Cost Estimation and Development Approach of the EURASTROS Concept

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Abstract

The cost estimation from the European Astronautical Space Transportation (EURASTROS) study involved analogy, parametric and engineering build-up methodologies to identify the potential cost of a future European crew launch system to Low Earth Orbit. The total non-recurring program development cost of the EURASTROS concept are in the 4000 M€ range, whereas the average recurring mission cost would be in the 400 M€ range. The development approach considers four different test flights for certification. The results indicate comparability with other crew transportation programs/services, considering that reusability, which could further reduce mission cost in the future, was not part of the study.

1. Introduction

The European Astronautical Space Transportation (EURASTROS) study, which was carried out in 2021, was a joint undertaking of the German Aerospace Center (DLR) and ArianeGroup GmbH with the main objective to identify missing technologies and infrastructures for an independent European human space transportation (EHST) to Low Earth Orbit (LEO) and to predict the corresponding cost. The study included several trade-offs regarding e.g. ascent, descent and abort trajectories, space system design and launch abort system concepts.

The present work is focused on the cost estimation of an EHST program and shall provide a discussion basis for initial financial budget planning, funding and business opportunities. Since the development planning plays an important role for the cost assessment, a baseline proposal including preliminary model philosophy is described in a dedicated section. The paper starts with a very brief system concept overview, followed by the development approach. Afterwards, the cost estimation approach, assumptions and results are described. A subsequent section provides additional analyses and discussion of the results before this work concludes with a summary and outlook for future study and analysis opportunities regarding cost and finance.

2. EURASTROS System Concept Overview

The EURASTROS system concept covers all elements needed to implement a European crew transportation program to LEO destinations. This includes the launch vehicle, the payload (i.e. the crew and service module) and related launch abort/escape means, as well as the ground infrastructure and personnel involved. As described also in [1] and [2], one high-level requirement was the adaptation of existing Ariane 6 launch vehicle. It turned out that the A6.4 version with 4 boosters is more suitable mainly due to its performance margin compared to the A6.2 version. In the future, there may be new developments of the launch segment but for now the A6.4 is considered as baseline.

It is planned to (re)use the recently inaugurated ELA-4 launch pad at Guiana Space Center (GSC) for launch and the existing surrounding infrastructure for launch vehicle and payload preparation. More details are presented in section 5.4 of this paper.

The space segment consists of a crew module (CM), which is the capsule, a service module (SM) and a corresponding launch abort system (LAS). Based amongst others on the experience from the ESA Atmospheric Reentry Demonstrator (ARD), Automated Transfer vehicle (ATV) and the Orion European Service Module (ESM) projects, the baseline selection for the EURASTROS crew module is an Apollo-shaped capsule design and a separate service module which builds on the ASTRIS Kick-stage layout using BERTA engines. More details regarding trade-offs and design choices can be found in [2] and [3]. Preliminary system concept layouts are shown in this paper within the respective cost result subsections 5.2, 5.3 and 5.4 for the different segments.

3. Development Approach (Space Segment)

The development approach and planning, especially for all items which are sent to space, is a major driver of the non-recurring cost. Already available technologies, equipment or even subsystem assemblies can significantly decrease cost, while newly required technologies or equipment which still needs to be designed, developed or are subjects to major modifications, will increase the cost.

For EURASTROS, a top-level development logic for the space segment was established on system and subsystem level to come up with an overall system test and test flight approach, and to support the estimation of the non-recurring cost. The development logic shown in Figure 1 provides a tentative timeline and milestones, and highlights the major development and qualification efforts per module on subsystem level (left white boxes), the intended test campaigns on module-level (yellow), the system modules needed in the development phase (pink boxes), the flight model developments until certification (white boxes in the middle), and the corresponding (test) flights (blue boxes). We assess that a minimum of 6-7 years development time is needed until program certification, depending on the design, heritage and also the programmatic momentum.

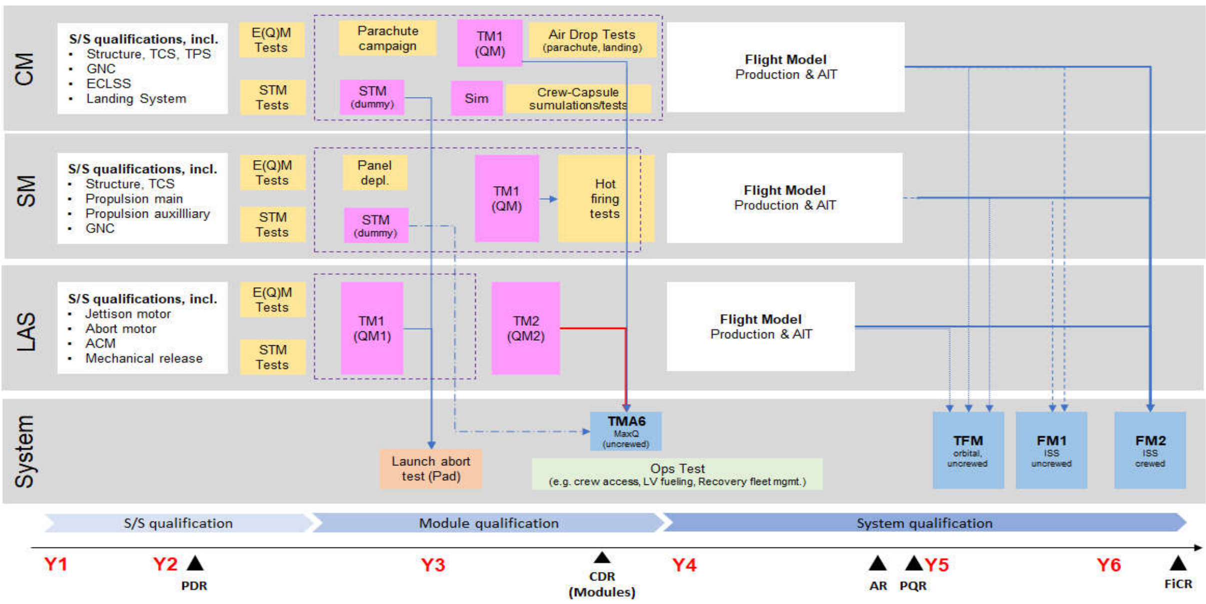

Figure 1: EURASTROS top-level development logic and preliminary timeline for the space segment

Table 1 further details the different models per space segment modules, reflecting also the (re)use for subsequent subsystem (S/S) models and tests. Wherever possible, combined engineering models (EM) and qualification models (QM), which can also be structural-thermal models (STM) for mechanical elements, are foreseen in order to optimize non-recurring efforts and cost, while pre-mature technologies require dedicated development models (DM). The model philosophy is broken down to subsystem level and implemented into the cost model. Table 2 then further translates the development logic from Figure 1 into a list of system tests and test flights and the required model maturity per module. It provides launch system considerations and indicates particularly the use of system models per major system test and test flight.

