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Orbital Hub: A concept for human spaceflight beyond ISS operations

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ABSTRACT

The International Space Station (ISS) is the greatest endeavour in low Earth orbit since the beginning of the space age and the culmination of human outposts like *Skylab* and *Mir*. While a clear schedule has yet to be drafted, it is expected that ISS will cease operation in the 2020s. What could be the layout for a human outpost in LEO with lessons learnt from ISS? What are the use cases and applications of such an outpost in the future? The System Analysis Space Segment (SARA) group of the German Aerospace Center (DLR) investigated these and other questions and developed the Orbital Hub concept. In this paper an overview is presented of how the overall concept has been derived and its properties and layout are described. Starting with a workshop involving the science community, the scientific requirements have been derived and strawman payloads have been defined for use in further design activities. These design activities focused on Concurrent Engineering studies, where besides DLR employees also participants from industry and astronauts were involved. The result is an expandable concept that is composed of two main parts, the Base Platform, home for a permanent crew of up to 3 astronauts, and the Free Flyer, an uncrewed autonomous research platform. This modular approach provides one major advantage: the decoupling of the habitat and payload leading to increased quality of the micro gravity environment. The former provides an environment for human physiology experiments, while the latter allows science without the perturbations caused by a crew, e.g. material experiments or Earth observation. The Free Flyer is designed to operate for up to 3 months on its own, but can dock with the space station for maintenance and experiment servicing. It also has a hybrid propulsions system, chemical and electrical, for different applications. The hub's design allows launch with just three launches, as the total mass of all hub parts is about 60,000 kg. The main focus of the design is on autonomy and reducing crew maintenance and repair efforts, and reducing the need for extravehicular activities. Following a description of the design approach and technical details, a cost estimation and a detailed discussion of the use cases for such a station concept, along with the possible scenarios of international cooperation, are also presented in this paper.

KEYWORDS
Human spaceflight, LEO, Post-ISS, Free Flyer, Orbital Hub

1 Introduction

The International Space Station (ISS) is a remarkable example of successful international cooperation as it demonstrates long-term collaboration of the 15 partner governments during the almost 20 years of in-orbit operation and at the same time created significant engineering and programmatic achievements. The continuation of the ISS program has been confirmed by all partners until at least 2024. Even though the lifetime of the ISS is theoretically extendable also beyond this timeframe, the overlapping question by all users is, if and in which way the important research in Low Earth Orbit will be realized after the ISS stops operation. As existing examples in history show, the transition phase between two crewed orbital platform concepts takes between 10 and 15 years. [1]

This fact underlines the importance of taking actions now to pave the way for a successor platform to ensure a continuous human presence in LEO, as stated as a goal in Europe's LEO 2020 roadmap and as discussed by the ISECG [2]. Germany is a strong supporter of permanent human presence in LEO, which is the reason why the executive board of the German Aerospace Center (DLR) already in 2013 initiated the Post-ISS project and assigned the task to its department for System Analysis of Space Segment to perform system studies on this topic to answer the following question: How to continue with space research and space technology development in LEO after the ISS utilization period (after ~2024)?

As an important first step, the current ISS setup has been analysed to derive lessons learned which need to be considered and incorporated in a potential follow-up design [1]. Despite its great success, it has shown several characteristics which make it cumbersome for the user and expensive in operation. The ISS is by far the biggest and most complex structure in space. In conjunction to this it is apparent that it was only feasible through financial support from a big consortium. Along with the high number of stakeholders comes a big overhead, higher management cost and also potential conflicts of interests. The fact that human spaceflight will only be possible by international cooperation remains true also for new concepts. However, smaller platforms with elementary capabilities only and a more modular approach could reduce the overhead and the necessary consortium size, thereby making decision-making and operation more agile. Commercial interest and direct involvement of industrial partners are promising, e.g. for maintenance & operation or hardware provision. The necessary budget can also be reduced by implementing new operational concepts. Even though the astronauts are obligated to perform sophisticated tasks, they should be disburdened as much as possible. The platform should be designed in a way that it allows autonomous payload operations where applicable and, in contrast to the ISS, to only foresee Extra Vehicular Activities (EVAs) in contingency cases. The precious crew time could then be distributed more efficiently and thus the necessary crew size could be reduced, or scientific and commercial output of the station could be increased.

