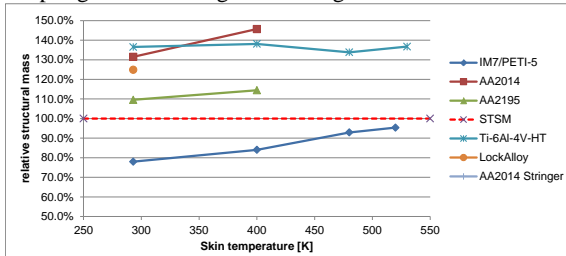

Figure 15: Relative structural masses (wing plus fuselage) for SpaceLiner7 passenger stage as function of skin temperature and material choice

These analyses do not yet consider the TPS integration which will result in a structural mass increase. Overall tendencies for the different materials are expected to remain similar and thus relative data as in Figure 15 are only slightly affected.

4.4 Subsystem definitions

4.4.1 Main propulsion system

Staged combustion cycle rocket engines with a moderate 16 MPa chamber pressure have been selected as the baseline propulsion system right at the beginning of the project [1]. Two types of staged combustion cycles (one full-flow and the other fuel-rich) have been considered for the SLME and traded by numerical cycle analyses [13]. A Full-Flow Staged Combustion Cycle with a fuel-rich preburner gas turbine driving the LH2-pump and an oxidizer-rich preburner gas turbine driving the LOX-pump is a preferred design solution for the SpaceLiner. This approach should allow avoiding the complexity and cost of additional inert gases like Helium for sealing.

The expansion ratios of the booster and passenger stage/orbiter engines are adapted to their respective optimums; while the mass flow, turbo-machinery, and combustion chamber are assumed to remain identical in the baseline configuration.

The SpaceLiner 7 has the requirement of vacuum thrust up to 2350 kN and sea-level thrust of 2100 kN for the booster engine and 2400 kN, 2000 kN respectively for the passenger stage. All these values are given at a mixture ratio of 6.5 with a nominal operational MR-range requirement from 6.5 to 5.5.

The SpaceLiner's ascent reference mission requirements define engine cycle times per flight [33]:
- Nominal operation time of Booster engine: 245 s with 122 s @ MR=6.5 and 122 s @ MR=5.5 or earlier cut-off

- Nominal operation time of Passenger Stage engine: 463 s with 336 s @ MR=6.5 and 127 s @ MR=5.5

The average engine life-time should be 25 missions. Table 3 gives an overview about major SLME engine operation data for the nominal MR-range as obtained by cycle analyses.

Table 3: SpaceLiner Main Engine (SLME) technical data [33]

	Booster			Passenger Stage		
Mixture ratio [-]	5.5	6.0	6.5	5.5	6.0	6.5
Chamber pressure [MPa]	15.1	16.0	16.9	15.1	16.0	16.9
Fuel-rich Preburner pressure [MPa]	29.4	30.0	30.8	29.5	30.2	31.0
Oxidizer-rich Preburner pressure [MPa]	29.1	29.7	30.5	29.2	29.9	30.7
Fuel-rich Preburner TET [K]	732	735	738	720	722	724
Oxidizer-rich Preburner TET [K]	773	775	778	772	774	777
Mass flow per engine [kg/s]	481	517	555	481	518	555
Expansion ratio [-]	33	33	33	59	59	59
Specific impulse in vacuum [s]	439	437	435	451	449	448
Specific impulse at sea level [s]	387	389	390	357	363	367
Thrust in vacuum per engine [kN]	2061	2206	2356	2116	2268	2425
Thrust at sea level per engine [kN]	1817	1961	2111	1678	1830	1986

An Integrated Power Head (Pre-burner + Turbine + Impeller pump) as used on the SSME is the preferred design solution for the SLME. The reduced length of high pressure hot gas lines should enable significant mass saving and a compact and clean lay-out. The size of the SLME in the smaller booster configuration is a maximum diameter of 1800 mm and overall length of 2981 mm. The larger passenger stage SLME has a maximum diameter of 2370 mm and overall length of 3893 mm. A size comparison of the two variants and overall arrangement of the engine components is visible in Figure 16. All engines have a 2D TVC (thrust vector control) capability with gimbal mechanism which should be electro-mechanically actuated.

The engine masses are estimated at 3375 kg with the large nozzle for the passenger stage and at 3096 kg for the booster stage. These values are equivalent to vacuum T/W at MR=6.0 of 68.5 and 72.6.
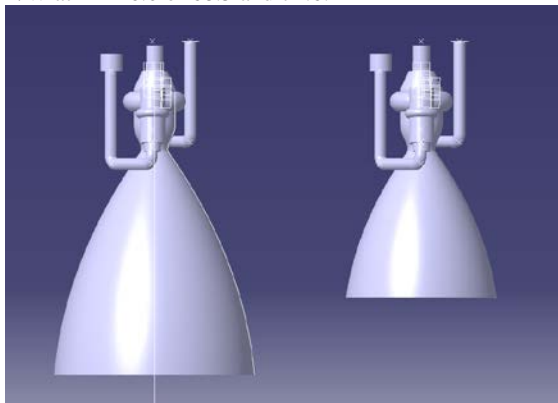

Figure 16: Size comparison of simplified CAD-shapes of SLME with ε=59 (left) and ε=33 (right)

4.4.2 Propellant feed and tank pressurization system

All main engines of the configuration should work from lift-off until MECO. A propellant crossfeed from the booster to the passenger stage is foreseen up to separation to reduce the latter's overall size. No crossfeed system for a configuration like the SpaceLiner has ever been built and therefore numerical investigations have been performed in the FP7-project CHATT with steady-state flow-simulation along the full powered trajectory and transient simulation of critical phases like engine cut-off or valve closing. In particular, the process of booster separation is a dimensioning factor for the design of the crossfeed system due to the switch of the propellant supply from the booster to the orbiter tanks. [33, 34]

The propellant feed- and pressurization system is preliminarily designed using the DLR-tool pmp. The SpaceLiner 7-3 arrangement of feed- and pressurization lines with the tanks of both stages in the mated configuration is shown in Figure 17. All other structural elements than tanks and lines are excluded from the picture for clarity.