Table 1: Model philosophy per space segment module

Models	Name	CM	SM	LAS	Remarks
DM	Development Model	selected S/S	selected S/S	all S/S	
EM	Engineering Model	all S/S		all S/S	re-used for QM/STM
QM/STM	Qualification Model	all S/S	all S/S	all S/S (2x)	
GRM	Ground Ref. Model	QM re-use	QM re-use	n/a	

Table 2: Top-level demonstration and flight logic, incl. system module model utilization

Tests & (Test) Flights	Main Systems to be tested	CM	SM	LAS	Remarks
Air Drop	CM	Several iterations up to QM	-	-	
Hot firing	SM, LAS	-	QM	Solid Motor QMs	Two campaigns
Pad abort	LAS, CM	dummy + parachutes	dummy + release mech. SM/CM	QM1	
Flight abort	LAS, CM	dummy + parachutes	dummy + release mech. SM/CM	QM2	using e.g. A6.2 or other possible alternative
Orbital Qualification	CM, SM, LAS	FM1	FM1	FM1	Non-crewed [a]
LEO cargo flight	SM, CM	FM2	FM2	-	Non-crewed, to LEO platform
LEO crew certification	CM, SM, LAS	FM3	FM3	FM2	Crewed, to LEO platform

[a] Flight w/o crew but with crew-rated launch vehicle (i.e. not with a potential ‘cargo-only’ version of A6.4)

In order to reach certification level, there is four flights included within the test program, a flight abort test, an orbital qualification flight, a cargo flight to the LEO destination (current plan is to the ISS) and eventually a crewed flight campaign to the LEO platform.

The objective of the flight abort test is to reach MaxQ conditions and to test following abort sequence: LAS ignition, LAS stabilization and guidance, CM release and CM parachute landing (and recovery). The orbital qualification flight will perform a nominal flight test to LEO incl. LAS separation, SM orbital maneuvers, SM re-entry burn, CM/SM separation and CM re-entry, landing and recovery. This flight requires flight models (FM) for all system modules. The LEO cargo flight demonstrates a nominal cargo delivery mission to the LEO platform, incl. rendezvous and docking/berthing. For such a mission, no (or a dummy) LAS is needed. As a last step, a crewed mission to the orbital destination is foreseen, which covers all activities of an astronautic flight.
Depending on future strategic decisions, the last two flights could be already used for commercial applications.

4. Cost Estimation Approach

So far, there is not many human space transportation programs in operation, and from the few ones which are or are in planning, access to cost data is limited. However, some international reference information has been published, and in Europe exist already several studies, technology demonstration and also system developments for human spaceflight programs, which support not only the future development of an EHST program but also the present cost estimate. Besides the assessment of the total non-recurring (NRC) and recurring cost (RC) for such a program, one aim of the EURASTROS study is also to identify the cost drivers and distribution over the various contributors. In the following subsections, the applied cost breakdown, cost estimation methodologies (CEMs) and key assumptions made are presented, as well as how this has been implemented into the cost model.

4.1 Cost Breakdown

The EURASTROS cost estimate is broken down into the three segments: space, launch and ground. Furthermore, it is divided into non-recurring cost for design and development, and recurring cost for production and operation. The RC start with the first crewed flight after the certification flight. Everything else before is counted within the NRC. Table 3 presents the cost breakdown down to the 3rd level (i.e. segment, element, sub-element).

The space segment cost considers all labor and material cost related to the CM, SM and LAS module S/S development and module integration. Additionally, it covers all overarching space system tests and managerial and engineering efforts under "system wraps".

The launch segment cost consists of expenditures related to the launch vehicle procurement, the adaptation of the launch vehicle as well as new fairing and adapter developments. Moreover, a project office cost percentage is added to reflect the management and coordination efforts for all launch segment upgrades, particularly for the NRC.

The cost of the ground system is a sum of all cost which are not part of the space and launch segment. This includes additional preparatory and operational activities for an EHST program, launch and landing site enhancements, new personnel and also recovery services. As for the launch segment, a percentage is added to cover project office related activities.

Table 3: Cost contributors per segment

Space	Launch	Ground

• Crew Module
• Service Module
• Launch Abort System [a]
• System tests, incl.
  o Hot firing
  o Abort, drop
• System efforts, incl.
  o Management
  o Engineering
  o AIV
  o PA
  o Supply Chain
	• Launch Vehicle (LV)
	• LV adaptation
	  o Hardware
	  o Software
	• New LV items
	  o Fairing
	  o P/L adapter
	• Project Office
		• Crew Preparation
		• Launch Site, incl.
		  o Infrastructure
		  o Operations
		  o Services, S/W
		• Mission Control, incl.
		  o Infrastructure
		  o Operations
		  o Services, S/W
		• Landing, Recovery
		• Project Office

[a]Launch Abort System categorized under space segment independently of actual design choice

4.2 Methodologies

For the EURASTROS study, all three major CEMs have been applied, namely parametric, analogy-based and engineering build-up (a.k.a. bottom-up) estimation, depending on the data available.

For the space segment, the chosen main methodology is parametric estimation. Using mass-based cost estimation relationships (CERs) the flight model cost are calculated. CERs are equations which are derived from historical data. They link the cost of a unit, subsystem or system to one or several technical parameters from a set of previous missions.

