ADVANCED STRUCTURAL OPTIMIZATION UNDER CONSIDERATION OF COST TRACKING

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ABSTRACT

In order to improve the design process of launcher configurations in the early development phase, the software Multidisciplinary Optimization (MDO) was developed. The tool combines different efficient software tools such as Optimal Design Investigations (ODIN) for structural optimizations, Aerospace Trajectory Optimization Software (ASTOS) for trajectory and vehicle design optimization for a defined payload and mission.

The present paper focuses to the integration and validation of ODIN. ODIN enables the user to optimize typical axis-symmetric structures by means of sizing the stiffening designs concerning strength and stability while minimizing the structural mass. In addition a fully automatic finite element model (FEM) generator module creates ready-to-run FEM models of a complete stage or launcher assembly.

Cost tracking respectively future improvements concerning cost optimization are indicated.

1. INTRODUCTION

The design of new launchers is traditionally an iterative process. Experts from various disciplines have to refine and update their subsystem designs in order to finally arrive at a consistent good design.

Multi-Disciplinary Optimization (MDO) is an European Space Agency (ESA) founded project and the name of the resulting software.

The Goal of the MDO software is:

- Concurrent optimization of mathematical models that span across various disciplines.
- Coupling and interaction of geometry, structure, aerodynamics, propulsion, controllability and trajectory.
- Integration of a detailed stage structural model.
- Automatic identification of critical load cases (e.g. ground, wind gust, engine thrust, aerodynamic loads tank pressure etc)

⇒ All-At-Once optimization

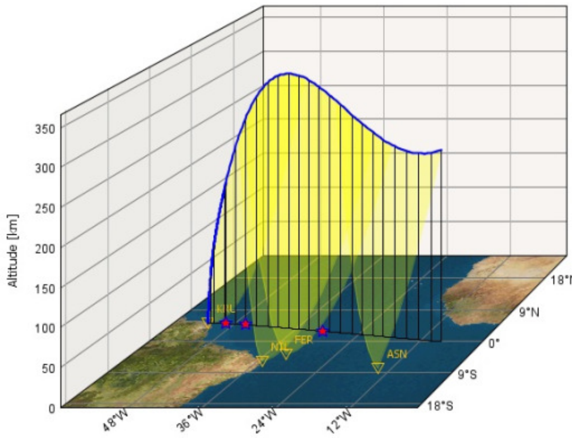


Figure 1. Part of a typical trajectory of a three-stage launcher (red = splash-down of stages, yellow = visual corridor of ground control, blue line = trajectory)

A precursor Astos Solutions activity on MDO has identified the structural mass estimation as the most critical discipline, followed by engine performance and aerodynamics.

Based on that, the structural mass estimation shall be clearly improved. As an answer to this need MT Aerospace has developed the Optimal Design Investigations (ODIN) tool. It allows a rapid evaluation of a broad range of tank and structural components.

2. MDO PROCESS

Starting with an initial design concept (staging) and a mass estimation by experience/top-down approach initial loads will be determined by the mission profile (orbit and payloads).

Within the MDO process a stage will be disassembled into substructures (Main Mass Drivers), Fig. 2, as Cylinders, Bulkheads, Y-Ring's, Cones and Strut-Cones.

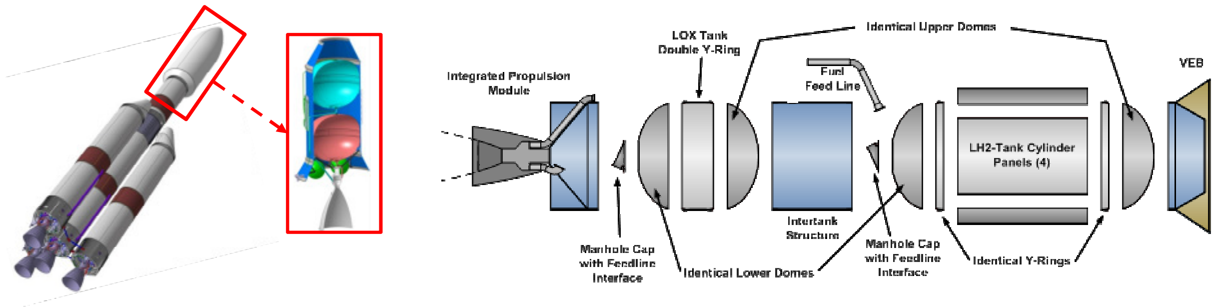


Figure 2. Disassembly of stage into substructures (Main Mass Drivers)