The steady-state simulation results from PMP for the feedline pressure during the ascent on LOX and LH2-side are visible in Figure 18. A tank to tank crossfeed from the booster LOX-tank, positioned more than 25 m

forward, generates significant hydrostatic pressure, indirectly forcing ullage pressure in the second stage tank up to more than 6 bar. Further downstream in the feedline pressure values can exceed 15 bar. The effects of throttling and staging are clearly visible in Figure 18. NPSP at the LOX-turbopump entry is generous and might allow for reducing the ullage pressure close to MECO. On the LH2-side NPSP is close to its lower limit. As a consequence of additional feedline valves in the iterated design and hence pressure losses the ullage pressure in the 7-3 booster LH2 tank had been selected at 340 kPa.
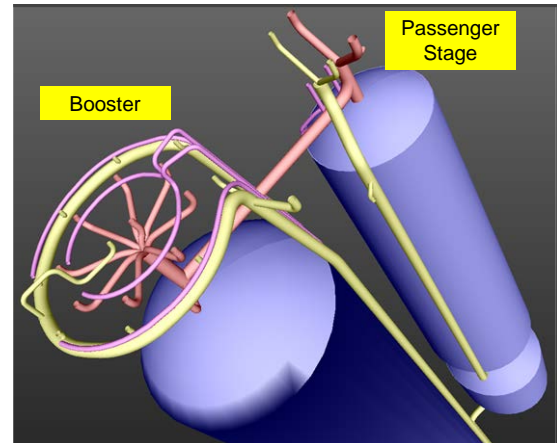

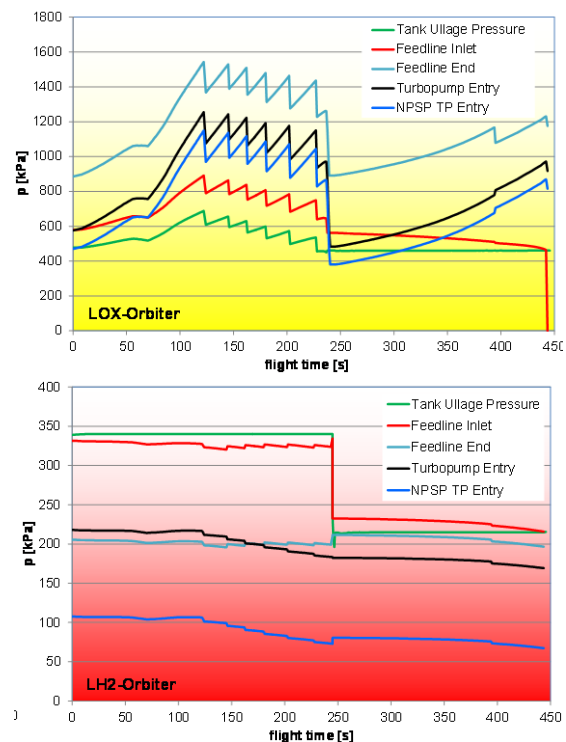**Figure 17: Feedline architecture of the SpaceLiner 7-3 mated configuration**

Figure 18: Pressure at certain stations of the SpaceLiner 7-3 passenger stage propellant system, crossfeed is active until stage separation at 244.9s

Beyond the steady state simulation also the transient behavior in the propellant feed-system has been analyzed for critical conditions along the powered flight and its preferred actuation sequence has been preliminarily defined. [34]

The LOX-tanks are pressurized by gaseous oxygen and the hydrogen tanks with gaseous hydrogen. This approach is selected in order to avoid any excessive use of expensive and rare helium. The fuel tank pressurization gas is supplied from the SLME after leaving the regenerative circuit while the oxidizer tank pressurization gas is bled from the oxidizer line behind the OTP discharge and then heated-up in a heat exchanger.

Tank pressures are selected that the minimum NPSP requirements in all feedline segments are respected along the full mission; especially those at the engine entry. The booster LOX tank pressure has been further reduced (compared with [33, 34]) to just 1 bar differential pressure to the external conditions because its forward position is always generating a lot of hydrostatic pressure down the line which is beneficial for good NPSP. Due to this fortunate situation, the required oxygen gas at booster stage MECO is considerably below 3000 kg. The hydrogen gas mass inside the very large 2577 m^3 LH2-tank is currently slightly below 3400 kg due to the increase in ullage pressure requirement; however still acceptable because of hydrogen's low molecular mass.

For the LOX system, the tank-to-tank crossfeed approach is definitely recommended, because the LOX-transport is supported by the hydraulic head of the booster tank's forward position. Almost no transient critical issues have been found. If the line-to-line architecture will be used for LH2, the particular focus has to be on the valve timing and control. For the latest SpaceLiner 7-3 configuration line-to-line crossfeed for LH2 and tank-to-tank crossfeed for the LOX system is the baseline choice.

4.4.3 Cabin and rescue system

The passenger cabin of the SpaceLiner has a double role. Providing first a comfortable pressurized travel compartment which allows for horizontal entrance of the passengers, the cabin in its second role serves as a reliable rescue system in case of catastrophic events. Thus, the primary requirements of the cabin are the possibility of being firmly attached late in the launch preparation process and fast and safely separated in case of an emergency.

The capsule is able to fly autonomously back to Earth's surface in all separation cases. The abort trajectories are primarily influenced by the mass of the capsule and the aerodynamic performance with the most important subsystems being the separation motors, the thermal protection system (TPS), and the structure. These three subsystems have been investigated and sized for function, performance, and mass.

Four critical flight points have been chosen to simulate the abort trajectory to demonstrate the SpaceLiner7 capsule is able to fly safely back to Earth during any perceived abort scenario:
- Launch pad
- Booster separation
- Highest altitude of the SpaceLiner7 orbiter
- Main engine cut-off (MECO)

Results of the trajectory simulations are presented in [20].

The separation motors are designed to separate the capsule from the orbiter, without exceeding recommended maximum acceleration limits. The SRM must provide a high acceleration in a very short period of time. Due to severe geometry constraints, it has been decided to utilize a five motor configuration. Each motor has an approximate thrust of 800 kN and a burn time of almost 2 s while the total mass of the propellant for all five motors adds up to 2.6 t [20].

The capsule can be subdivided in a pressurized cabin of conical shape and an outer aerodynamic shell formed by the Thermal Protection System (TPS) and which provides space for housing several non-pressurized subsystems as shown in Figure 19.

The TPS of the SpaceLiner7 capsule is required to withstand several different heat load conditions driven by the different nominal and abort cases it encounters. In the course of this investigation, it has to be distinguished which areas of the capsule (i.e. the nose area, upper half or lower half) are considered. During nominal flight, the capsule is considered part of the orbiter. This means that the lower half and nose are protected by the orbiter structure and its TPS. They are therefore, not subjected to the external heat load until the capsule is separated in an abort case. In contrast, the capsule's upper half is part of the orbiter's outer shell and so is heated up during nominal flight.
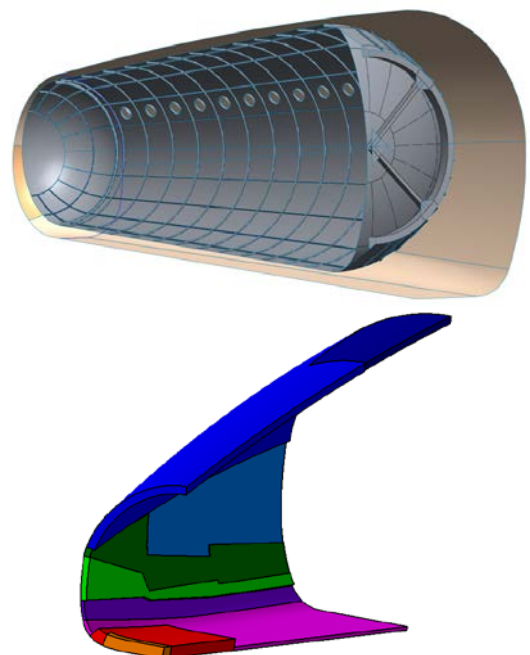

Figure 19: Integration of pressurized passenger cabin inside aerodynamic capsule shell (top) and TPS thickness distribution (bottom)

A potential internal cabin pre-design and the necessary life-support system mostly driven by medical requirements have been studied. Absolutely essential is a small shell-like protection around each seat which would automatically close in case of sudden cabin pressure drop. Light-weight inflatable solutions are most attractive.