From such a data set, a trendline can be generated using regression analysis. The EURASTROS cost model uses power functions as CERs as indicated in Equation (1) below. The unknown, dependent variable **Y** represents the cost while the known, independent variable **X** in our case is the mass, which is one of the most prominent cost drivers. The slope **a** defines the overall increase/decrease of cost vs. mass, whereas the exponential factor **b** introduces the economy of scale. Whereas the first is typically an outcome of the regression, the latter is based on experience and depends amongst other on the share between mechanical vs. electrical elements in the unit or subsystem to be costed.

$$\mathbf{Y} = \boldsymbol{a} * (\boldsymbol{X^b}) \tag{1}$$

While the production cost estimates for most parts of the space segment use CERs, the development cost are estimated using a T1-equivalent approach as described in [4] and [5]. Here, the (theoretical) first flight unit (TFU or T1) has a value of 1, while test models such as DMs, EMs or QMs are characterized by equivalents to T1, based on their cost compared to the flight models. In our case an early phase DM is the equivalent of 0.3 times the TFU, while the engineering model is considered 0.5 times “worth” a flight model. With a preliminary model philosophy available, which exists for EURASTROS down to subsystem level, the quantity of models multiplied with their respective factors is summed up and then multiplied further with the flight model cost, which provides the hardware cost for the development phase. For example, if the FM cost of a S/S assembly is 2 M€, and there is two DMs and two EMs needed during the development phase, the total hardware cost of the development phase would be 2 x 0.3 plus 2 x 0.5, times 2 M€, which leads to 1.6 times 2M€ and thus 3.2 M€. Additional factors for management, product assurance or engineering effort (with the latter strongly dependent on the technology readiness of the subsystem) add the labor cost to the NRC estimate. Besides the general description of this approach in [4] and [5], more information on the different steps, also regarding the system integration and test efforts, can be found in the space segment cost result section 5.2.

The ground segment development cost is mainly derived from analogy estimates for infrastructure constructions and adaptations, scaling up or down from e.g. public information regarding launch site construction contracts. The operational and service cost consist primarily of engineering build-up estimates using requests for information or quotations (RFIs/RFQs) from previous studies, and from infrastructure maintenance cost factors which were derived amongst others from typical, annual household expenditures.

The cost of ‘to be developed’ items for the launch segment, i.e. the fairing and adapter, were computed similarly to the space segment, using mainly CERs for production and the T1-equivalent approach for development cost, while the vehicle internal hard and software adaptation cost are based on best engineering guesses and analogy estimates.

More details and cost examples for the different segments are presented in the respective cost result sections within chapter 5.

4.3 Ground Rules and General Assumptions

For economic and technical aspects, following general and also segment-specific ground rules and assumptions have been made for the EURASTROS cost estimate:

- All values are normalized to Million Euro (M€), constant fiscal year (FY) 2021. Any deviations or exceptions are explicitly stated within the respective sections.
- The results are presented as ‘point estimates’, i.e. single values which are within the currently selected contingency and margin ranges. No probability or confidence levels statements are made.
- The NRC include all cost related to all test flights included in the development program.
- The average RC assume 20 missions over 10 years of operation (i.e. one mission every six months), and a learning curve for the space segment production with a conservative 90% slope.
- The cost per (test) flight are assumed to be incurred on a half-year basis, i.e. we assume two launches per year for this theoretical example (no dedicated market share of the EURASTROS program was identified).
- No Agency overhead cost are included, no award fees nor incentives are included.
- The launch abort system (LAS) is considered as part of the space segment.
- The launch segment estimate is based on Ariane 6 as reference and enabling launch vehicle.
- The ground segment is based on the re-use and adaptation of the Ariane 6 ELA-4 launch pad in Kourou and associated infrastructure at Guiana Space Centre.
- The cost estimate does not address or include reusability of the space nor launch segment.

4.4 Cost Model

In order to capture, compute and organize the cost data, a DLR Human Spaceflight Cost Model was adapted for the EURASTROS study. It is prepared for the T1-equivalent approach and automatically selects the assumed equivalent factors based on the proposed model philosophy and technical maturity. From top to bottom (i.e. per row) the various cost contributors are listed, grouped e.g. in segments, subsystems and operational activities. From left to right (per column) the model philosophy, the mass budget, direct input for infrastructure and tools, the CERs and the resulting recurring and non-recurring cost with and without margins are organized, as depicted within the cost model example in Figure 2.

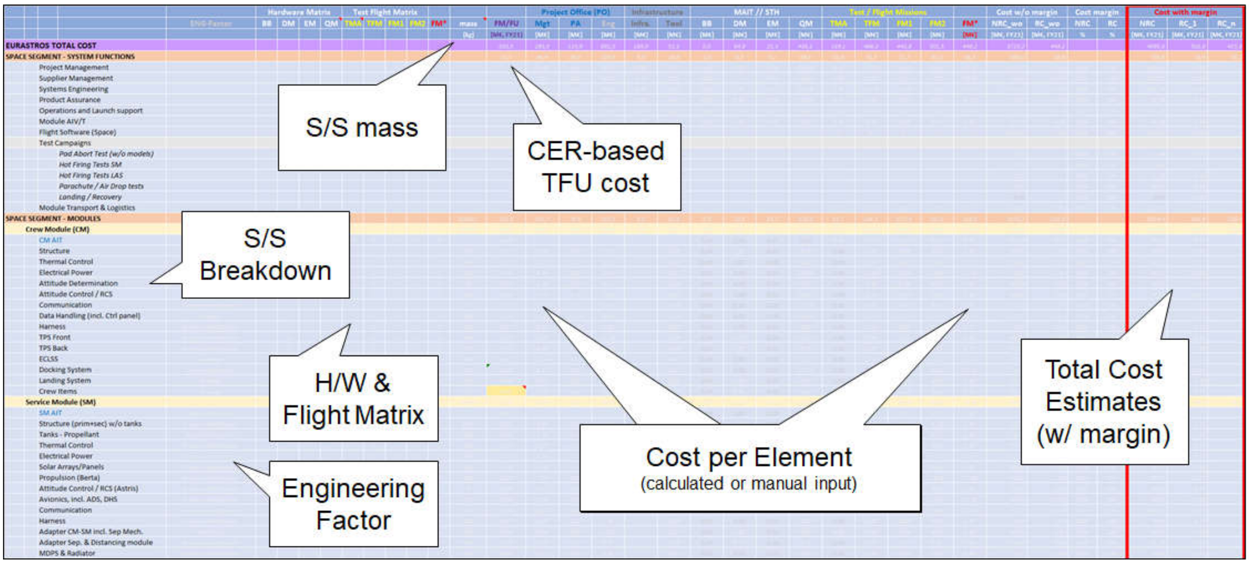

Figure 2: EURASTROS cost model snapshot (values intentionally 'blurred'), indicating the cost approach implementation which is primarily based on the T1-equivalent approach