Then in an iterative loop the MDO tool determines the loads for each substructure on basis of a one beam approximation considering maximum loads due to e.g. wind gusts. Thereby the ODIN tool is used to estimate new masses, which leads to new loads and so on. This loop is performed, until convergence is achieved.

After finishing this process a final verification will be performed with ODIN and/or with finite element analysis (FEA). Therefore a FE-mesh can be generated using a smeared thickness approach.

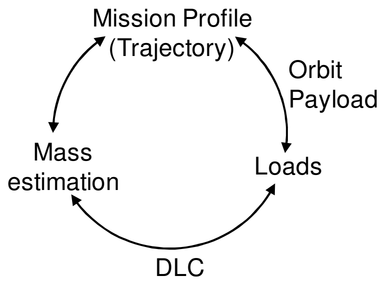


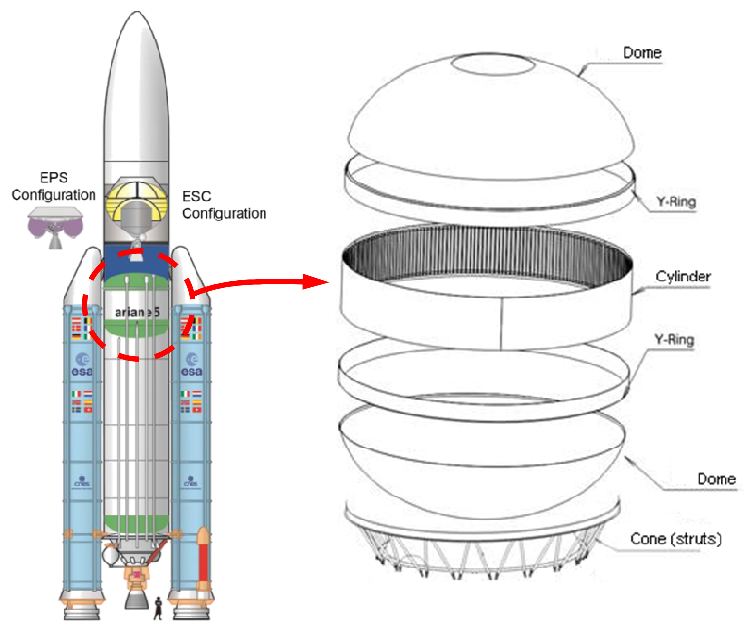
Figure 3. MDO Iteration Loop.

3. ODIN - EFFICIENT STRUCTURE SIZING TOOL

The ODIN tool incorporates a wide library of analytical formulas to size the elementary structures, such as domes, cylinders or struts. For each elementary structure various design options can be investigated, from basic thin-walled isotropic, to orthogrid, sandwich and other. The design options are evaluated for numerous design criteria including strength, global buckling, and local buckling modes. The analytical methods used have been collected from a broad list of literature, and include NASA's Design Criteria [1],[2], [3], [4], ECSS Standards [5], and various structural analysis sources.

3.1 ODIN Features

The list of structures and their design options currently completed is given in Fig. 4.



- Cylinder
  - Isotropic
  - Orthogrid
  - Sandwich
- Bulkhead (Dome)
  - Isotropic
  - Orthogrid
  - Sandwich
- Y-Ring
- Cone
  - Isotropic
  - Orthogrid
  - Sandwich
- Strut Cone

Figure 4. Features of ODIN tool currently available.

Aside of the analytical sizing formulas, ODIN includes also manufacturing limits and manufacturing factors for various design options. These range from minimum feasible (or practical) wall or rib thickness, to correlation factors between the idealized and real structures. These manufacturing limits and factors have been derived from a broad collection of manufactured parts at MT Aerospace.

