COST DRIVEN UPPER STAGE CONCEPT FOR VEGA EVOLUTION

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Summary

In an internal study the commercial and technical opportunities of the evolutionary development of the Vega launch vehicle have been investigated. Study objectives were: to identify market requirements and the resulting mission statement, as well as to explore design options and identify marketable concepts for a potential Vega Evolution. In the study primarily various upper stages have been investigated, with focus on tanks and structures.

During the study, an extensive market forecast for small satellites (500 – 3500 kg) within the time frame 2010 – 2018 has been established. This forecast has been used to define the Vega Evolution performance targets for payload and costs. Subsequently, several launch vehicle concepts have been investigated, with focus on the reduction of launch costs. For each concept, system analyses have been performed, including preliminary definition of major subsystems and their configuration, mass, dimensions, and performance. Furthermore, the vehicle performance has been obtained from trajectory simulations performed by ASTOS, and from component and subsystem cost estimates (RC and NRC).

Following the review of performance and cost, the Vega L4 concept is recommended for short term evolution. It is based on the existing Vega, but the 4th stage (AVUM) is replaced by a larger and more capable upper stage. The new stage comprises storable propellant and maximizes use of heritage components (Alphabus propellant tanks, AVUM avionics, Aestus engine, and other), which offers low development costs and low development risk. In addition, all major components considered can be obtained from European suppliers. An increase in performance allows this concept to launch two 800 kg satellites into reference orbit polar, circular LEO in 700 km.

1. INTRODUCTION

The goal of the study is to identify feasible evolution scenarios for the Vega launch vehicle. The evolution should increase the commercial competitiveness of the Vega system, by reducing specific launch price (EUR/kg), and by increasing the accessible launch market. The study aimed to explore potential concepts; however no formal trade-off was foreseen.

The study has first focused on satellite market forecast and definition of commercially viable evolution scenarios. The results have been used to establish market driven mission requirements. Next, several concepts have been identified for each scenario. The investigated concepts were also focused on reduced development costs and time. Each of the concepts has been sized and evaluated for performance – expressed as maximum payload mass, and costs – recurring and non-recurring. Finally, for each scenario, several observations and recommendations have been made.

2. VEGA LAUNCH VEHICLE

The Vega launch vehicle is currently under development by ELV with the first flight expected at end of 2011 [1]. The rocket is designed to satisfy a need for launch of small institutional payloads into Low Earth Orbit (LEO). The reference mission is the launch of 1500 kg payload into 700 km polar orbit, which is a common launch requirement for numerous scientific and Earth-observing missions.

Vega is composed by four stages – three propelled by solid rocket motors, and an upper stage with liquid propellant. The general technical data of Vega is presented in Table 1.

The rocket development has been financed by the European Space Agency (ESA), and includes several new solid rocket motor technologies.

Table 1: Vega launch vehicle data [2]

Stage	P80	Z23	Z9	AVUM
Propellant	solid	solid	solid	UDMH/NTO
Propellant mass, [t]	88.4	23.9	10.1	0.55
Dry mass, [t]	7.4	1.8	0.83	418
Diameter, [m]	Ø3	Ø1.9	Ø1.9	Ø2.18
Length, [m]	11.2	8.39	4.12	2.04

3. MARKET

To identify the commercially viable Vega evolution scenarios, a market research has been performed. The goal has been to identify the market opportunities, and to derive suitable mission requirements for Vega Evolution.

The market research considered the launch demand for Low Earth Orbit (LEO) satellites in the mass range of 300 kg – 3500 kg. The collected satellite forecast is based on FAA's 2009 Commercial Space Transportation Forecast [3] for Non Geosynchronous Orbits and on Generated Satellite List (GLS). The GLS has been compiled from a wider range of various (cross-checked and verified) sources, and covers international institutional, military, and commercial satellites. The resulting market forecast is valid for the period 2010 – 2018.

The synthesis of the results is presented in Figure 1. This figure depicts the expected average launch rate of LEO satellites as a function of the satellite's mass. The satellites represented in the figure are launched into a wide range of orbits, with majority of payloads launched to 600 – 800 km polar orbit or Sun Synchronous Orbit (SSO).