Within the model, a nominal margin/contingency of 10% has been added to all lowest level cost contributors for both NRC and RC, with the exception of RC for Space Segment subsystems which require at least a 're-design'. Here, a 20% cost margin has been added instead.

5. Cost Estimation Results

The following subsections present the estimation results per segment, with a slight focusing on the non-recurring cost which are needed to set-up the EURASTROS program. The recurring cost strongly depend e.g. on the mission frequency (i.e. number of launches per year), learning effects, supplier contract conditions and if modifications are planned or necessary throughout the program duration. Moreover, an upfront top-down assessment was made to get an initial idea regarding potential (life-cycle average) recurring cost per segment and to identify the respective cost shares. At last, a total cost overview with some major observations is presented.

5.1 Top-down recurring cost (RC) breakdown

Prior to the actual estimate, a top-down cost share for the recurring cost has been identified in order to assess remaining cost for certain elements based on different seat cost (or cost per mission) and already fixed or known cost. For one of the rather moderate scenarios the breakdown is shown in Figure 3. If such a program aims e.g. for a seat cost of 125 M€ with a system capable of bringing 3 crew members into orbit, the share would be the following: A total, average mission cost of 375 M€ requires an A6.4 launch vehicle which is assessed with 120 M€ for crewed flights. The remaining 255 M€ can be shared amongst the space and ground segment. Then we assume a ground segment cost of 1/3 compared to the launch vehicle cost, which is a not uncommon factor for expendable launch systems, leading to 40 M€. This leaves around 215 M€ for the space segment, which is assumed to be broken down to 55% for the crew module, 35% for the service module and 10% for the launch abort system, with system wraps (i.e. module integration and overarching management efforts) distributed here over the modules. Based on these percentages, a crew module would cost close to 120 M€, a service module around 75 M€ and a launch abort system between 20 and 25 M€. These values indicate that the production and operation of such program elements may be ambitious but not unfeasible.

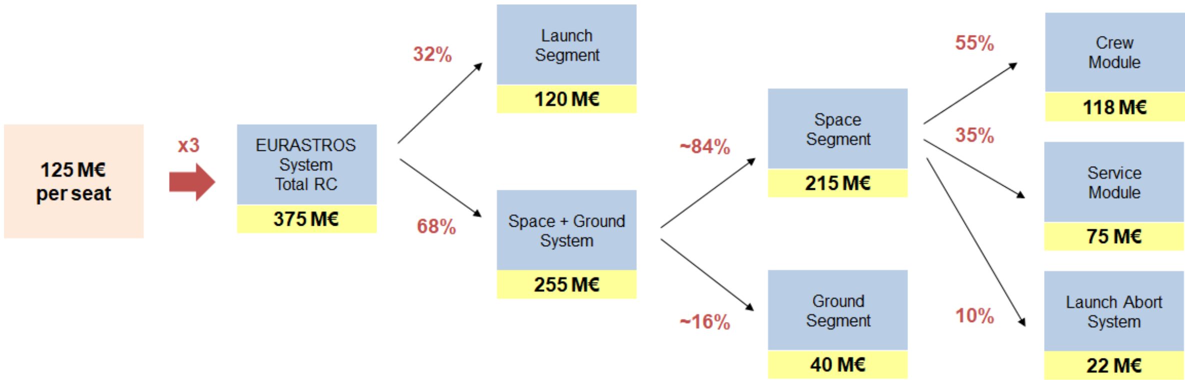

Figure 3: Selected top-down cost breakdown scenario for an average mission with 125 M€ cost per seat

5.2 Space Segment Cost

The space segment cost is broken down into the model cost for CM, SM and LAS which are shown in Figure 4, with the system management, integration and test cost summarized in a separate category.

The estimation methodologies selected is described already in chapter 4.2. However, the space segment cost estimation sequence is further detailed in the following:

- The RC for the *first flight* unit on subsystem (S/S) level are identified using mass-based CERs which were developed together with Industry partners in previous DLR projects and studies, such as BERT [6] and Post-ISS DLR Orbital Hub [7]. Validation and adaptation of selected S/S CERs for EURASTROS has been done amongst others with a commercial H/W cost estimation tool.
- The *average* RC are calculated using a unit-based learning curve theory, with a slope of 90%, and considering 20 missions in 10 years. A slope of 90% means in this case that each time the production quantity doubles, the next unit produced cost only 90% of the one before doubling the quantity.
- Then, the NRC are identified using the (theoretical) flight-unit (TFU, T1) equivalent approach considering the H/W model philosophy on S/S level per module, an engineering (ENG) factor which depends on the re-use and heritage per S/S and an additional Management and Product Assurance (MA/PA) factor of 15 % per S/S NRC. Additionally, each module includes an 8% Assembly, Integration and Test (AIT) factor on top of the H/W model cost.
- For both NRC and RC additional system-level ‘wrapping’ cost are included on top of all module cost which are listed together with the system-related test campaigns under system wraps.

The non-recurring development cost for the space segment, including all models needed for the current baseline test flight approach, which is described in chapter 2, add up to 2800 M€.