To reduce the discrepancies between detailed FEA calculations and related ODIN results, both results are compared and correlation factors are derived. If necessary, correlation factors are then used to calibrate the ODIN results. This method leads to more reliable design solutions as potential overestimation of load bearing capabilities are reduced.

The main goals of ODIN can be addressed as:

- Mass estimation for the MDO process.
- Analytical pre-dimensioning of main structural components and mass estimation for trade off purposes and Phase A studies.
- Preliminary sizing close to final design solution to reduce the number of FEM-calculations.
- Export of preliminary axis-symmetric FE-models for complete stages.

Due to the analytical approach ODIN of course has some limitations:

- Loads are restricted to inner/outer pressure and axial-symmetrical fluxes (line loads). Effects of local load introduction cannot be considered, since they cannot be accurately modelled with analytical formulas. In MDO the maximum axial flux peak (membrane + bending) is considered as constant circumferential load.
- Thermal load cases are not included.
- The approach is based on the optimization of single sub-structures, neglecting the stiffness of adjacent structures.

3.2 Optimizer

ODIN is coupled to an external optimizer, see Fig. 5. Dimensions of each stiffening design options can be mass optimized. The optimization takes into account all failure criteria (strength, general and local buckling) as well as manufacturing limits and factors. For example for an orthogrid stiffened cylinder, ODIN can calculate the mass optimal dimensions of pocket width, wall thicknesses, rib height etc, while ensuring positive margins of safety for strength, general and local buckling. The optimization can be carried out for several load cases simultaneously.

3.3 ODIN Architecture

ODIN is an object orientated program written in C++. An overview over the architecture and comprised objects is given in Fig. 5. The wrapper and the solver are organized as dynamic link libraries (dll).