The user has the wish for fast access to space with efficient and profitable science and operation, without undue bureaucratic impedance. Especially the long planning horizon and the high safety standards, and thus a long lead time for any planned experiment to be brought to the ISS, are contrary to this desire. Therefore any new platform concept has the objective to reduce the number of obstacles which prohibit a fast access to space and to thereby facilitate a faster return of data or investment to also motivate and attract new partners and users. One solution for this is the usage of standardized interfaces and components. Examples as the International Docking Standard (IDS) or International Standard Payload Racks (ISPR) should be incorporated in the design solutions to support the modular approach.

Also the type of applications and payloads for new platforms should be reconsidered. Currently ISS payloads are still primarily aimed at scientific research [3]. This may not be sufficient to convince the stakeholders to provide the necessary funding. Space tourism should not completely be omitted but also cannot exclusively be used as justification. The need to create a platform providing the capabilities for new applications and thereby the extension of the user community beyond traditional space industry is strong. The present observation of an opening of the ISS for commercial applications is a step in the right direction and needs to be further strengthened and supported by new platform concepts.

2 Deriving the station concept and design

The following paragraphs contain a description of how the first concept has been set up and from that a detailed design was developed by DLR experts and partners.

From the beginning the basic premise has been to incorporate the customer along with people from operations as well as astronauts into the design process, ensuring that all relevant aspects have their respective impacts on the final design and lessons learnt from the operation and utilization of ISS would be applied to the design.

A major tool for the derivation of the hub design has been the Concurrent Engineering (CE) process. This iterative process is based on the simultaneous design work of an expert team, including experts for all relevant domains, e.g. science payload, thermal control and life-support system.

The basic premise for the path leading up to the final design has been the continuation of utilization of a crewed outpost in low Earth orbit. Foci of the utilization should be micro-gravity research, human physiology resp. medical experimentation and Earth and Deep Space observation, which had been identified before as most relevant. Derived from ISS experience it has been deemed necessary to increase the turnover rate of experiments and, in general, to have modular utilization.

The path to the final design contained three major steps:

1) Establishment of station concept options based on the general premises.
2) Derived from the basic station concept, listing of possible and desired utilization

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ideas and experiments by the relevant science community.

3) Fleshing out of the initial concept into a full-fledged design, based on the results from the utilization review in step 2.

Finalizing this phase of the design, cost estimation has been conducted to provide the information necessary for programmatic decision making.

The details of these steps are elaborated in the following subsections.

2.1 Concept workshop: Filtering all scenario options

An obvious interplay exists between the design of a LEO station and the experiments which can be performed there. As such, maturing the station design requires an iterative process. To start these iterations an initial station concept is required however, and it is for this reason that a two-day workshop was organized at DLR's Institute of Space Systems in Bremen.

Specific aims of the workshop were to define multiple station architecture concepts and to subsequently evaluate these alternatives in order to arrive at a baseline design.

A number of initial requirements were outlined to guide the invited experts in developing their ideas. A subset of these requirements is listed in Table 1.

Table 1: Initial requirements for the concept development workshop

Number	Description
Mission Requirements	
MI-010	The Base Platform shall have an orbit altitude of more than 300 km
MI-020	The station shall allow for deep space and Earth observation
System Requirements	
SY-010	The station shall accommodate approximately 10 tonnes of payload mass
SY-020	The station shall provide a microgravity environment of 10^{-4} to 10^{-6} g.
SY-030	The International Docking standard is applied (IBDM diameter 80 cm)

Based on a functional analysis of a LEO station, the experts developed concepts within two main categories:

1) A European mini-station
2) German/European contributions (e.g. a free flyer) to an international space station

These two categories address alternate future scenarios in which political, economic and other strategic considerations result in varying levels of international support and funding for LEO research and commercial activities, especially under the premise of the agencies` focus on future exploration missions, prohibiting anything similar to the scale of the current ISS.