Overall length of the capsule without separation motors is 15.6 m and its maximum external height is 5.6 m. The estimated masses are about 26.4 tons for the dry capsule

(reference SpaceLiner 7-3), about 7600 kg for the passengers, crew and luggage, and 3400 kg for all propellants of separation motor, retro-rockets and RCS.

A fundamental requirement for the design of the rescue capsule is its integration in the front section of the passenger stage. The capsule should be separated as easily and quickly as possible. Therefore, it cannot be an integral part of the fuselage structure, however, its upper aft section is conformal with the SpaceLiner's fuselage while the lower side is fully protected by the fuselage bottom structure. The current requirement of capsule separation being feasible at any flight condition and attitude is highly challenging from a technical point of view. Analyses revealed some critical issues to be addressed in order to improve the safe functionality of the cabin rescue system. Alternative capsule integration concepts have been proposed and technically analyzed [43]. However, each of the explored design options is linked to severe challenges and drawbacks. Further investigations are necessary to find a promising and reliable system.

A preliminary design for the capsules main subsystems has recently been performed. This includes the parachute system for transonic stabilization and landing, the electro-mechanical actuators and their batteries, and the reaction control system (RCS). The preferred RCS choice is characterized by 2 clusters of thrusters located in the rear part of the passengers' cabin escape capsule. Each cluster provides a thrust of 3 kN along each of the double axis for a total delivered thrust of 12 kN. This architecture allows performing quick maneuvers and is characterized by sufficient volume available also for implementing larger thrusters. A non-toxic bi-propellant combination is desirable for passengers' safety and ease of handling and this precludes the use of any variant of hydrazine. The combination H_2O_2/kerosene is chosen because of its storability: for months or even years, potential hypergolic ignition by additives, and its non-toxic behavior. From an operational standpoint the storability is especially attractive due to the fact that once the tanks are filled, multiple flights can be performed without needing to empty or refuel them. The RCS tank architecture is characterized by a shared system of tanks connected close together, ensuring redundancy at very low mass penalty.

A highly innovative investigation on design options to improve the capsules flight performance after separation has been performed in the European Commission funded FP7-project HYPMOCES aiming to investigate and develop the technologies in the area of control, structures, aerothermodynamics, mission and system aspects required to enable the use of morphing structures [37, 42]. Inflatable as well as rigid deployable wing options have been studied. The baseline design is inflating its lower section after separation in order to increase the flat lower surface for increased lift in hypersonic flight enabling better gliding range. Note in Figure 20 the double instead of previously single bodyflap derived of IXV and the deployable control fins which are now baseline of all capsule variants. Cutting edge research has been accomplished in the fields of aerothermodynamics (Figure 20) and suitable flexibly foldable materials which can also withstand the thermal loads of high-speed atmospheric reentry. The principal

feasibility and flyability of the morphing structure concept has been demonstrated by numerical simulations.
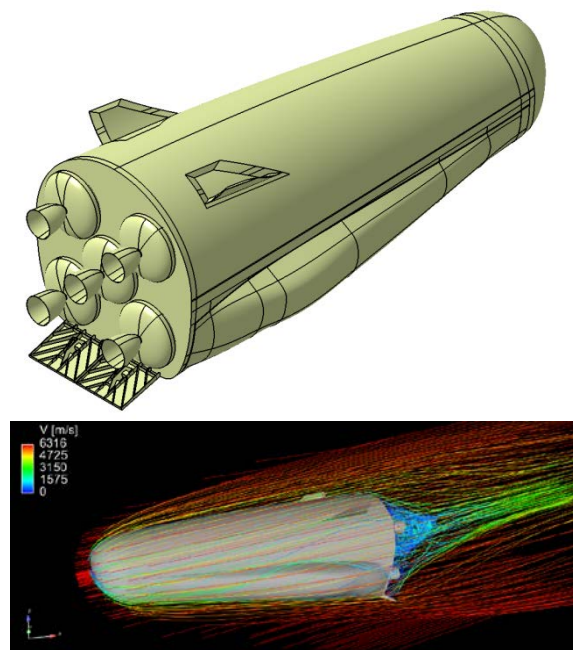

Figure 20: SpaceLiner capsule option with inflatable morphing lower section and deployable fins and CFD-simulation of ONERA

The additional mass of the morphing structure and of related sub systems is not negligible and should be justified by significantly improved passenger safety.

4.4.4 Thermal protection and active cooling subsystem

The preliminary sizing of the SpaceLiner7's Thermal Protection System (TPS) has been carried out for several different heat loads according to nominal flight and also for different abort cases. To be able to determine the heat loads for a full vehicle surface along different trajectories, fast engineering methods have to be used [2]. A fully turbulent flow along the flight path has been assumed for the TPS dimensioning as a conservative assumption. The heat fluxes at each mesh point are calculated at numerous selected flight conditions with Mach number, altitude, and angle of attack known from trajectory simulations. By this approach a heat flux profile over time is obtained for the complete vehicle surface.

Due to the requirement of reusability, only non-ablative materials are suitable on the SpaceLiner's surface. According to the different maximum temperatures occurring at the different surface areas, different materials are chosen. Most important are **AFRSI** (Advanced Flexible Reusable Surface Insulation) and multi-layer **CMC**-Alumina insulation, a composite of a ceramic matrix composite and fibres [25]. The TPS of SpaceLiner 7-3 has been significantly updated compared to the previous version 7-2 [7]. Besides major mass savings an alternative TPS on the vehicle's upper surface has been considered, consisting of two layers of a metallic skin under development by *Dutch Space (Airbus)*. The TPS tile consists of mainly two layers, a metallic skin (Haynes 230) and thermal insulation (IFI). Haynes 230 is used for all "hot" metallic parts of the

TPS and in particular for the skins of the TPS tiles which are directly exposed to the aerothermal heat flux. Although significantly heavier than thermal blankets (in comparison to the use of TABI, a metallic TPS would have an additional mass of approx. 1.4 t it should be operationally more robust [40]. Figure 21 shows different areas of maximum temperature on the passenger stage's fuselage which could be covered by the metallic surface TPS.
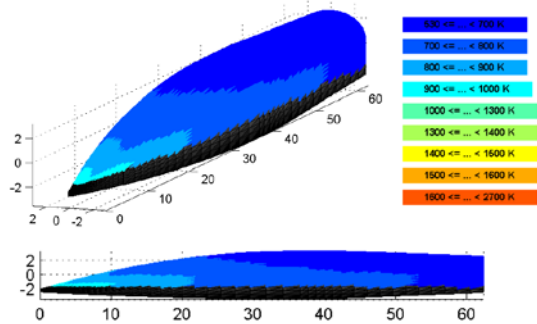

Figure 21: Overall maximum surface temperature areas (considering nominal and abort trajectories) on upper side of passenger stage

The maximum acceptable temperatures for the passive TPS is limited to approximately 1850 K to be compliant with the reusability requirement. The structure is set to be allowed to heat up to 530 K. This leads to a total (partially metallic) TPS mass on the passenger stage (without capsule and tank insulation) of approximately 17.8 tons (20.3 tons including system mass margin).