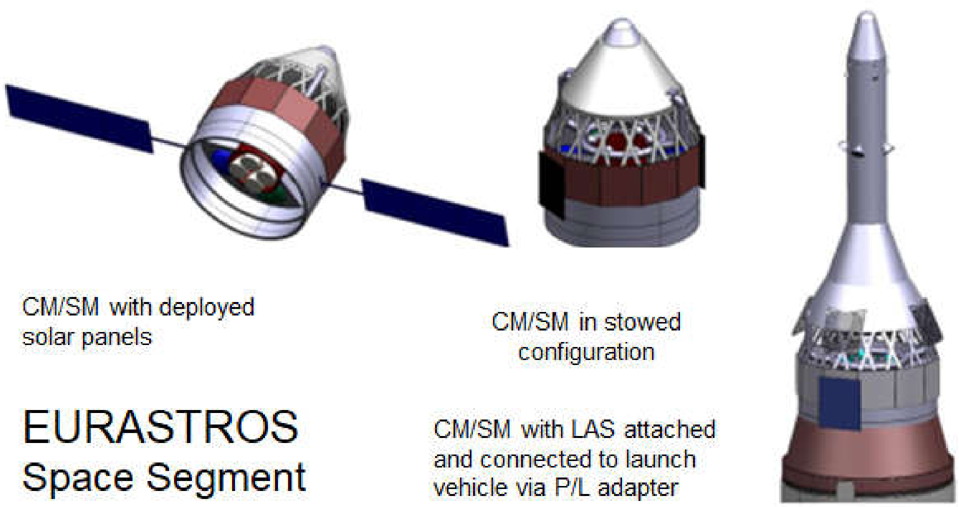

Figure 4: EURASTROS space segment in 3 different configurations, adapted from [2]

The breakdown shown in Table 4 clearly identifies the crew module (CM) as biggest contributor, due to the complexity of accommodating humans on-board and the technology and engineering effort needed to develop such a module. The proposed service module (SM) is based on an ASTRIS Kick-stage and a set of BERTA engines, whereas the preferred launch abort system (LAS) is defined as a 'tower concept' using solid motors. The system activities cover all overarching management, product assurance, integration, test and engineering tasks, as well as efforts related to system test activities such as CM air drop tests or firing tests campaigns for the SM and LAS. The mass budgets and design details, which have influenced the cost estimate are described in [2] and [3].

The average RC per flight (or mission) for the entire space segment, including all three modules and system related activities, are – based on the current assumptions listed before – around 235 M€.

Table 4: Space segment cost breakdown

	NRC [M€]	**RC [M€]**	**Remarks**
System Wraps	750	55	Incl. system tests and efforts
Crew Module	1050	95	
Service Module	650	60	
Launch Abort System	350	25	Tower concept selected
Total – Space Segment	2800	235	

5.3 Launch Segment Cost

The launch vehicle selected for all (test) flights is the Ariane 6.4, amongst others due to its availability and performance. The intention is to change as little as possible to the current configuration in order to keep the development effort at a minimum level. However, a few modifications and adaptations have to be made, such as the development of a new fairing and launch vehicle to payload (i.e. the space segment) adapter, as well as some stage-internal adaptations, as presented in Figure 5:

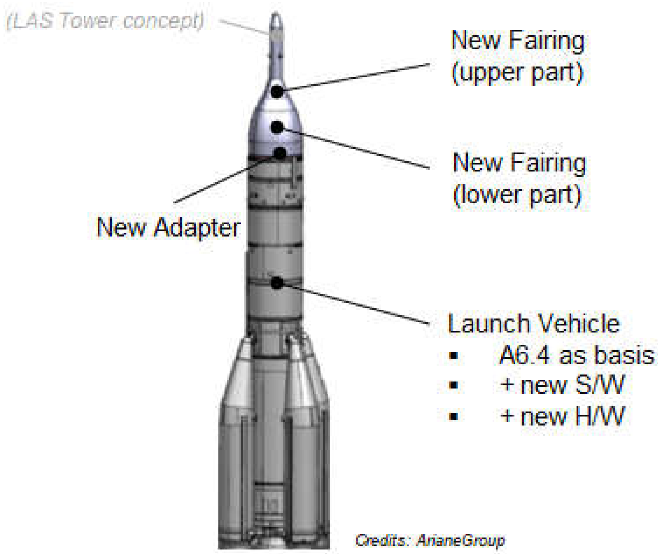

Figure 5: Adapted Ariane 6.4 for crew transportation

Table 5 indicates the breakdown of the NRC assessed for the Launch Segment. The 600 M€ estimated for the Ariane 6.4 consists of 4 test flights plus additional engineering effort and H/W and S/W cost needed to adjust for the required crew transportation capabilities and reliability.
For the average RC, an A6.4 price estimate with the new fairing and adapter replacing the old one(s) is made, which leads to a cost in the 130 M€ range including project office and margins.

Table 5: Launch segment cost breakdown

	NRC [M€]	RC [M€]	Remarks
Launch Vehicle	600	130[a]	NRC incl. H/W + S/W adaptations
New Fairing	150	n/a here	Upper and lower part combined
New Launch Adapter	50	n/a here	
Project Office	50	n/a here	
Total – Launch Segment	850	130	

[a]RC for launch vehicle includes adapted stages plus new fairing and adapter which are part of crew-rated A6.4

5.4 Ground Segment Cost

The EURASTROS Ground Infrastructure and Operation, also referred to as "Ground Segment", can be divided into four different categories, which are described in the following. The aim is to maximize the re-use of already existing infrastructure and personnel, and to identify what is needed additionally to enable a European crew transportation program, as similarly proposed by a CNES-led study on human spaceflight from Guiana Space Center (GSC) [8].

For each category, there are different options in terms of capabilities, comfort, independence and also regarding the development timeline, which can influence the cost. For EURASTROS, the selected launch site is also the GSC in Kourou, French Guiana. Figure 6 presents an overview of infrastructure elements on-site Kourou and particularly the Ariane 6 ELA-4 launch pad (shown within the picture) and additional infrastructure which may be launch site independent. In the following, the identified categories are described in more detail, indicating what the current assessments, proposed options and uncertainties are.