Within both categories, concepts were developed for varying levels of capability by in- or excluding specific elements. The elements under consideration were:

1) An experiment platform, either in the form of an observation deck, a micro-g platform, or a platform with capacity for both.
2) A habitat module with internal laboratories
3) A habitat module without laboratories
4) A stand-alone laboratory module

The assumption was made that the elements listed above included their own support subsystems, such as power generation and attitude and orbit control.

Based on the experts' assessment, a number of possible designs were rejected as implausible. Additionally, the number of concepts for evaluation was further reduced by combining those with limited or negligible differences (e.g. an Earth observation platform versus a deep space observation platform).

A description of the different concepts and their relative strengths and weaknesses can be found in [4]. Ultimately, four of the developed concepts were selected for a final evaluation.

1) A mini-station with observation platform
2) A mini-station with a laboratory module and an experiment platform
3) A mini-station with a habitat module, with integrated laboratories, and a detachable experiment platform
4) An uncrewed free flyer, consisting of a laboratory and an experiment platform.

The participants in the workshop were asked to rate each of these concepts on a number of criteria in comparison to two reference architectures:

1) A theoretical European station consisting of an ATV and a Columbus module
2) The International Space Station

Ratings could vary from -3 to +3, with -3 being very much worse than the reference architecture, 0 being equal to, and +3 being very much better than the reference.

The averages of all the experts' ratings were multiplied by the relative weights of the different criteria to obtain final evaluation scores for each concept.

A total of 19 criteria were used to evaluate the concepts. These criteria, listed in Table 2, were grouped into four classes with specific weight factors; political, social, technical and economic.

Table 2: Concept evaluation criteria and weights

Criterion	Weight
Political	0,3
Agreement with European space roadmap	
Agreement with German space roadmap	
Prestige	
Social	0,15
Environmental impact	
Potential for international collaboration	
Scope of scientific research possibilities	
Technical	0,15
Complexity	
Potential for electrical energy production	
Mass	
Technology Readiness Level (TRL)	
Accessibility	
Modularity	
Payload volume capacity	
Crew safety	
Economic	0,4
Existing expertise	
Operating costs	
Development costs	
Work force utilization	
Expandability	

The Analytical Hierarchy Process (AHP) was used to determine the relative importance of each of the four classes and the relative importance of the different criteria within each of the classes. The AHP method is described in detail in [5] and [6].

The final scores of the four concepts with respect to reference 1 (ATV and Columbus module as European elements for a future international station) and reference 2 (ISS) are listed in Table 3.

Based on the scores listed in the table it can be concluded that the third and fourth concepts are significantly better than the first two. However, the difference in overall score between the third and fourth concept are not significant enough to justify a choice for one over the other.

In order to obtain a single baseline design, the SARA team elected to combine the characteristic elements of the two concepts into an 'Orbital Hub' design.

Table 3: Final evaluation scores

Concept	Reference 1	Reference 2
Mini-station with observation platform	-0,0032	-0,5011
Mini-station with lab and platform	0,3610	-0,2394
Mini-station with a habitat and platform	0,5995	-0,0227
Free Flyer	0,5573	0,0157

The Orbital Hub consists of a mini-station with a habitat and integrated laboratories. However the detachable platform foreseen in concept 3 is replaced by the free flyer design, with laboratory module and experiment platform, of concept 4. Merging these two concepts brings together the advantages of both resulting in a score significantly better than Reference 1 and equally to Reference 2. As Reference 2 would be the ISS, which as discussed above will not be available long after 2024 / 2028, nor will be any comparable system of that scale, the selected concept promises both a realistic solution and high performance w.r.t. the evaluated criteria.

The two parts of the Orbital Hub were designated the "Base Platform" and the "Free Flyer".

2.2 User workshop: Accounting for the science

The observed need for a LEO station which is more flexible and more specifically tailored to scientific and commercial activities implies a requirement to involve stakeholder input, particularly from potential users (e.g. scientists), in the early design phases of a project.

The SARA group applied a two-step approach to defining stakeholder requirements and their impact on the station design.