In a similar design procedure the TPS of the reusable booster stage has been defined, however, only for the nominal trajectory because no flight abort maneuvers were considered necessary. Large upper surface areas are to be covered by thermal blankets. The booster's TPS mass reaches approximately 16.2 tons (without cryogenic tank insulation) (18.5 tons including system mass margin) assuming 420 K maximum tolerable structural temperature.

The maximum acceptable temperature of any passive TPS on the SpaceLiner is 1850 K. In those areas (leading edge and nose) where the heatflux and temperatures exceed those values acceptable by CMC, transpiration cooling using liquid water is foreseen [2, 7, 8, 12]. In FAST20XX this innovative method has been experimentally tested in DLR's arc heated facility in Cologne using subscale probes of different porous ceramic materials [27]. A water storage tank system, a feedline manifold including control and check-valves and some bypass and redundancy lines are sized for accommodation inside the SpaceLiner volume.

Besides the overall promising results also some technical challenges of the active transpiration cooling system have been detected in the FAST20XX-investigations. Precise controllability of the water flow through the porous ceramic media has been found difficult [40]. The experiments sometimes were running into over or under supply of water which could not be recovered within the same experimental run. A more sophisticated supply system would be needed in a flight vehicle. Another concern is the fact that the gas flow from the coolant might trigger early boundary-layer transition. As a consequence, some areas of the passive TPS might need to be reinforced. Therefore, the active transpiration cooling of leading edges and nose is still the reference design option but could once be replaced by other means of active cooling [39, 40].

4.5 System masses
Based on available subsystem sizing and empirical mass estimation relationships, the passenger stage mass is derived as listed in Table 5. The total fluid and propellant mass includes all ascent, residual, and RCS propellants and the water needed for the active leading edge cooling. The stages' MECO mass is approximately 151.1 Mg. The SpaceLiner 7-3's GLOW reaches about 1850 Mg (Table 7) for the reference mission Australia – Europe while the TSTO is at 1820 Mg (Table 8) still below that of the Space Shuttle STS of more than 2000 Mg and therefore technically within reach.

Table 4: Mass data of SpaceLiner 7-3 booster stage

Structure [Mg]	Propulsion [Mg]	Subsystem [Mg]	TPS [Mg]	Total dry [Mg]	Total propellant loading [Mg]	GLOW [Mg]
123.6	36.9	19	19.1	198.6	1285	1484

Table 5: Mass data of SpaceLiner 7-3 passenger stage

Structure [Mg]	Propulsion [Mg]	Subsystems including cabin [Mg]	TPS [Mg]	Total dry [Mg]	Total fluid & propellant loading [Mg]	GLOW incl. passengers & payload [Mg]
55.3	9.7	43.5	22.3	129	232.1	366

Table 6: Mass data of SpaceLiner 7 Orbiter stage (GTO mission)

Structure [Mg]	Propulsion [Mg]	Subsystems [Mg]	TPS [Mg]	Total dry [Mg]	Total fluid & propellant loading [Mg]	GLOW incl. kick-stage & payload [Mg]
60.1	9.9	9.8	22.3	102	207	309.1

Table 7: Mass data of SpaceLiner 7-3 passenger launch configuration

Total dry [Mg]	Total propellant loading [Mg]	GLOW incl. passengers & payload [Mg]
327.6	1515	1850.4

Table 8: Mass data of SpaceLiner 7-3 TSTO launch configuration

Total dry [Mg]	Total propellant loading [Mg]	GLOW incl. kick-stage & payload [Mg]
300.6	1480	1820

4.6 Feasible point-to-point trajectories under several constraints

Different trajectory options have been traded in the past mostly for the Australia – Europe reference mission for up to 50 passengers. These were following a standard launch vehicle vertical ascent with an initial azimuth in North-Eastern direction overflying the arctic sea before approaching Europe from the North-Eastern Atlantic. This trajectory had already been established as baseline for the SpaceLiner 4 using ASTOS optimizations [11]. The propulsive phase of approximately 8 minutes duration is directly followed by hypersonic gliding succeeded by landing approach after approximately an additional hour and 20 minutes of flight. Several other, shorter intercontinental missions exist which potentially generate a larger market demand. For this reason a SpaceLiner configuration derivative has been studied, which could transport up to 100 passengers [23].

Flight path as well as groundtrack constraints and demands for operationally interesting launch and landing sites influence the selection of practical reference trajectories. The launch and ascent noise as well as the sonic boom reaching ground are most critical for a viable SpaceLiner operation in the future. There-fore, operational scenarios of the SpaceLiner are established taking into account realistic launch- and landing sites as well as groundtracks which are acceptable with respect to sonic boom constraints overflying populated areas and fast accessibility to major business centers. Conventional existing airports located close to densely populated areas are not suitable for SpaceLiner operations. Three alternative launch and landing site concepts should fit for almost all potential locations [45, 31]. Systematic and extensive analyses on worldwide trajectory options beyond the reference mission have been started and a first set of results is now available.

The Europe – Australia and return route is still the baseline for other investigations. As a preliminary and currently non-binding assumption, the flight connection is assumed for two on-shore launch landing sites located in Queensland, Eastern Australia and in the German North-Sea-coastal region. Both locations have the advantage of the complete launch ascent and supersonic gliding approach capable of being performed over the sea while still being relatively close to each continent's major business centers. These are two key-requirements for successful future SpaceLiner operation.

The reference mission from Australia to Europe of the current SpaceLiner7-3 configuration is fully feasible, meeting all requirements imposed by the vehicle: dynamic pressure, acceleration and heat flux. The covered range is approximately 16000 km and the simulated flight time no more than 71 minutes to TAEM cylinder before final landing approach. The MECO

conditions reached at the end of the ascent flight is approximately 7.2 km/s in an altitude of 73.1 km and the flight path angle γ is close to 0°. The descent ground track of the nominal reference mission is shown in Figure 22 and the potential return flight ground track in Figure 23. Noise and sonic boom impact on inhabited areas is very low and actual proof of full public acceptability of the vehicle flying at very high altitude is under assessment.
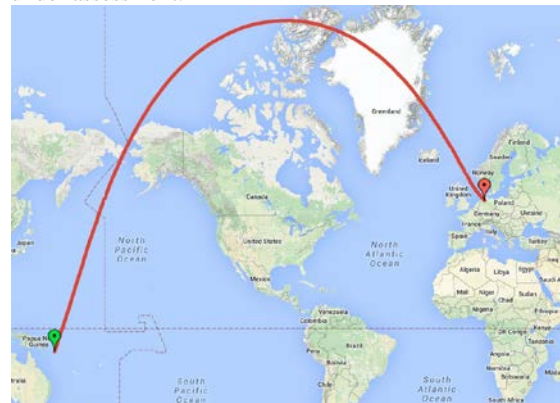

Figure 22: Simulated SpaceLiner 7-3 descent ground track nominal mission Australia to Europe
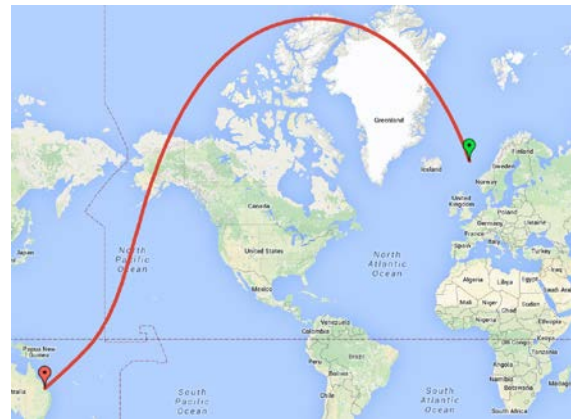

Figure 23: Simulated SpaceLiner 7-3 descent ground track nominal mission Europe to Australia

As a preliminary study, the comparison between nominal and off-nominal conditions for the trajectory Australia-Europe has enabled to better understand the influence of different parameters on the vehicle downrange. These results might be helpful to reduce some margins in the preliminary design of a future version of the SpaceLiner.