It is assumed that in global launch market, Vega could capture 25% market share. Based on the forecast and the assumed market share, the Vega launch rate is estimated at 1.7 single launches per year for satellites in the 900 – 2000 kg class. This includes launches to various orbits and inclinations.

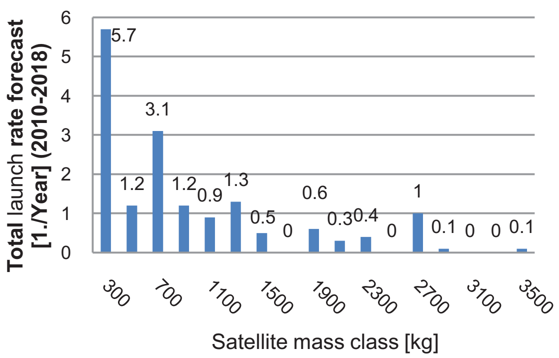


Figure 1: Market forecast – satellite spectrum

Based on the above forecast, two major evolution scenarios can be contemplated.

3.1. Scenario 1 – lighter payloads focus

Scenario 1 targets the evolution of Vega for launches of double or multiple payloads, with focus on smaller payloads and the launch of two 700 kg class satellites. It is expected that this scenario would require an increase of performance to approximately 1800 kg to guarantee a sufficient margin for multiple payload adapters and additional manoeuvring propellant. This could extend the launch demand (with 25% market share) to approximately 3 launches per year, for 5.5 satellites per year Consequently the mission requirement for scenario 1 is the launch of 1800 kg payload into the reference orbit polar, circular LEO in 700 km.

3.2. Scenario 2 – heavier payloads focus

Scenario 2 aims at the evolution of Vega for launches of heavier payloads in 1500 – 2700 kg class. This capacity would still allow access to Vega's baseline market, with launches of two 1100 kg satellites, or multiple smaller satellites. The potential launch rate would be approximately 3.5 launches per year for average of 6 satellites, with the 25% market share assumed. Consequently, the mission requirement for scenario 2 is the launch of 2700 kg payload to reference orbit polar circular LEO in 700 km.

A further opportunity for scenario 2 is the performance increase to allow launches of small satellites into GTO or MEO. One option could be maintenance missions of the Galileo constellation satellites. However, due to time and budget constraints such missions have not been considered in this study.

4. GENERAL ASSUMPTIONS

To meet the mission requirements of the aforementioned scenarios, several concepts of the Vega Evolution have been established and considered. While multiple concepts already exist, and some have been investigated in different studies [4] and [5], this study has focused on concepts which minimize the recurring costs (manufacturing and operations) as well as non-recurring (development) costs. Consequently, the following ground rules have been used to generate the concepts:

- Maximize use of existing Vega components and technologies – solid propulsion for lower stages
- Maximize use of existing, heritage, components from other European programs
- Storable or LOX/Methane upper stage propellants

The above ground rules include two notable points – exclusion of LOX/LH2 propellants (Vinci engine), and inclusion of LOX/Methane propulsion. First, the LOX/LH2 propellants have not been considered, due to higher stage development, manufacturing, and operation costs. Especially the recurring costs are expected to be higher, and it is unlikely that they could balance the fact that LOX/LH2 rocket engines are already available in Europe (HM-7, Vinci). Furthermore, application of Vinci engine to Vega Evolution would require down scaling of the thrust and potentially redesign of nozzle, requiring some development costs.

In contrast, the LOX/Methane stages have potentially lower recurring costs, and lower stage (excluding engine) development costs. This can be attributed to reduced stage volume, potentially simpler configurations (propellant tanks have comparable volumes), higher temperatures (and in case of LOX/Methane temperature gradients), reduced helium requirements, and other. The major disadvantage of LOX/Methane is the higher engine development costs, since currently there are no such engines available in ESA/EU-member states. Nevertheless, technology programs are under way (such as the Italian MIRA project, [6]), so it is conceivable that such rocket engines will be available within several years.