Initially, in May 2014, a user workshop was held in which SARA members and scientists from a number of research fields (e.g. material sciences, astrophysics, and robotics) defined the basic requirements of each field with respect to LEO experiments, such as approximate mass and volume requirements, a need for gas and/or vacuum supply, and water requirements. These requirements could then be applied in the concept evaluation process

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described previously, in order to converge on a single baseline concept.

Subsequently, these requirements were developed further, into payload designs, during a CE study in December of 2014. The resulting payload designs provided more comprehensive resource budgets and operational requirements which could then be filtered into the detailed design process of the station.

An example of one of the designed experiments is an astrobiology experiment to test chemical and mineral probes, as well as bio signatures, under space environmental conditions, as well as simulated Mars conditions. The plume simulator experiment would inject a mixture of water, organic materials and minerals into a container, in which it is exposed to the space radiation environment.

Some of the relevant characteristics for this experiment are listed in Table 4.

Table 4: Plume simulator design parameters

Criterion	Requirement
Volume	0.24 m^3
Mass	>100 kg
Modular	Probes and sensors
Re-supply / sample return	>15 kg, once per year
Power	400 W
µg-level	No specific constraint
Data rate (downlink)	10 Mbps
Downlink frequency	1/week
Life time	>2 years
Temperature (minimum)	-80 °C
Temperature (maximum)	+60 °C

Aside from scientists, the workshop and design study also included experts familiar with ISS mission operations, as well as an astronaut with experience on board the ISS. As a result, the SARA team was able to utilize lessons learnt from ISS utilization and operation in their detailed design phase.

Specific suggestions with respect to the Orbital Hub operations are:

Increasing flexibility for the station crew:

Currently, crew activities aboard the ISS are planned out in great detail, limiting the astronauts' freedom. Allowing for a greater degree of self-determination would result in a better work environment (psychologically) and yield potential improvements in overall productivity.

Varying cleanliness / safety levels throughout the station:

Distinctions can be made between crew working areas, which could accept a lesser standard of cleanliness, and other areas which must, without fail, be cleaned after use and the design could potentially foresee internal airlocks between different areas. Similar to this, different levels of safety could be defined for the different work areas, e.g. between the permanently crewed Base Platform and the only man-tended Free Flyer.

This ties in to the previous suggestion, with respect to crew flexibility. Within reason, on-board decisions can be delegated to the crew to evaluate the risk, without undue impact on the overall safety.

Enabling direct communication between scientists and the experiments and station crew:

Loosening the rules of the strict CAPCOM/EUROCOM communication concept to allow direct communication between scientists and crew would allow for crew-tended experiments to be carried out in a faster and more controlled fashion.

Moderation for these communications can be implemented to limit risks.

Similarly, for the automated experiments, the ground segment should provide scientists and commercial partners simple, secure and reliable access to their experiments. A centralized ground segment with the possibility of direct interaction for the users via secured connection exclusively with their payloads would take the burden from the ground operations team and could significantly reduce the number of required User Support and Operation Centers (USOCs). A complex ground segment as currently operated by ESA for Columbus is to be avoided. Activities which are out of the daily routine (e.g. installations) should be monitored from central operation centers for a direct intervention.

Tailoring crew selection and crew scheduling towards the planned experiments:

Crew selection and crew scheduling should be tailored towards scientific experiments and commercial activities. For example, more time should be set aside for human physiology experiments. Additionally, it should be considered whether specialist crew should be selected based on the planned activities aboard the station.

This could provide more flexibility in terms of the experiments which could be performed, as the available on-board expertise would be increased. However, providing multiple experts to accommodate the different research fields may require a significantly higher crew exchange rate, with a resulting operating cost increase.

Improving inventory management and station health monitoring:

Related to crew flexibility and tailoring of crew schedules towards experiments and commercial activities, the Orbital Hub design should reduce crew maintenance time through increased automation.

Some possible technical solutions could be, for example, implementing passive (RFID) and active markers, automatically informing about changes, on all items aboard the station and implementing wireless station health monitoring, comparable to the promising and evolving Internet of Things (IoT) topic.