Three off-nominal cases have been simulated: Engine Isp degraded by 3 s under all conditions (equivalent to a c*-reduction of 29.4 m/s). In a conservative approach the assumption is that all engines are affected. Further, nominal ascent propellant mass in the booster stage has been reduced by 20 tons while increasing residuals and reserves by the same amount. The third off-nominal case is the impact of one engine inoperative: the entire ascent phase is simulated with only 8 booster engines, instead

of 9. Flight times are slightly increased and realized ground tracks are somewhat altered. However, in all investigated cases the mission success has been demonstrated even under significantly degraded off-nominal conditions.

The flight route from Australia to North-East America, previously never investigated for the SpaceLiner, has now been studied and is found more difficult and challenging to be achieved under similar constraints. Although it is possible to reach the East Coast of the United States, either approaching from the north or the south, the assumed potential launch sites for return trajectories were not suitable to complete the mission. The proposal for a new launch site on the west coast of Florida seems to be most promising for the North East America – Australia mission. However, this option might cause problems during the ascent phase over a highly traffic loaded area (Gulf of Mexico).

Regarding the shorter distance Europe to California mission using the SpaceLiner 100-passengers version, the simulated trajectories under consideration are preliminary. The chosen ascent trajectory for this case has a significantly different altitude profile than the previously investigated variants. The maximum reached altitude goes beyond 100 km whereas the final velocity is only slightly above 6 km/s due to the heavier upper stage and the shorter flight distance required. The analyses performed on the SL7-100 configuration show on the one hand that with the 100 PAX orbiter stage of SpaceLiner the route Europe – California (Figure 24) can be served despite of a flight with suboptimal aerodynamic performance. On the other hand it becomes obvious that the increased ballistic coefficient of the 100 PAX orbiter stage leads to higher velocities in denser atmosphere layers which increases the thermal load on the stage.

Figure 24: Simulated SpaceLiner 7-100 descent ground track nominal mission Europe to California

In order to reduce the working time for the determination of active controls (angle-of-attack and bank angle) during descent, the additional use of preliminary re-entry guidance has been proposed, developed and tested on many different trajectories and circumstances. The algorithm implemented in Scilab® allows accurately assessing the value of bank angle capable to cover the range determined by the great circle arc approximation, keeping the angle of attack fixed. The use of a model based on the drag acceleration appears to be efficient for the determination of the bank angle and simulation results indicate the effectiveness of the guidance with a comparison between drag acceleration resulting from 3DOF trajectory simulation and the reference value estimated by the Scilab® script. Moreover, the introduction of an intermediate waypoint in the route allows respecting in a better way the requirement of not to overfly highly populated areas.

All the results of the application of this guidance on entry trajectories so far examined show the potential of the algorithm but also its limitations. Additional work in the future will refine the method and should allow for fast trade-offs on different feasible flight routes under multiple constraints.

An alternative option is a trajectory with a few degrees of γ in the MECO point which would result in a ballistic arc duration of a couple of minutes for the SpaceLiner. The vehicle would travel during this phase more than 1000 km almost outside of the atmosphere at very low drag. However, in order to avoid excessive heatrates, an increased angle-of-attack is subsequently needed at lower altitude which has a strongly decelerating effect. A definitive answer on the best trajectory requires detailed system studies taking into account flight path optimization, adapted TPS-sizing, and reliable data on the friction drag in low atmospheric density. The Italian aeronautical research establishment CIRA's and University of Naples DSMC calculations of the SpaceLiner at high altitudes [30, 41, 52] are providing realistic drag coefficients under these conditions.

4.6.1 Ascent flight control of asymmetric SpaceLiner 7 launcher

Trajectory simulations of the SpaceLiner under nominal and off-nominal conditions as described above have usually been based on an idealized point-mass model. The unpowered gliding reentry of the passenger stage has been also assessed on its flying qualities [38]. Extensions to this model are necessary to investigate the attitude dynamics and related controllability issues of the asymmetric launcher configuration (compare Figure 1 and Figure 3). A 6 DOF model of the SpaceLiner 7-3 vehicle has been developed as a function of mission elapsed time based on the mass data of Table 7. This is especially mandatory for the dimensioning of the thrust vector control system (TVC).

The aerodynamic reference database of [24] has been extended by all aerodynamic moment coefficients and derivatives necessary for 6 DOF. These coefficients are estimated by simplified engineering assumptions mostly depending on empirical methods which is sufficient for the early feasibility analyses. Further, the mass model is extended by considering the mass distribution and moments of inertia at sub-systems level. The transient behavior of the vehicle's mass, inertia and center of gravity (CoG) is calculated along the ascent flight phase.

As typical for every rocket launch system and even reinforced by the propellant crossfeed from the booster to the passenger stage (see section 4.4.2), the CoG is subject to a major movement during mated ascent flight. Right before stage separation when the booster propellant tanks are almost drained, the CoG had moved

21.7 m backward and 3.4 m towards the attached upper stage.

The TVC tasks are to control the vehicle during ascent on its optimized flight path by means of adequate engines gimballing considering the variable position of the CoG as well as external perturbations generating aerodynamic moments. A logic is defined that for pitch control all engines are deflected simultaneously in vertical direction, while yaw control is provided by equivalent horizontal deflections. Roll control is executed during mated ascent by inducing an additional horizontal deflection of the passenger stage engines only. After stage separation roll control is realized by differential vertical deflections of these two engines.