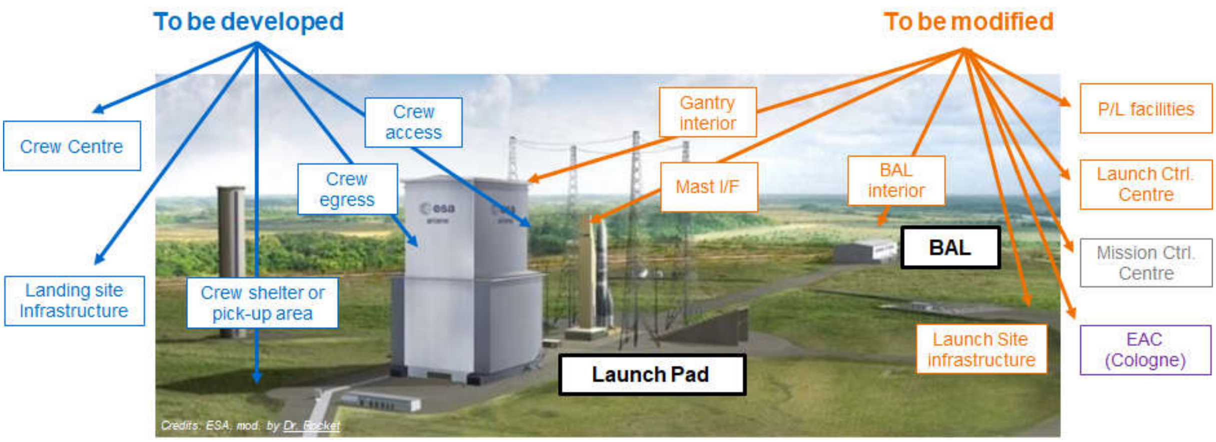

Figure 6: Impression of ELA-4 Launch Pad at Guiana Space Center (GSC) with indications of infrastructure either to be modified or newly developed, on-site or outside of ELA-4 or GSC respectively (Credits: ESA; Dr. Rocket)

Crew Preparation and Training. Independently of the launch vehicle and site, the European astronauts (or any other partners or customers) need additional EURASTROS-specific training. Since there is already an existing European Astronaut Centre (EAC) in Cologne, the intention is to enhance the already existing capabilities there. Considering not only additional tasks but also an increased frequency of crew members to be trained, additional offices, laboratories and training personnel will be required. The assumption is that up to 20 people for e.g. training, supervision and medical support are needed. Furthermore, two crew module mock-ups, one for functional and operational, one for under-water training are necessary, as well as a simulator to train flight and emergency cases. Additionally, crew items such as suits and a variety of crew supplies should be kept on stock.

Launch Site Infrastructure and Launch Operations. The majority of adaptations and new required elements is expected for the launch site. Since A6.4 is selected as reference launch vehicle, the recently reconstructed ELA-4 launch pad is also the baseline for the EURASTROS program. However, several buildings need either to be modified, or added to the existing assets. This includes e.g. the interior of the Mobile Gantry as well as a new crew module access gangway and a crew egress system for emergency escapes. Furthermore, the mast on the launch pad requires additional electrical and mechanical interfaces while the newly build launcher assembly building (BAL) probably only needs little modification. However, depending on the final LAS design and fairing connections, certain tools and/or office space may be needed still. In case of a high-frequent launch manifest for Ariane 6 related to EURASTROS and other missions to be launched, an additional payload building within the preparation facility (EPCU) may be also considered. The amount of adaptations, the construction timeline and also the level of modernization strongly depends on the needs driven by the program. In any case, some additional general infrastructural modifications are required, such as (rail) roads or for the P/L fueling area to comply with the crew specific needs for this new spacecraft type. Moreover, the Launch Control Centre (LCC) needs to be enhanced with additional work stations, S/W, back-up and training rooms and of course additional personnel. A completely new infrastructure to be constructed is a Crew or Astronaut Centre to host the crew members, training and medical personnel, as well as family members for the duration of the launch preparation. This includes also a car pool to allow quick transportation on the launch site.

Mission Operations. After lift-off, the LCC hands over the responsibility to the Mission Control Centre (MCC). The latter could but does not necessarily need to be close to (or at) the launch site. There are several existing options which could be used, re-used or enhanced, such as the ATV-Control Centre in Toulouse, the European Space Operations Centre (ESOC) in Darmstadt or the German Space Operations Centre (GSOC) close to Munich. This depends on the availability, the infrastructure expansion-potential and Agency support promises. In any case, additional office space, work stations, S/W elements and personnel is needed to serve this program. To maintain contact between ground and launch/space segment as much as possible, several ground stations slots need to be reserved, with additional use of space-based TDRS/EDRS service links to reduce or eliminate potential communication gaps.

Landing Site and Recovery Infrastructure and Operations. A significant part, especially for the EURASTROS recurring operation, is the preparation and execution of the landing and recovery activities, for nominal and emergency cases. Currently, a water landing is planned for the crew module. For nominal landing, a crew reception infrastructure incl. medical check-up laboratories and rooms is foreseen, either in Kourou, or alternatively on the Azores (to be decided, depends on the actual trajectories). For the CM recovery, the current baseline is to rent and request three naval (or commercial) recovery support teams, including transportation vessels and helicopters along the trajectory within the Atlantic Ocean. In the future, an acquisition of an own fleet could be possible, similar to SpaceX.
Both, nominal landing site personnel as well as recovery teams require initial and regular operational trainings for both nominal and emergency cases, which means that the related team members to be hired/acquired and all service providers need be selected already early in the EURASTROS development program, which is considered in the cost.

It is important to note that the present cost estimate only covers the (G/S) non-recurring and recurring expenses which are required for EURASTROS *in addition* to what is already available and financed as part of existing services and e.g. launch contracts. Table 6 presents the cost for all identified ground segment categories described plus an additional percentage of 10% for project office related expenditures. Including operations for all four planned test flights, the total NRC is estimated to be around 450 M€. The recurring cost are mainly driven be the recovery activities/services and will be in total around 50 M€ per mission, given the current assumptions.