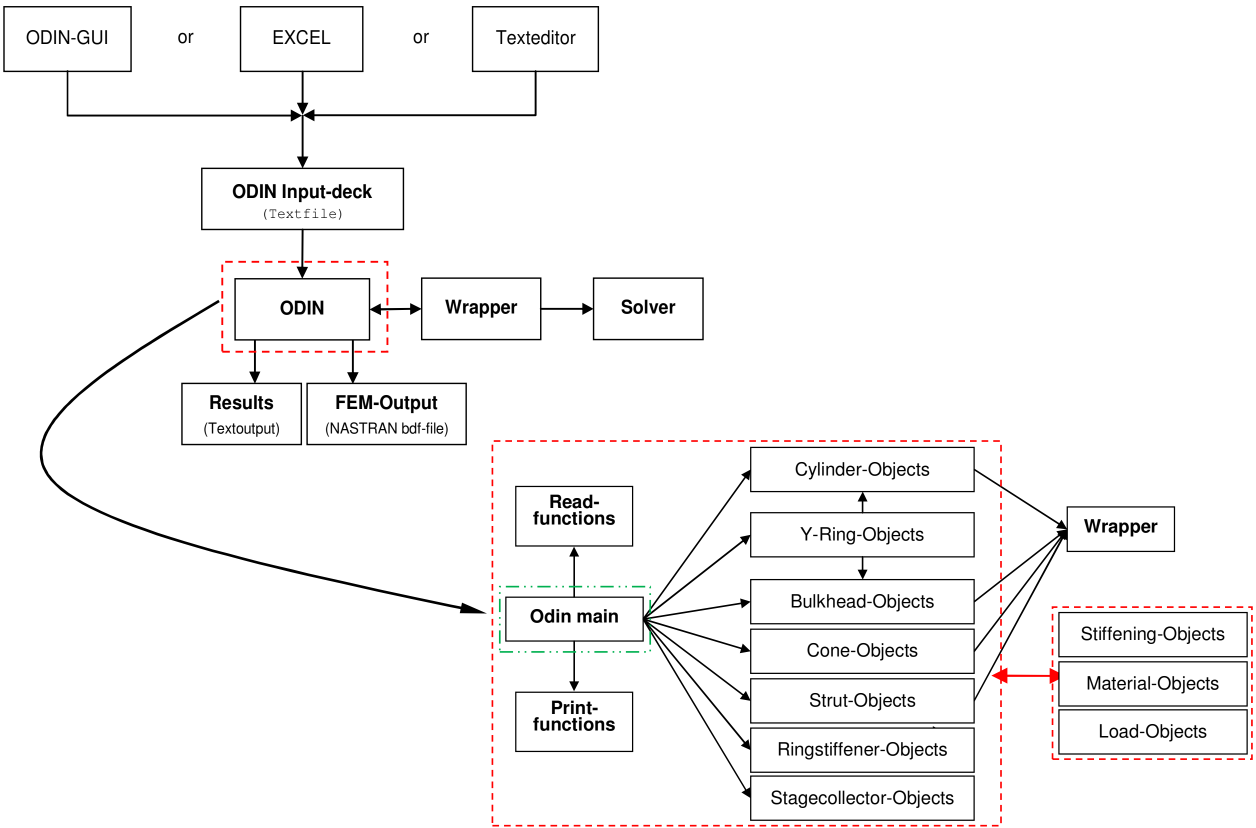


Figure 5. ODIN architecture

3.4 Stagecollector and FE Model Generator

As mentioned before, the ODIN calculations and optimizations are based on single structural components. Nevertheless a 'stage-collector' is integrated which allows to join together the single components at their interfaces. All components building the stage are added to a "stage collector" specifying for each component which is the parent component and which interface shall be connected with its corresponding parent interface. All other information, e.g. the geometrical position of each component in the stage assembly, is calculated by the program. Finally, an FE-Model generator produces an axis-symmetric shell model based on a smeared thickness approach. Examples of the model generator are presented in Fig. 6.

With the aid of the stage collector and the FE Model Generator axis-symmetrical FE-models can be efficiently established.