Figure 25 displays for the reference Australia to Europe mission the necessary roll (ξ_{TVC}), pitch (η_{TVC}) and yaw (ζ_{TVC}) deflections for static trimming of the SpaceLiner 7-3 during the whole ascent phase. The sign convention is defined that a positive TVC command is also causing a positive moment along the respective vehicle axis. It has been assumed that all operating engines are controlled with the same orientation requiring maximum absolute deflections which remain always below 2.5° during nominal flight. This result is well within the limits for realistic TVC design. Furthermore, it can be noticed that the successive throttling of the booster engines after 150 s (starting at lowest outboard position) is effectively limiting the necessary pitch deflections of the TVC. On the other hand the yaw moment, which is induced by the asymmetric throttling of the engines, can easily be handled by slight yaw control.
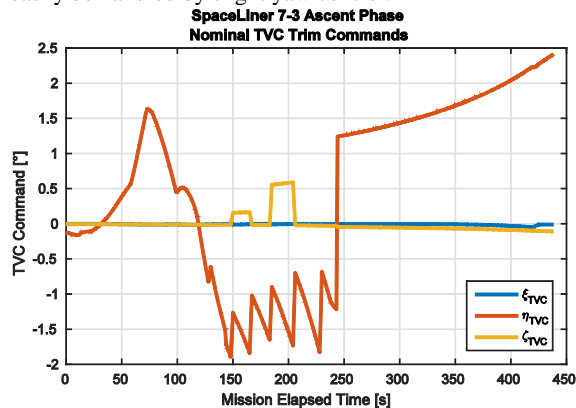

Figure 25: TVC deflection commands for static vehicle trimming during the nominal reference ascent trajectory

Up to now only the static trimming of the vehicle has been examined. However, dynamic analyses of the ascent flight as well as the evaluation of the stability and controllability are under current investigation.

4.7   ATM integration

Integration of the SpaceLiner into Air Traffic Management (ATM) is following a generalized approach. For efficiently integrating space vehicles into ATM, its implementation has to be as predictable as possible to allow for optimized planning and air traffic route optimization in preparation of a space vehicle flight. Situational awareness for all relevant stakeholders before, during and after the relevant flight phases is crucial to allow for timely reactions and sound decision making during nominal flight and in case of off-nominal events. An approach based on an information service solution has been proposed and further modified to also fit the interoperability requirements of the next generation ATM development programs SESAR and NextGen and achieving a harmonized European / U.S. concept [54][55].

For developing and evaluating the specific aspects of integrating the SpaceLiner operational concept into the designed Space and Air Traffic Management, an integration use case has been designed, utilizing the Traffic impact analysis framework and Space & ATM Operational (SATM) testbed at DLR in Braunschweig. The Australia – Europe mission trajectory again has been chosen as the reference case, with specific focus on the hypersonic gliding phase and its approach to the destination spaceport, which is assumed to be located in the northern coastal region of Germany (Figure 26).

Figure 26: SpaceLiner final approach trajectory for destination in northern Germany; showing also danger areas, restricted areas and temporary restricted areas within German airspace[1]

The final approach segment of the SpaceLiner is not yet modelled in detail. It is expected that a Terminal Area Energy Management (TAEM) maneuver will have to be added to get the SpaceLiner orbiter lined up with respect to the runway at the correct amount of energy. TAEM will require a cylindrical or cone-like area close to the landing site. The size of the TAEM cylinder will depend on its entry speed and can have a radius of up to 15 km if the vehicle is still in supersonic flight. A turn with supersonic speed would cause high sonic boom effects on ground in the area of operation, which means it should be avoided close to inhabited regions. The design of the final approach segment of the SpaceLiner trajectory will therefore be subject of further optimization. An iterative process is expected to be carried out as part of the ATM integration use case.

To represent the SpaceLiner within the SATM testbed, a simulation model for the Space Flight Simulator, using X-Plane, had to be developed. The Space Flight Simulator represents the space vehicle within the distributed simulation setup, which also includes an air traffic control simulator. It is able to act with human-in-the-loop as well as flying the space vehicle on a predefined trajectory. Using the PlaneMaker feature of X-Plane, a fuselage cross section modeling, wing geometry and airfoil characteristics, gear modeling, and a center of gravity alignment has been performed for the SpaceLiner. The flight characteristics and performance has been evaluated against the SpaceLiner aerodynamic reference database [24].

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[1] Airspace visualization using GoogleEarth and OpenAir-data from DAEC

Sufficient comparability has been achieved after selecting NACA 66-206 airfoil shapes with additional fine tuning using the airfoil-maker of X-Plane. The simulation model has been evaluated to provide a sufficiently realistic and comparable aerodynamic setup and flight performance and will be further used for the SpaceLiner use case simulations [56].

With the preparation of the Traffic Impact Analysis Framework and the SATM testbed in place, the case study for the SpaceLiner approach scenario will be carried out as a next step. The SpaceLiner use case will determine ways on how to integrate a hypersonic point-to-point intercontinental passenger transport into the air traffic system and deliver further requirements for the SpaceLiner flight performance as well as for its concept of operation.

5   COST ESTIMATION AND BUSINESS CASE ANALYSES

The SpaceLiner development and operations should be funded mostly by private investment. Forms of private public partnerships are potential options. In any case a reliable estimation of to-be-expected costs during development, production, and operations is already required early in the technical design process. Using this approach, a market oriented development can be performed. An extensive study at DLR has been published [44, 28] giving a detailed description from which important results are summarized here.

5.1   Cost estimation approach

In the early phase of development, a parametric cost estimation approach is most promising. The TransCost model [29] of cost engineering for space transportation systems has been used as the baseline tool. At least concerning the development cost fraction, the TransCost model seems to be well suited as it includes targeted reference data also on different RLV-projects from the past. [28]

Beyond that, an innovative *Amalgamation Approach* (AA) has been developed at DLR for the SpaceLiner cost estimation [44]. Many of the significant cost estimations, in particular for large scale complex projects like those undertaken within the space sector, rely on one main cost estimation source, model, tool or CEM. The AA definition hinges on a cost estimate, whether at a macro- (AA_{MAC}) or micro level (AA_{MIC}), being derived through a formalized cross-check with multiple other means, such as through a different CEM or tool and model [44]. A minimum of three cost estimate results are required and contrasted amongst each other. In this way, multiple points can be used by the estimator as reference, with strategic analyses then employed to justify selection of a most representative cost estimate or range. Three estimate results which are thoroughly and strategically executed should allow for the cost estimator to make an easier identification of where any inconsistencies might originate from.

Reference 44 proposes a formalized standard, the AA, for such an approach, which harnesses a strategic combination of multiple, justifiably selected CEMs and consequently models or tools to increase the reliability and representativeness of the cost estimate. Through

AA, an added redundancy is incorporated into the cost estimate through multiple results which can then be analyzed and contrasted.

The cost estimation domain through the AA_{MAC} formulation of multiple (three) independent cost estimates in an iterative process, with the resulting cost estimates produced as a synthesis of three results. The aim here was to determine the program development (Phase C) and prototype production & test (Phase D) cost ranges for the SpaceLiner reference concept. Three models and tools were selected to implement within the AA_{MAC} framework. These were the parametric TransCost, and two other commercially available models used widely in the aerospace sector. The AA_{MAC} development and production costs, as synthesized from three independent results and from multiple extensive analyses as intermediary steps to arrive at the final range, result in a more defensible, justifiable and consequently representative cost estimation [44].