Table 6: Ground segment cost breakdown

	NRC [M€]	**RC [M€]**	**Remarks**
Crew Preparation	75	5	At ESA EAC in Cologne
Launch Site & Control	175	15	At GSC
Mission Control	100	10	No centre for (re)use selected yet
Landing Site, Recovery	60	15	Water landing chosen
Project Office	40	5	
Total – Ground Segment	450	50	

5.5 Cost Summary

The total non-recurring cost of EURASTROS is assessed with 4100 M€, as summarized in Table 7, and an average recurring cost of around 415 M€ per flight. This leads to an NRC/RC ratio of around 10:1 which is reasonable for such complex, and particularly crewed systems.

Table 7: EURASTROS total cost overview

	NRC [M€]	RC [M€]	Remarks
Space Segment	2800	235	Incl. launch abort system
Launch Segment	850	130	Based on Ariane 6.4
Ground Segment	450	50	
Total – Program	4100	415	

Given the RC of 415 M€, the cost per seat would be close to 140 M€. This is slightly more the initial top-down cost breakdown which was used to identify a potential cost share. However, the RC distribution is still very similar with around 57% (vs. 57%) for the space segment, 31% (vs. 32%) for the launch segment and 12% (vs. 11%) for the ground segment. Moreover, other human space transportation services such as SpaceX Crew Dragon and Boeing Starliner have also a similar share from 24% to 36 % respectively for the launch segment and the remaining 76% and 64% combined for the space and ground segment, as derived from a NASA study in 2019 [9].

6. Discussion and Analysis

This section provides some selected additional discussion aspects and analyses, such as sensitivity checks, additional system and cost options as well as a description of the cost driver for the overall program. Furthermore, it elaborates on the cost model validation and provides some ideas on cost savings and other financial considerations.

6.1 Cost Options

The most prominent trade for the EURASTROS concept was made for the launch abort system. Several options have been investigated with the two finalists called the tower concept (our final proposal) and a hot concept which aims to keep the nominal fairing geometry, leading to an integrated solution with all LAS motors under the fairing. In the end the reduced complexity and lower cost decided for the tower concept as shown in Figure 4 and 5. Given the current assumptions and estimates, the hot concept would increase the LAS NRC up to 40% and the RC up to 35%, with a total program cost increase for the NRC of around 6% and for the RC of around 4%.

6.2 Cost Driver

For both the NRC and RC more than 50% of the cost are associated to the space segment, in particular the crew module. The major contributor of the NRC in terms of activities are the planned test flights, which make up to 40% of the current estimate, as depicted in Figure 7. The flight tests (which are named here using an internal terminology: TMA, TFM, FM1 and FM2) are described in chapter 3 and listed in Table 2. Additionally, from the cost model data it could be derived what cost contributors, depending on the categorization and grouping, are dominating the NRC and RC. For the development phase, the Data Handling S/S from the crew module turned out to be the biggest contributor with around 250 M€, including all crew control panels. The same subsystem ranks also on top of the RC list with around 25-20 M€ per flight. Since this S/S is based on a CER, this equation has to be considered with care, since a too high or too low RC cost produces also a too low/high estimate on the NRC side. For both, NRC and RC the space segment systems engineering and project management contribute a lot to the cost. While for the NRC the launch site infrastructure and launch operation ranks amongst the top 5, for the RC it is the landing site and recovery infrastructure and operations category. Another big driver on S/S level is the new launch vehicle fairing development which is assessed with around 150 M€ development cost. Please note that the A6.4 launch vehicle itself was intentionally excluded because it is anyway the biggest single cost contributor for the NRC and considered a ‘buy-item’ for the RC.

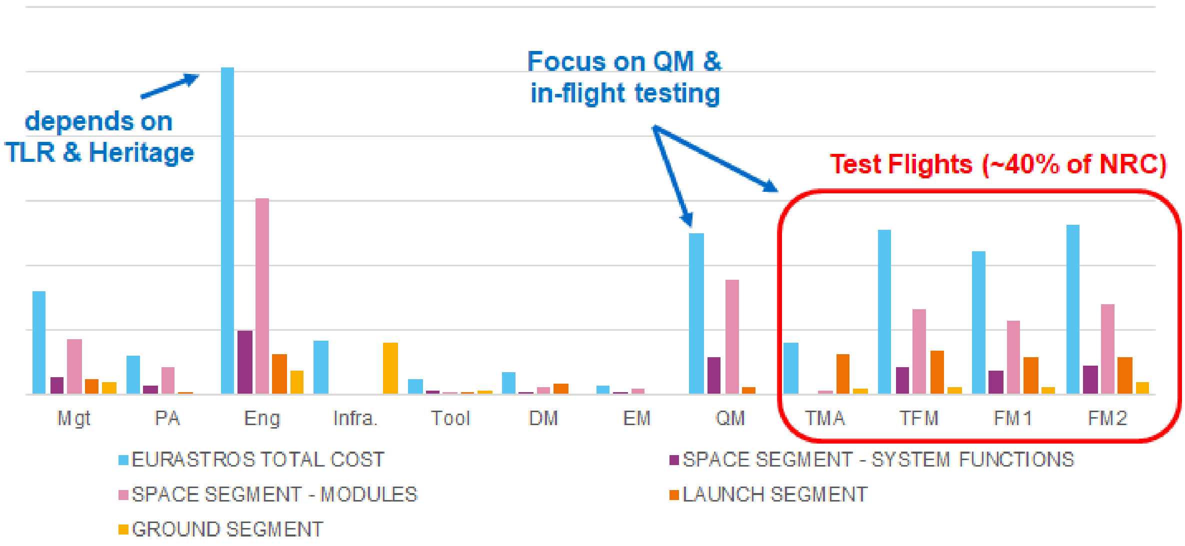

Figure 7: EURASTROS qualitative non-recurring cost distribution per activity and segment (with Mgt = Management, PA = Product Assurance, Eng = Engineering effort, Infra. = Infrastructure)

6.3 Cost Sensitivity

As shown in Figure 7, a strong contributor to the NRC is the engineering effort. Depending on the S/S maturity, the cost model (and the T1-equivalent approach in general) provides the assessment options from off-the-shelf via e.g. simple modification up to new development or even beyond state-of-the art. In the EURASTROS case, this selection changes the factor, which is also translated into an T1-equivalent, from e.g. 1 (simple modification) up to 7 (new development). In order to receive an idea about the sensitivity, two additional scenarios besides the nominal one with all S/S individually assed were analysed: a) all engineering factors set to simple modification, and b) all factors are set to new development.