The final argument for the LOX/Methane concept is that until now it has been often disregarded in the majority of other Vega Evolution studies, so that the system level impact of LOX/Methane has not been fully considered.

5. CONCEPTS INVESTIGATED

With the aforementioned general assumptions six Vega evolution concepts have been generated – three for each scenario. These are summarized in Table 2 and Table 3, while the following sections present the results of sizing and evaluation.

The concepts for scenario 1 use the same Lower Composite (L/C) stages as Vega, namely P80, Z23 and Z9. The performance increase is achieved with a new, larger upper stage (U/S).

For scenario 2, new stages are considered. The L/C is comprised of solid stages based on Vega's technology and manufacturing capabilities: P120 and P40. The same L/C stages are used for all three. The upper stage is propelled by LOX/Methane, and is equipped with a prospective MIRA engine. For the U/S, different architectures and diameters are considered.

6. SIZING AND ANALYSIS METHODS

To compare and evaluate the concepts, their performance and costs have been estimated. Both of those estimates required a preliminary sizing of the major subsystems and components. The achieved level of detail is represented by mass breakdowns in Table 8 (mass tables for L4 and C10 2.5m CB). Furthermore, an example of the sized upper stage (L4) is depicted in Figure 2. The sizing has been performed in the following steps.

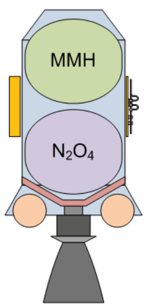
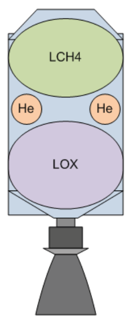
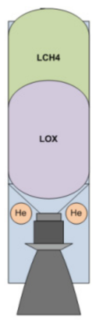
First, a rocket equation has been used to obtain the preliminary propellant masses needed to achieve the mission requirements. The dry masses have been obtained from historical regressions for rocket engines, stages, and fairings.

Subsequently, the major subsystems have been sized. The propulsion subsystems (engine and associated equipment) have been taken from the available literature for the engines used. Exception is the Aestos M (LOX/Methane) engine, for which a preliminary performance has been obtained with a Rocket Propulsion Analysis (RPA) tool [8].

Stage tanks and structures – the largest stage dry mass contributions, have been broken down into tank domes, cylinders, Y-rings (interface between tank domes, cylinders, and flanges), and cones (for Engine Thrust Frame). In order to size these components, quasi static loads have been derived from vehicle thrust, accelerations, and expected aerodynamic forces and pressures. Preliminary dynamic analyses based on mass-spring models with several nodes have also been carried out in order to derive representative dynamic loads.

Subsequently, the tanks and structures have been dimensioned, in order to satisfy the loads and volume requirements. The tanks and structures have been dimensioned for strength, buckling (global and local), and strain for solid motor cases. The above sizing has been done with an in-house tool, which includes an optimizer of stiffening elements (stringers, orthogrid, sandwich, etc).

Table 2: Scenario 1 concepts investigated

Name	Vega - L4	Vega - C4	Vega - C8
Number of stages	**4**	**4**	**3**
Lower Composite	**P80 / Z23 / Z9**	**P80 / Z23 / Z9**	**P80 / Z23**
Upper Stage	 L4	 C4	 C8
U/S propellant	4t, MMH/NTO	4t, LOX/Methane	8t, LOX/Methane
U/S engine	AESTUS	AESTUS M (LOX/Methane)	AESTUS M (LOX/Methane)
U/S diameter	Ø1.65m	Ø1.9m	Ø1.9m
U/S configuration	Under-fairing, separate non-structural (Alphabus) tanks, heritage components: AVUM avionics, Ariane 5 EPS pressure system components, CFRP structure	Structural separate aluminium (Al2219) tanks, inter-tank volume used for He and ACS tanks, aluminium (Al2219) structure, AVUM avionics	Aluminium (Al2219) structural tanks, common bulkhead (convex), no reverse pressure, AVUM avionics (also in VENUS study)