5.2   Cost estimation of SpaceLiner Passenger Transport

The SpaceLiner is a two stage vehicle system comprising of the reusable booster stage (SLB) and the passenger stage (SLP). Furthermore, the SLP features an integrated passenger cabin (SLC) which has a hybrid function of serving as a passenger cabin and as a rescue capsule in case of a catastrophic emergency. In this regard, the SLC features its own solid propulsion system and is a potentially flying vehicle (see section 4.4.3). As such, within the scope of the cost estimation, the SLC is taken to be a separate stage in its own right. Ramifications of this assumption are significant, since development costs, if calculated for a separate stage, would be considerably higher than if this stage was considered as an integrated component within another already existing stage [28]. The SpaceLiner main engine needs to be newly developed, with the key challenge being the required reusability of at least 25 missions. The booster uses very similar engines to those of the passenger stage (see section 4.4.1), and thus only one common engine development cost is incurred. [28]

Four SpaceLiner components encounter both non-recurring development costs, as well as consequent production costs. These are:
- SpaceLiner Booster (SLB)
- SpaceLiner Passenger Stage (SLP)
- SpaceLiner Main Engine (SLME)
- Passenger cabin and rescue capsule (SLC)

5.2.1   Development cost of SpaceLiner 7

Preliminary cost results from TransCost 8.2 calculated for the SpaceLiner development, ground testing, and prototype flying were presented with a certain degree of uncertainty in [7, 28] in the range 25 to 32 B€ Subsequently generated AA results for the development in Phase C&D of the SpaceLiner yield a cost range between 26 and 31 B€ (2013 e.c.) [44]. At a top program level, the result congruency was very good (±20%), especially for such an early program phase as the SpaceLiner. Figure 27 shows the shares of the major components and the results deviations of the tools. The cost deviations and variations between the multiple models are, in fact, not at all surprising, and should be expected when applying the Amalgamation Approach.

System engineering and programmatic costs are not included in Figure 27 but in the total cost range mentioned above.
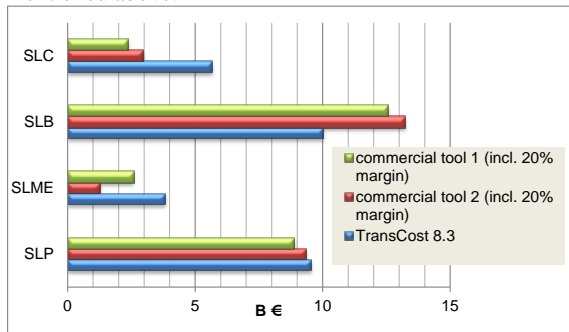

Figure 27: Estimated SpaceLiner development costs for major components obtained by different models

A key distinction between the TransCost estimate and the commercial tools relevant to development effort of SLME engines was that both commercial tools do not take into account the number of test firings, which is a key cost driver in the top-level TransCost calculation [29], which assumes 1200 engine test firings. The intended safety and reliability levels of the SLME definitely require a large number of test firings, with the chosen value considered to be representative. Thus, the estimated TransCost model development cost for the SLME is the most credible. On the other hand in case of the cabin, the TransCost CER data-points refer to capsules like Mercury and Gemini, which significantly differ to the SpaceLiner SLC, both in purpose, PAX capacity and lifetime. Therefore, the two highly congruent commercial models' data are probably more realistic. However, it should be kept in mind that a high level of safety might require a considerable number of expensive flight-tests for which cost in the end might approach the TransCost-estimated 5.66 B€ as shown in Figure 27.

5.2.2 Production cost of SpaceLiner 7

A similar calculation for the production cost based on TransCost estimation of the Theoretical First Unit (TFU) cost and a learning curve assumption has been performed [28]. The SpaceLiner production process should be much more organized, and more closely resembling civil aviation trends than typical launcher hardware production. While the TransCost model seems to be the most appropriate tool for estimating the development costs of the SpaceLiner, for the production cost calculations, no TransCost CERs exist to ideally address all four SpaceLiner system elements. While suitable CERs exist for the SLME and maybe SLC, no dedicated CERs could be identified for the SLP or the SLB system elements [44]. Therefore, the TransCost estimation is less suitable and AA has again been applied.

The reference size of the total production batch for the SpaceLiner concept was chosen to be a baseline of 500 vehicle units. This could allow for approximately 15 years of full scale worldwide operation. The airframe vehicle lifetime is assumed to be 150 missions. Realistic and safe SLME lifetime with today's technologies is no more than 25 missions and as 11 engines are needed for each launch configuration, the total numbers of rocket engines to be produced is 33000.

The production costs, also using the AA theory and AA_{MAC} mode, varied within the range from the highest TransCost figure of 376 B€, through to 238 B€ or 209 B€ (2013 e.c.) for a total of 500 SpaceLiner sets produced [44]. The corresponding average flight unit costs have been calculated to be 752 M€ (TransCost), 475 M€ (tool1) and 466 M€ (tool2), including an additional 20% margin for the commercial tools to allow for a relative comparison with TransCost, which already incorporates this margin. The average production cost per flight ready unit (including 11 engines but without production overhead) is presented in Figure 28 for all the four SpaceLiner major components.

It's interesting to note that the two commercial estimation tools are close to each other in the assessed average production cost while TransCost delivers significantly higher values. This outcome might be explained by the fact that the parametric tool TransCost is specially adapted to the space transportation field relying on statistical data. However, it is impossible to find any empirical data on similar reusable rocket-powered stages of which the SpaceLiner consists. The sub-component based approach of the two other tools might be more appropriate for the production cost estimation of such new types of vehicles. The average SLC-cost of more than 160 M€ per item from TransCost is extrapolated from small manned space reentry-capsules. The necessary hardware and complexity of integration is less than for small airliners so that the obtained value is difficult to justify.
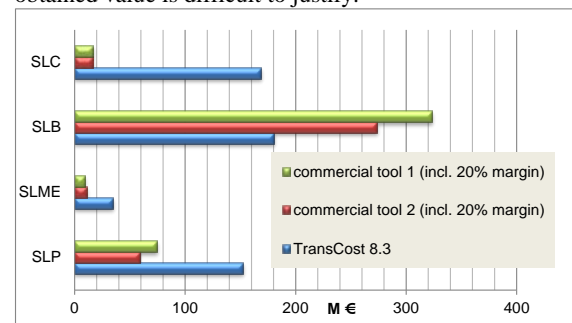

Figure 28: Estimated SpaceLiner average production costs per flight unit for major components obtained by different estimation models

The cost estimations deliver a valuable baseline for further, more detailed analyses in the future. Sensitivity analyses, conducted within the scope of both development and production cost estimations across all three AA_{MAC} models [44], also support the next steps. Nevertheless, as the SpaceLiner case-study progresses through to a maturity where technical specifications are finalized and frozen, the cost estimate will need to be modified, and updated to reflect all new information.

5.3 Cost estimation of SpaceLiner Satellite Launch Service

Based on the production cost assessment of the passenger transport with more than 30 vehicles and over 2000 engines produced per year in the baseline worldwide operational scenario, the production and, subsequently, the launch cost of the TSTO can be estimated. The satellite launcher components should be manufactured on the same line as those of the passenger vehicle.

Assuming again an airframe life-time of 150 missions and 25 missions per engine, further taking into account additional costs for maintenance, refurbishment, satellite launch preparation, and (if needed) for an expendable kick-upper stage, the launch cost can be calculated.

The GTO-mission cost is well below 15 M€ and the LEO-(ISS-resupply)mission cost without expendable stage is significantly below 10 M€ These values translate into attractive specific launch cost of less than 2000 €/kg and less than 1000 €/kg under conservative assumptions. This major improvement might allow creating new business opportunities in space which are not affordable with today's infrastructure.