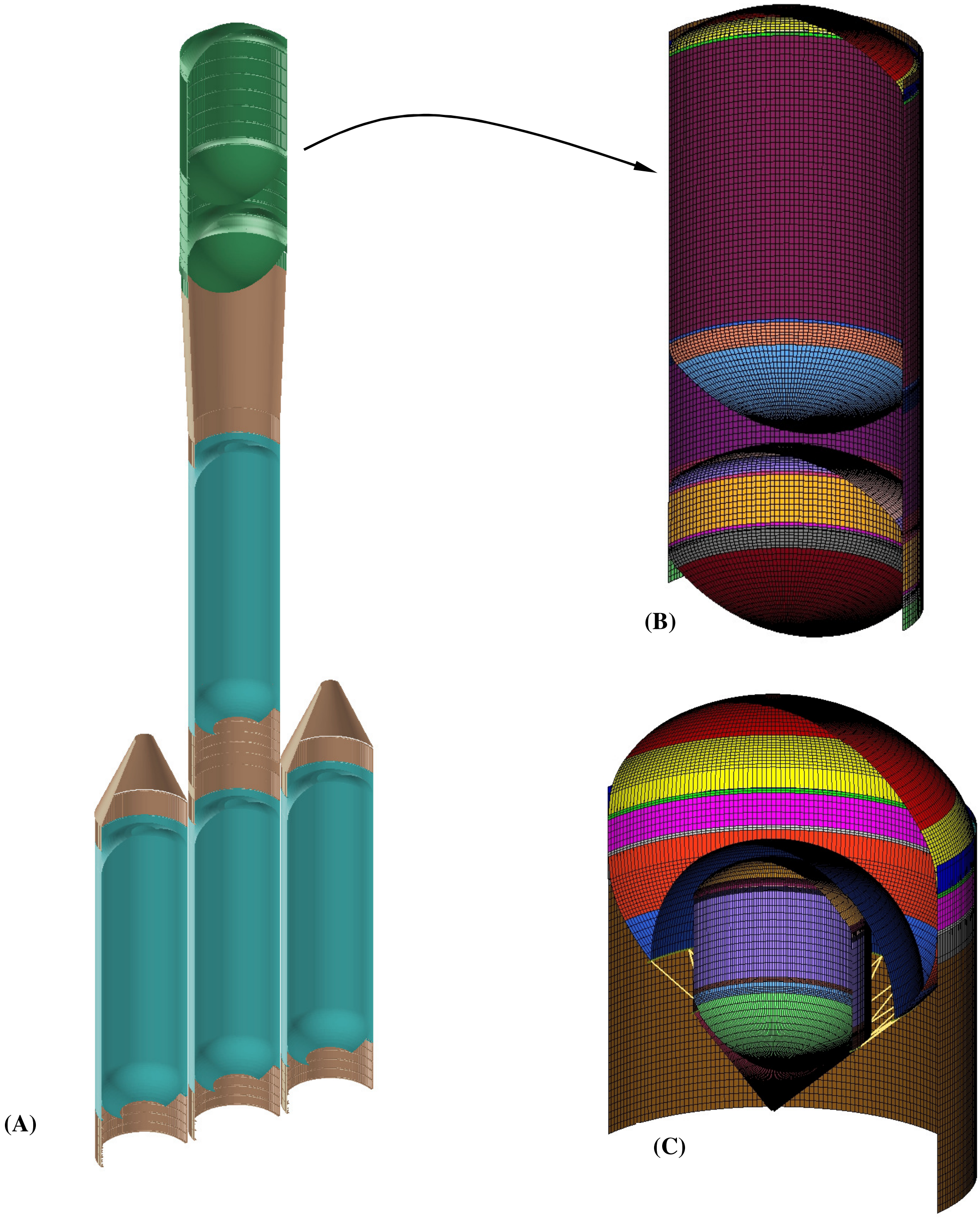


Figure 6. FE Model Generator ((A) Ariane 6 Request for Proposal (RfP) configuration, (B) Ariane 6 RfP Upper Stage Tanks ($Ø_{max}$ ~ 4.0m), (C) Ariane 5 ESC-A Upper Stage Tanks ($Ø_{max}$ = 5.4m)).

3.5 ODIN Graphical User Interface

The ODIN input deck can be created with a text editor, but much more comfortable is a graphical user interface.

For ODIN a graphical user interface was developed by Astos Solutions. An example for the stage-collector section is presented in Fig. 7.