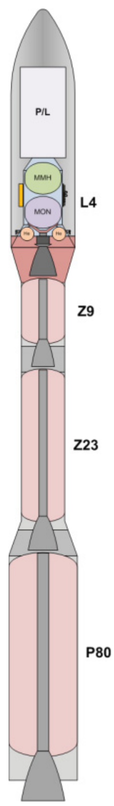
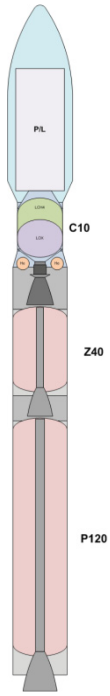
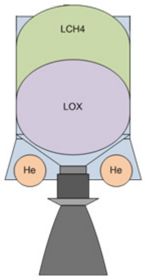
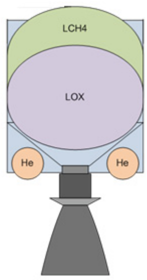
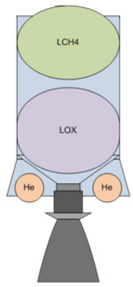


Table 3: Scenario 2 concepts investigated

Name	**Vega E - C10 2.5m CB**	**Vega E - C10 3m CB**	**Vega E - C10 2.5m ST**	
Number of stages	**3**	**3**	**3**	
Lower Composite	**P120 / Z40**	**P120 / Z40**	**P120 / Z40**	
Upper Stage	 C10 2.5m CB	 C10 3m CB	 C10 2.5m ST	
U/S propellant	10t, LOX/Methane	10t, LOX/Methane	10t, LOX/Methane	
U/S engine	MIRA	MIRA	MIRA	
U/S diameter	Ø2.5m	Ø3.0m	Ø2.5m	
U/S configuration	Aluminium (Al2219) structural tanks, common bulkhead (convex), no reverse pressure, aluminium (Al2219) structures	Aluminium (Al2219) structural tanks, common bulkhead (convex), no reverse pressure, aluminium (Al2219) structures	Aluminium (Al2219) structural separate tanks, aluminium (Al2219) structures	

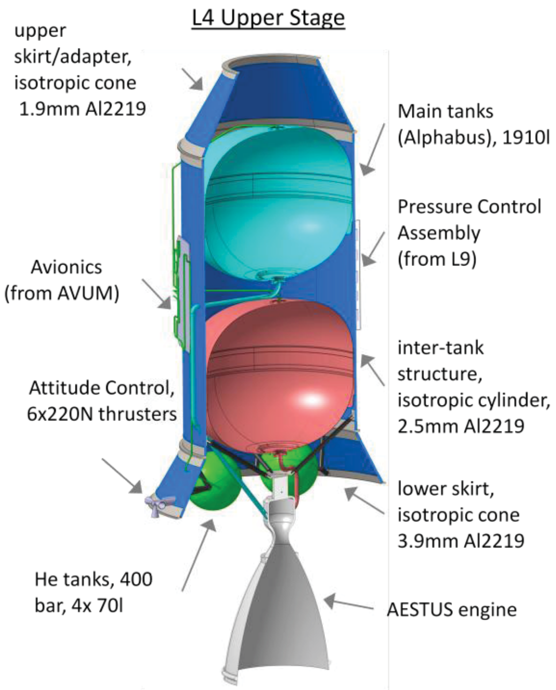


Figure 2: Vega L4 Upper Stage concept

For tank pressurization system a preliminary layout has been made, including the pressurant (e.g. helium) budget, pressurant tanks sizing and an estimation of feed lines and attachments.

Finally the attitude control subsystem was investigated. The sizing requirements have been based on attitude performance (pointing accuracy, roll/yaw/pitch rate, etc) of other known launch vehicles. Subsequently, the attitude control propellant mass has been estimated, together with ACS tanks sizing, and thrusters selection.

Other subsystems (avionics, electrical, pyrotechnics, etc.) have been sized based on average dry mass fractions of comparable stages, as found in literature.

After the aforementioned preliminary sizing, a detailed trajectory calculation has been done. This has been carried out by ASTOS Solutions, with their simulation tool [8]. For each of the investigated concepts an optimal trajectory to 700 km polar orbit has been calculated. The simulation has included splash-down, de-orbit, and maximum acceleration and aerodynamic load constraints. On average, each trajectory has been divided into 30 flight phases.