5.4   Business case

The preliminary cost inputs derived from the TransCost calculations were fed into an Orbspace developed Business Case Simulator (BCS) software tool, for the preliminary establishment and analysis of a business case. The combination of the process to establish initial and justifiable development and production cost estimates to use as input for a business case simulation tool is considered a solid foundation and methodology for future development of the SpaceLiner LCC assessment. Early results indicated that the SpaceLiner is not only a technically feasible concept but also one for which a viable business case might exist [28, 7].

Proper and timely project appraisal can dictate if a company's business endeavor succeeds or fails. Before starting a new business case simulation, the appraisal of the innovation 'SpaceLiner' has been assessed, focused on the economic, touristic purpose of the acquisition of gain (space tourism) [47]. Using the qualitative method addressed by the '*House of Quality (HoQ)*' and the quantitative procedure of '*Risk Analysis (RA)*' a suitable solution has been found for the evaluation. Two questions were addressed: *How customer oriented is the SpaceLiner?* and *Which chances of investment success can be expected?*

The HoQ shows how customer-oriented the SpaceLiner is and which characteristics are the most important with regard to the target group. Different sensitivity analyses and the comparison to an already existing A380 airliner delivered a promising customer value [47]. The RA demonstrates the risks and chances of the concept. Overall cost estimation (see section 5.2) and several sensitivity analyses show that the idea of the SpaceLiner is connected to some uncertainties und financial risk, but can also offer great chances. These results are not surprising for an advanced highly innovative concept addressing a new type of market. The quantified data of [47] allow for further optimization in SpaceLiner design and operations.

6   MISSION REQUIREMENTS REVIEW AND PROGRAMMATIC PLANNING

6.1   MRR

The SpaceLiner Mission Requirements Review (MRR) has been successfully concluded in summer 2016. Intentionally, external reviewers with long-term experience in large-scale space projects had been invited for an independent assessment of all necessary requirements and soundly structured development logic. The Mission Requirements Document (MRD) [57], carefully reviewed at the end of May, constitutes the top-level mission requirements of the SpaceLiner System. The meanwhile finalized MRD is the baseline and starting point for all technical and programmatic follow-on activities of the SpaceLiner Program. The MRD takes already into account the two variants for passenger transport and for payload transport to orbit. The objective of the passenger version is to provide a safe, reusable, hypersonic, intercontinental, point-to-point, passenger transportation system [57].

The SpaceLiner program must be in full agreement with international regulations and national laws of all participating nations. However, specific binding regulations for the operation of high-speed passenger transport vehicles operating at the edge of space do not yet exist in a similar way as for all kinds of manned and unmanned aviation. Nevertheless, a safety standard is in the preparation process which might become applicable to the SpaceLiner Program [58]. A first evaluation of this standard is scheduled in the near future. The SpaceLiner Project structure shall also be oriented on the European ECSS standards and the Metric System (SI) shall be used.

The MRD lists 11 Technical Requirements, 30 Operational, Environmental, Exploitational Requirements, and 9 Programmatic and Cost Requirements [57]. Several of the specifications included here are to be verified in Phase A which is to be addressed by extensive trade-off studies. The current issue 1 of the MRD will be updated in future project phases based on the results of these studies or commercial and economical needs.

The MRD is available to all SpaceLiner project partners.

6.2   Development Planning

Based on the ECSS standard development logic a dedicated SpaceLiner Master Program Schedule as visible in Figure 29 has been defined.
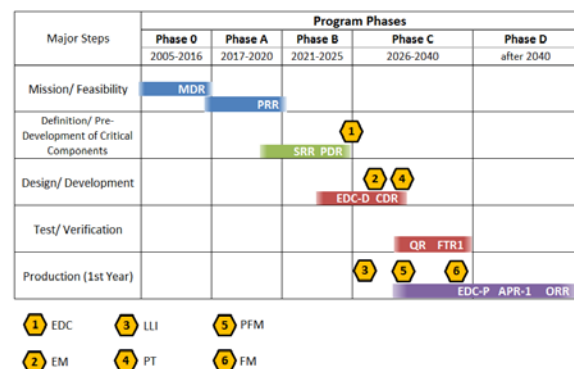

Figure 29: SpaceLiner Development Roadmap [57]

Following the SpaceLiner Master Program Schedule of Figure 29, a well-structured development process is initiated. Actual industrial development beginning with Phase A is scheduled to start at T0 in 2020. During the current pre-development and technology maturation phase, running until 2020, a few key milestones and reviews are to be addressed:
- MRR completed in 2016

- Early concept reviews ("BCR") or subsystem reviews in 2016ff.
- PRR in approximately 2019

Afterwards – depending on available funding – the technical development of the SpaceLiner will follow in rough estimation this timeline:
- SRR in 2020
- PDR in 2025
- CDR in 2030

First Flight of a SpaceLiner prototype should occur ca. 2035 and subsequently extensive flight testing and the certification process is expected. An operational SpaceLiner high-speed passenger transport system should be reached in 2040+ at least for one point-to-point destination.

The overall hardware testing and qualification process is extremely demanding compared to all previous launcher projects including the reusable Space Shuttle and Buran systems. The high number of tests is driven by the safety requirements of a passenger transport system. In order to support reliable development cost estimation, some basic data have been selected [46]. All these data are still to be confirmed by a detailed development roadmap but can already give an indication of the necessary effort:
- Engine prototypes (for firing on test stand): 30 (1200 test firings, 40 firings /engine)
- SpaceLiner vehicle prototypes: 6 with a few hundred test flights
- Prototype flight testing and qualification time: 6 years

7   CONCLUSION

The DLR proposed reusable winged rocket SpaceLiner for very high-speed intercontinental passenger transport has further matured in its conceptual design. Research on the vehicle has been performed with support from the EU projects FAST20XX, CHATT, HIKARI and HYPMOCES with several European partners. Assuming advanced but not exotic technologies, a vertically launched rocket powered two stage space vehicle is able to transport about 50 passengers over distances of up to 17000 km in about 1.5 hours.

A newly designed, fully reusable TSTO satellite transport version of the SpaceLiner with internal cargo bay but overall very similar lay-out to the passenger transport has been defined. Iterative design with simulation of all stage's trajectories demonstrate that larger than 8 tons separated satellite mass can be lifted into GTO when using an additional expendable kick-stage. Simulations proof that the SpaceLiner TSTO version stays within the load constraints of the PAX-version which confirms that the baseline design can be reused without major development effort.

Based on the production cost assessment of the passenger transport, attractive specific launch cost of less than 2000 €/kg in GTO and less than 1000 €/kg in LEO are achievable.
The latest iteration step of the SpaceLiner concept is the version 7-3 which is based on preliminary design of

different subsystems and vehicle structures. Potential worldwide flight routes under realistic operational and environmental constraints are under investigation considering advanced flight control and guidance methods.

The Mission Requirements Review (MRR) of the SpaceLiner has been successfully concluded in summer 2016. Work on the visionary SpaceLiner concept has reached a new milestone and is gaining momentum in the European aerospace community.

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Further updated information concerning the SART space transportation concepts is available at:
http://www.dlr.de/SART