Figure 8 presents the sensitivities per space segment module and for the launch and ground segment. While the G/S remains unaffected (since the T1-approach has not been used here), it can be seen that the launch segment and the LAS nominal scenario cost is close to the new development settings since both are characterized by rather new developments. The SM on the other hand has a nominal scenario close to the simple modification settings since not many new design or development efforts are assumed here because most technologies and units are already available. In total, these two extreme settings would lead to a 15-20% cost decrease or increase respectively.

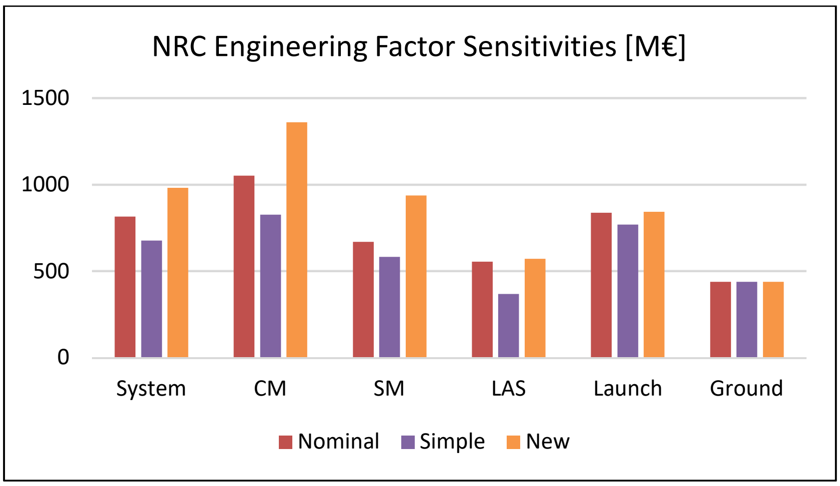

Figure 8: EURASTROS engineering factor sensitivity for NRC in M€, per segment and space segment module for three different scenarios, with nominal covering the as-is setting for the actual point estimates

6.4 Cost Saving Potentials

Since a big portion of the NRC comes from the test flights, and more specifically from the A6.4 launch vehicle to be provided, this leaves the program already with some cost savings or rather business potentials, as listed below:

- Reduce or combine test flights, e.g. TFM (orbital, un-crewed) and FM1 (cargo to ISS, un-crewed),
- use (and commercialize) FM1 already as first cargo flight to the ISS, utilizing the available volume and mass usually occupied by the crew,
- use (and commercialize) FM2 (to ISS, crewed) already as first regular crewed flight, depending on the EURASTROS certification approach.

However, it has to be kept in mind, that less test flights may impose higher risks, which have to be mitigated or accepted otherwise.

Another saving potential is to maximize the A6.4 launch vehicle and also crew module capacity by increasing the payload volume and mass to accommodate more crew members (currently 3), which can significantly reduce the cost per seat. Increasing the CM size, however, is not considered as additional driver of the NRC and RC cost due to the economies of scale and mainly more and bigger mechanical elements and units.

Depending on the needs, the ground segment infrastructure (and also related teams) could be set-up or adapted incrementally throughout the operational program to reduce the upfront investments.

6.5 Cost Validation Approach

The Excel-based cost model is prepared for parametric estimates, using CERs and the T1-equivalents. Furthermore, it allows for direct inputs at any level in order to overwrite calculations which are not applicable for a certain cost element or in case better data is available. Several assumptions have been made, as inputs for calculations, the calculations themselves and for direct inputs. For the latter, best engineering estimates or extrapolations from reference information were applied. The CERs which were used primarily for the space segment S/S, and partly also for the new launch vehicle elements, were generated in the frame of previous studies related to human spaceflight missions (see e.g. [6], [7]). The data used to create the CERs were derived primarily from European technologies developed throughout the Columbus and ATV programs, and elaborated within follow-on studies. In order to check and adjust the data, wherever possible the CERs were validated using a commercial hardware cost estimation tool called SEER for Hardware [10]. Additionally, public contract data was gathered and compared with the estimates within the EURASTROS cost model. For example, in 2007 the American company ATK received a contract for the Orion Abort Motor which was worth 62.5 M$ in 2007 economic conditions and included 4 test and 8 flight models [11]. Combining the NRC and RC data for a similar motor which was considered for the LAS hot concept, and with an equal number of models, the EURASTROS contract cost would be around 70 M€ in 2021 economic conditions. Adjusted for inflation and currency rates the cost would be almost equal. Although this could be a pure coincident, such examples still provide a certain confidence to the EURASTROS cost data, indicating a reasonable order of magnitude.

7. Summary and Outlook

Besides the technical findings, the cost of the EURASTOS concept was estimated with 4100 M€ for the development and, in average, with 415 M€ per mission. This is comparable with other crew transportation programs and studies. This study identified cost drivers and uncertainties which both need particular attention during further investigations. Moreover, a DLR cost model for human spaceflight missions has been adapted as such that additional analyses and future estimation updates as well as system and cost trades can be done fast and easily.
Please note that the current cost values are not to be understood as quotation prices by the study team parties but as model values which methodically combine reference data with assumptions. The cost estimate is considered as point estimate, providing an initial starting point for further business considerations, such as NRC amortization, seat pricing, or profitability increase.

During the study, reusability aspects were not considered. All launch and space segment elements are assumed to be expandable. However, the current market underlines that reusability, in this case for launch vehicle elements and the crew module, could be key for a sustainable and commercially viable EHST program (or service). For future studies or first steps towards such a European program, the current findings can be used as a reference for further comparing these two philosophies.

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