Following the above mentioned analysis, the upper stages' subsystems have been resized for updated loads and requirements. Any dry mass changes in the upper stages have been balanced with the payload masses, so that the vehicles maintain the same burnout mass (dry mass plus payload mass).

6.1. Scenario 1 sizing

The scenario 1 concepts are based on the Lower Composite (L/C) stages, as summarized in Table 4. The propellant masses and the performance are based on the available literature [2], while the dry masses have been estimated during the study. This allows a direct comparison with the scenario 2 concepts (L/C especially), since the sizing methods are the same.

The results of the upper stage sizing are presented in Table 5. Dry masses of the upper stages do not include payload adapter or interstage structures.

Table 4: Vega Lower Composite – sizing results

L/C Stage	P80	Z23	Z9
Propellant mass [t]	87.7	23.8	10.6
Stage dry mass [t]	7.4	2.65	1.08
Diameter [m]	Ø3	Ø1.9	Ø1.9
Length [m], (incl. nozzle)	11.2	8.4	4.1
Max. Thrust [kN]	2260 (SL)	1200 (SL)	225 (vac.)
Isp [s]	280 (vac.)	289 (vac.)	295 (vac.)

Table 5: Vega Upper Stage concepts

Upper Stage	AVUM	L4	C4	C8
Propellant mass [kg]	550	4200	4200	8000
Inert mass [kg]	470	860	1340	1400
Diameter [m]	Ø1.9	Ø1.65	Ø1.9	Ø1.9
Length [m], (incl. nozzle)	-	5	5	6.7
Max. Thrust [kN], (vac.)	8.6	30	33.8	33.8
Isp [s], (vac.)	313	318	353	353
Fairing mass [kg]	490	660	490	490

6.2. Scenario 2 sizing

The scenario 2 concepts are based on the Lower Composite stages, as summarized in Table 6. Same sizing methods (requirements, loads derivation, material properties, etc.) have been used as for sizing of Vega's Lower Composite.

The results of the upper stage sizing are presented in table 7. Dry masses of the upper stages do not include payload adapter or interstage structures.

Table 6: Vega Evolution Lower Composite

L/C Stage	P120	P40
Propellant mass [t]	120	40
Stage dry mass [t]	9.5	4.0
Diameter [m]	Ø3	Ø3
Length [m], (incl. nozzle)	15.7	6.6
Max. Thrust [kN]	5000 (SL)	1590 (SL)
Isp [s]	280 (vac.)	288 (vac.)

Table 7: Vega Evolution Upper Stage concepts

Upper Stage	C10 2.5m CB	C10 3m CB	C10 2.5 ST
Propellant mass [kg]	10 000	10 000	10 000
Inert mass [kg]	1530	1710	1740
Diameter [m]	Ø2.5	Ø3	Ø2.5
Length [m], (incl. nozzle)	6	5.9	6.8
Max. Thrust [kN], (vac.)	98.1		
Isp [s], (vac.)	364		
Fairing mass [kg]	605		

6.3. Mass breakdown

Each of the six concepts has been sized down to the level represented by mass elements given in Table 8. For all components sized, a 15% growth margin has been applied. For heritage components (flight hardware) no margins have been applied. No cumulative margins were used – margin is applied only on the lowest mass elements in a given subsystem.

7. COST ESTIMATION METHOD

A significant portion of the study has been dedicated to establish cost estimates for the investigated concepts. For this purpose a commercial cost estimation tool SEER-H has been used. This tool allows calculation of recurring and non-recurring costs depending on: component or subsystem, its mass and dimensions, as well as various influencing factors such as complexity, similarity, material type, etc. The influencing factors have been selected comparing the cost of existing components, in order to calibrate the cost estimate. The use of SEER-H allowed cost estimates for each mass breakdown element, down to component level such as batteries, thrusters, high-pressure tanks, etc. The detailed impact of required flight and ground hardware modifications (particularly due to trajectory) on non-recurring costs has not been addressed.