2.3 Concurrent Engineering: From concept to design

The work explained in the previous sections culminated as planned in a more detailed design. Due to the nature of the concept, i.e. consisting of two major parts, namely the Free Flyer and Base Platform, it was likewise decided to split the Concurrent Engineering study into two parts. Consequently one study was conducted for each part.

The CE process has been used by DLR for more than 60 studies and has established itself as a very useful tool. A detailed description of the CE process as applied by DLR in Bremen can be found in [7] and [8]. More information on the data model used by DLR for these studies is presented in [9].

The CE approach is based on the usage of a common design model, documenting all relevant design data, e.g. mass and power values of all subsystem components (e.g. a reaction wheel or thruster). For establishing design cases of the power supply system, so called modes of operations are defined, listing power budgets and duty cycles for each possible design case, e.g. for this study a Survival Mode or a Crew Exchange Mode, which occurs when two crews are present on-board for station handover.

Furthermore the process incorporates all relevant design aspects, referred to as “domains” in the following. The domains and tasks for the studies are listed in Table 5. Although the launch scenario involves all parts of the Orbital Hub, i.e. including the Free Flyer, the scenario was established in the first study, to keep the overall picture in mind. The launch scenario subsequently put a constraint of 19,000 kg as total launch mass in the Free Flyer design study.

The studies were conducted in the typical, iterative process. A first draft design was set up and, alternating between group sessions and offline work, was refined until it was ensured that all requirements were fulfilled and the design was consistent. All domains including the accommodation of parts were discussed regularly each study day to root out any design errors or inconsistencies.

The requirements for the studies have been the most relevant backdrop for the designs. They are listed in Table 6 for the Base Platform and Table 7 for the Free Flyer.

The mission requirements for both studies limit the orbit to ISS-like inclination and altitude. This has several advantages for the platform design and operations, which are described in more detail in Chapter 3.3.

Originally the station was also required to be nadir oriented, which during the study was just placed as a constraint on the Free Flyer, due to its observation payloads. As those are not foreseen for the Base Platform, nadir pointing was ruled out as a premise for the Base Platform. Therefore it can rotate along its axis simplifying the pointing mechanisms of the solar arrays for sun tracking, as only one axis needs to be included in the mechanisms, the other one can be taken care of by attitude changes.

The approach is rather conservative regarding technology, only allowing usage if the respective technology is expected to be ready in 2025. Regarding launch, existing launchers or future launchers, if their availability by the envisaged launch date has a high probability (e.g. Ariane 6 or Falcon Heavy), have been assumed for launch and assembly. This way the feasibility of the station does not depend on unrealistic launch capacities which do not exist yet, are outside of the program for the station, and could not be influenced by possible station partners.

The absence of regular EVAs requires robotic capabilities for servicing, but also reduces the space, cost and time demands on the station, as the equipment necessary for regular EVAs can be saved. The Free Flyer is the main payload carrier of the station and is based on existing standards for payloads.

By comparing the list of requirements (Table 6 and Table 7) from the first with the second CE study it can be seen that the number of requirements increased by 15 requirements between the Base Platform and the Free Flyer study. This, for one, is due to the fact that lessons learned and major points of discussions which had been addressed in the first study (e.g. envisaged system lifetime or maximum duration of complete loss of power generation) were considered and introduced from the beginning for the subsequent study. Furthermore, the knowledge

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Table 5: Domains for the CE design studies of Orbital Hub