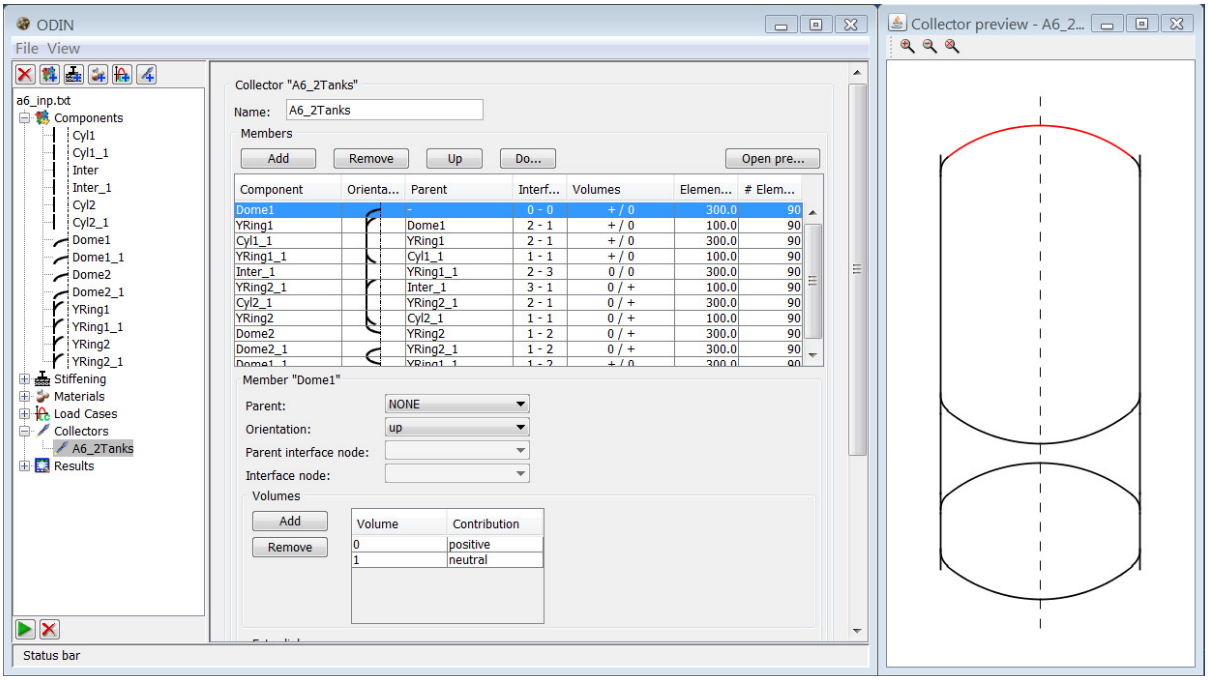


Figure 7. Example of ODIN-GUI: Stagecollector

3.6 ODIN Verification

Considerable amount of checks have been performed to assure the adequate chosen set of equations and the correct implementation in ODIN:

- Comparison with existing analytical tools.
- Comparison with FEM (on substructure level).

The verification of the functions implemented in ODIN has shown that the estimation errors of stresses and buckling loads range from 3% to 15% compared to detailed FEA, depending on structure type, general dimensions, and loads applied. This is a reflection of analytical formulas which lie at the base of ODIN. These formulas, as documented in global literature, have been derived under set of assumptions and simplifications, and consequently such error as observed is expected.

One example of comparison between ODIN and FEM is shown in Fig. 8. There the global buckling load is compared for a cone with different R1/R2 ratios (→ different cone angles). For higher cone angles (smaller minimum radius R2) the deviation increases somewhat but is acceptable for a first estimation.

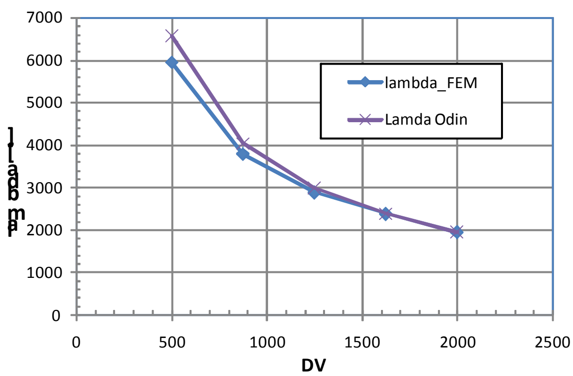


Figure 8. Exemplarily comparison of global buckling between ODIN and FEM for cones with different varying min. radius R2. Such comparison was performed for each Design Variable (DV).

4. COST TRACKING

Currently a cost tracking on basis of mass specific costs is individually possible, but no cost optimization is implemented in MDO. The pre-condition of cost tracking is that mass specific costs are available for the different launcher elements, e.g. for the structures, the propellants, the equipments etc.

A pure mass optimization and a pure cost optimization of a launcher configuration leads normally to different solutions. To combine both, mass and cost optimization, a weighted target function has to be established. Furthermore a relative cost comparison to the cheapest solution is recommended to get a more general assessment independent of various changing cost influences, e.g. company specific costs, variation of material prices and currency translation.

For each defined configuration a sizing can be performed using gradient optimization methods and a combination of real cost for e.g. propellant and relative costs for e.g. structure considering manufacture specific cost factors. The cost difference between different configuration with respect to stiffening concepts of the sub-structures is not continuous and requires solvers based on random search methods. The optimization process determines the optimal stage sizing trading between small mass and propellant costs at high structural costs, and higher mass and propellant cost at lower structural costs.

5. CONCLUSION

MDO is an ESA founded project started in 08/2012. Astos Solutions and MT Aerospace are commonly developing the software. The MDO software, based on ASTOS, is capable to perform a trajectory and launch vehicle design optimization under treatment of the coupling and interaction of structure, aerodynamics, propulsion system and controllability. Line loads (fluxes) and tank pressures are calculated and the critical load cases for buckling and strength for each sub-structure are computed. ODIN is used for quick structural mass estimation. The benefits are:

- All-At-Once optimization including accurate estimation of the structural mass considering material and stiffening concept
- Reduced reaction time during tender process and Phase A studies
- Cost reduction

The combination of ODIN and ASTOS in the developed MDO software enables the user to perform a closed-loop optimisation at early design-phases. The increased efficiency of this process yields a potential in terms of development cost and time reduction.

6. REFERENCES

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