For recurring costs of structural elements, in-house cost estimation relationships have been used. These relationships have been developed based on known manufacturing process costs and on existing components as manufactured in house. Consequently, these cost estimates are considered as the most reliable in the study.

A comparative study has shown that the SEER-H cost estimates for rocket engines strongly deviate from the known engine costs. Therefore, for liquid rocket engines, TRANSCOST 7.3 model has been used. This model comprises cost estimation formulas based on existing launch vehicle engines, stages and operations. TRANSCOST 7.3 has also been used to estimate the flight preparation and operation costs.

All cost estimates have been done on the price basis of 2010 in Euro, assuming an average launch rate of 4 per year.

Table 8: Mass breakdown

Subsystem Dry Masses [kg]	L4 U/S	C10 2.5m CB U/S
Propulsion S/S	**144**	**382**
Engine(s) components	111	295
Thrust vectoring or Engine ACS	0	12
Propulsion Equipment	33	75
ACS S/S	**21**	**28**
Thrusters (6)	15	15
ACS Feed lines	6	4
ACS Tanks	0	9
Tank S/S	**218**	**527**
Equipped Fuel Tank	85	232
Upper Dome	-	22
Upper Y-Ring	-	36
Cylinder	-	66
Inter-tank structure (CB)	-	89
Tank Equipment	-	30
Equipped Oxidiser Tank	85	180
Cylinder	-	56
Lower Y-Ring	-	59
Lower Dome	-	30
Tank Equipment	-	35
Pressurization tank	48	115
Structure S/S	**272**	**337**
Lower skirt	33	59
Inter-tank structure	64	-
Engine Thrust frame	3	96
Upper Skirt	16	74
Interfaces and attachments	66	67
Structure Thermal Insulation	41	42
Elongated Lower Skirt	49	-
Electrical Equipments	**147**	**126**
Avionics	39	34
Electrical Power Supply	83	71
Harness, cabling	25	21
Lines sub-assembly	**25**	**25**
Pyro-equipment	**2**	**6**
Fluids	**34**	**86**
Pressurant	14	31
ACS propellant	20	55
Inert mass (Σ) [kg]	**863**	**1529**
Propellant mass [kg]	**4200**	**10000**
Oxidiser mass	2752	7727
Fuel mass	1448	2273

8. CONCEPTS PERFORMANCE

The above described concepts have been evaluated for launch performance (payload mass), and for costs (recurring and non-recurring). The performance and the costs of the baseline Vega launcher have also been estimated with the same methods, allowing a meaningful comparison of the concepts with the baseline design.

8.1. Scenario 1 – Results

The results of the concepts of scenario 1 are depicted in Figure 3.

Each of the considered evolution concepts can achieve the 1800 kg payload target for the reference orbit (700 km, polar), allowing dual launch of 700 kg satellites (including 400 kg for additional adapters and manoeuvres). The Vega C8 concept further offers a reduction of launch costs as compared to Vega, principally due to the reduction of the number of stages. Since each stage has a certain amount of fixed (non-scalable) costs (avionics, power supply, engine thrust frame, propulsion equipment do not scale with propellant load), consequently the elimination of one stage eliminates the corresponding fixed costs. This reduction of fixed costs is lower than scaling (mass- and cost-wise) of larger propellant tanks. Nevertheless, the Vega-C8 concept is expected to have significant non-recurring costs (4.5 times higher than AVUM development), primarily due to additional development of the AESTUS M engine.

Comparable development costs are expected for a smaller C4 upper stage. This concept, while achieving the 1800 kg payload target, has slightly higher recurring costs than Vega-C8 while comparable to the baseline Vega. That is caused by maintaining the four stage configuration with the same reasoning as for Vega-C8.

The Vega-L4 concept offers the highest performance (1940 kg), potentially allowing double launches of 800 kg satellites, and single launch of 1900 kg payloads. The recurring costs are expected to be 10% higher than those of Vega, or 12% higher than Vega-C8. However, the specific costs (EUR/kg) are lower due to higher payload capacity. At the same time, this concept has the lowest estimated development costs of all the Vega evolution options considered. This is achieved primarily by use of multiple off-the shelf components (Alphabus tanks, Aestus engine, Ariane 5 EPS pressurization components, AVUM avionics, etc). Furthermore, since the aforementioned components are manufactured for other systems, there is a potential for additional cost reduction due to increased production rate of these components. The final advantage of this concept, while not quantified in this study, is the development time, which due to use of off-the-shelf parts, could be significantly lower than that of Vega-C4 or Vega-C8.

Consequently, Vega-L4 is an interesting concept for a short term evolution of Vega. If the LOX/Methane propulsion programs advance further, the Vega-C8 concept is another potential improvement.

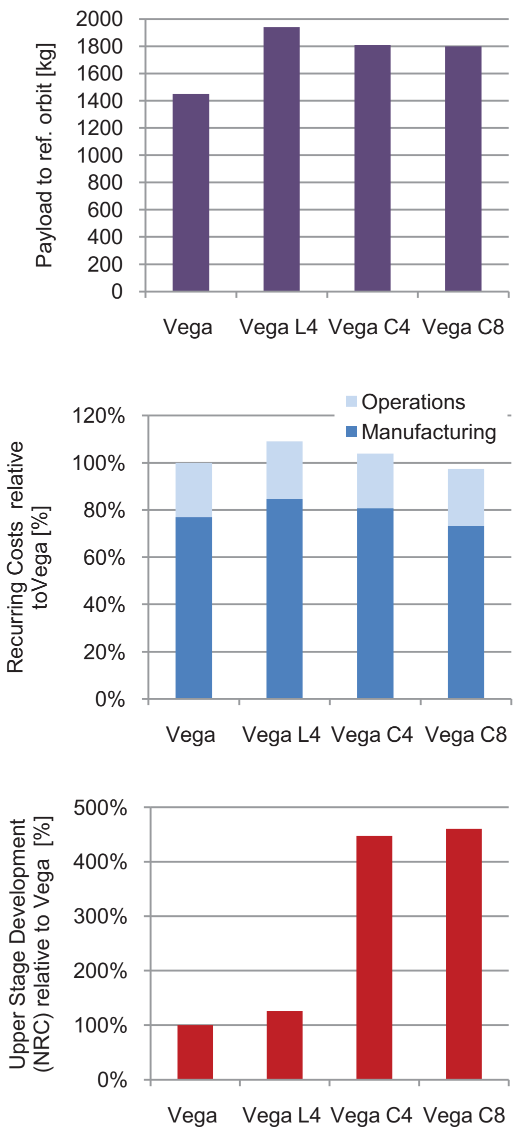


Figure 3: Scenario 1 concepts - results

8.2. Scenario 2 – Results

The results for the concepts of scenario 2 are depicted in Figure 4. The considered Vega Evolution C10 concepts achieve the required 2700 kg performance or higher. Comparing the performance of the concepts, the 2.5 m common bulkhead (CB) option can launch 6-10% heavier payload than the alternatives. This is due to the lower dry mass of the upper stage with the common bulkhead than a comparable upper stage with separate tanks. It indicates that the CB offers visible performance mass advantage.

As evident from the results, the differences between the concepts' costs are small. Unsurprisingly, this indicates that the Vega Evolution -C10 costs are dominated by the Lower Composite, which remains constant for the three concepts. Nevertheless, there are several conclusions that can be drawn. First, the manufacturing costs are expected to be comparable, regardless if the common bulkhead or the separate tanks architecture is used. Evaluation of only the upper stage costs indicates a difference of less than 3% between the 2.5m common bulkhead concept and the other two concepts. In regard to the propellant volumes, also the stage diameter has effectively no impact, primarily since for all concepts the tanks have very short cylindrical sections. It is expected that in case of higher volumes the difference between the concepts would be larger, since then the elongated cylinder could require stiffening, and consequently it would be more expensive.

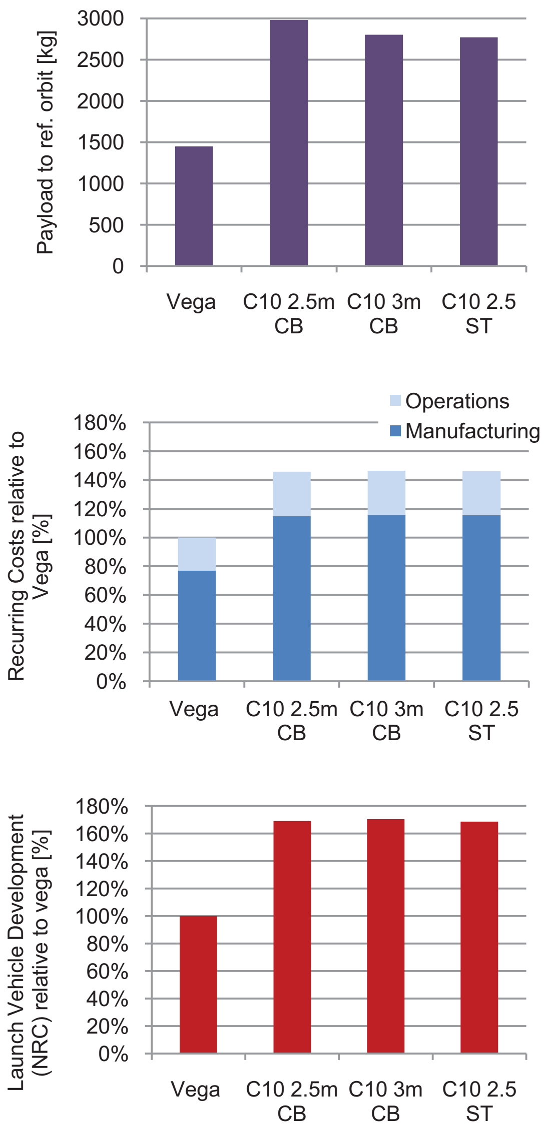


Figure 4: Scenario 2 concepts - results

The recurring costs of Vega Evolution-C10 concepts are approximately 40% higher than those of the baseline Vega. This is strongly dependent on the Lower Composite costs and should be further verified. However, it is notable that the specific launch costs (EUR/kg) are reduced by 30%.

The development costs of all concepts are effectively the same (the estimates have less than 1% difference). This shows, that although the common bulkhead technology does require additional development, its

NRCs could be comparable to those of two bulkheads, and a stiffened cylinder (required for the inter-tank structure).

The comparison of development costs of Vega Evolution-C10 with those of Vega and the scenario 1 evolutions shows, that the Vega Evolution would require a significantly higher investment and development time. This is mainly due to the expected high NRC of larger solid stages. These costs could be significantly reduced if the same infrastructure as for Vega would be used. While some commonalities have been considered in the estimates, these assumptions still have to be verified.

9. CONCLUSIONS

In this internal study six Vega evolution concepts have been investigated, and compared with the baseline Vega launcher. Considering performance and costs, the Vega-L4 concept could be a viable short term evolution. It offers significant performance increase (1940 kg compared to 1450 kg for the baseline), at a 10% recurring cost increase; however with low development costs and a short development period.

For the heavier scenario, Vega Evolution-C10 is a viable candidate; however it should be compared to other concepts with LOX/LH2 or storable propellants. Such a comparison should have a common set of assumptions and references. For a recommendation of the Vega Evolution concepts further investigations on the basis of a set of requirements need to be performed.

10. ACKNOWLEDGEMENTS

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12. ABREVIATIONS

ACS	- Attitude Control System
CB	- Common Bulkhead
ETF	- Engine Thrust Frame
GSL	- Generated Satellite List
GTO	- Geostationary Transfer Orbit
Isp	- specific impulse
L/C	- Lower Composite
LEO	- Low Earth Orbit
LH2	- liquid hydrogen
LOX	- liquid oxygen
MEO	- Medium Earth Orbit
NRC	- Non-Recurring Cost
RC	- Recurring Cost
ST	- Separate Tanks
SSO	- Sun Synchronus Orbit
U/S	- Upper Stage