Domain Title	Description
Team Leader	Organizes study and team work, notes action items and tracks them
System	Handles requirements and system view of the design
Customer	Provides mission statement and objectives, has final decision regarding design adaptations
Configuration	Handles Computer Aided Drawing (CAD) of the design, accommodation of all components
Payload/ Science	Handles the strawman payloads selected for the study to base the design on actual data relevant for scientific or other user applications
Crew Facilities	Handles equipment relevant for the crew, e.g. quarters, food station, hygiene, toilets
EVA	Handles equipment relevant for extravehicular activities (EVA), including the airlock
Environment Control & Life Support Systems	Handles equipment used for maintaining an environment sufficient for comfortable living onboard the station
Mission Analysis	Handles orbit calculation and everything associated with that e.g. contact times to ground station
Onboard Computer & Data Handling	Handles the equipment relevant for the onboard data handling, including personal computers of the crew and control computers for equipment and experiments
Communication & Ground Segment	Handles equipment relevant for the communication and data transfer between the station & ground, station & visiting vehicles and station& Free Flyer
Power Supply	Handles equipment for power generation, power distribution and conditioning
Thermal Control	Handles equipment for thermal control of the station
Structure & Mechanisms	Handles structure, including solar panels, docking rings, launch adapters and mechanisms for deployment of equipment
Robotics	Handles robotic arms for experiment placement and servicing
Attitude and Orbit Control	Handles equipment for attitude and orbital control, including thrusters to counter effects of atmospheric drag
Propulsion	Handles equipment required for e.g. docking and debris avoidance maneuvers
Launch Scenario*	Establishment of launch scenarios for orbit assembly and station operation
Cost	Cost estimate of all relevant figures, i.e. operation/ utilization, development and construction

* only for study of Base Platform, launch scenario was established for complete station including Free Flyer

Table 6: Design requirements for the Base Platform as used during the first CE study.

Number/ Type	Description
Mission Requirements	
MI-010	The Base Platform shall have an orbit altitude of 400km +/- 50 km
MI-020	The Base Platform shall have an orbit inclination of 51.6°
System Requirements	
SY-010	The design shall be based on technologies available by 2025
SY-020	Each module shall be compatible with currently available launch systems (mass and envelope)
SY-030	The International Docking standard is applied (IBDM diameter 80 cm)
SY-040	The Free Flyer has to be able to dock and undock from the Base Platform which supplies the life-support functionality for the pressurized part of the Free Flyer during docked configuration
SY-050	The Base Platform shall support a permanent crew of 3 (temporarily more during visits of vehicles) for the Base Platform and for 2 persons in the pressurized part of the Free Flyer during docked configuration.

SY-060	No EVA shall be required for assembly or operation. EVAs are only foreseen for emergency repairs.

Table 7: Design requirements for the Free Flyer as used during the second CE study.

Number/ Type	Description
Mission Requirements	
MI-010	The Free Flyer shall have an orbit altitude of 400km +/- 50 km
MI-020	The Free Flyer shall have an orbit inclination of 51.6°
MI-030	The Free Flyer orientation shall be adaptable (e.g. Nadir as standard case, attitude for minimal perturbations and optimal µg (magnitude < 10^{-6} g) for up to 14 days, inertial attitude)
MI-040	The Free Flyer shall be the active part during assembly
MI-050	The Free Flyer shall dock on average every 3 months for a duration of 14 days. Docking maneuvers are not conducted during crew exchange of the Base Platform.
MI-060	The last phase of docking shall be finished within one shift of the operations team, i.e. within 6 hours.
System Requirements	
SY-010	The design shall be based on technologies available by 2025
SY-020	The lifetime of the system shall be 15 years.
SY-030	The Free Flyer shall have a diameter < 5m, length < 15 m, a launch mass < 19,000 kg and a mass on orbit of < 25,000 kg
SY-040	The Free Flyer shall provide a pressurized lab, an external platform and a service module
SY-050	The International Docking standard is applied (IBDM diameter 80 cm).
SY-060	The Free Flyer has to be able to dock and undock from the Base Platform which supplies the life-support functionality for the pressurized part of the Free Flyer during docked configuration
SY-070	The Free Flyer's pressurized lab shall be able to support 2 crew members during docked configuration
SY-080	The pressurized lab shall have room for 12 International Standard Payload Racks (ISPR)**
SY-100*	The external platform shall provide an area for 10 JEM EF equivalent payloads (8 nadir pointed, 2 pointed into space) and an area of 8 m² for payloads with a height < 500 mm
SY-101	The JEM EF equivalent payload interfaces shall provide 5 kW cooling, 5 kW power, 300 Mbits/ s Ethernet and 1553 data interfaces
SY-102	The smaller payloads shall be provided with 3 kW of power and 3 kW cooling, 300 Mbits/s Ethernet, video- and 1553 data interfaces
SY-110	Maintenance shall only be able in the pressurized parts by astronauts. No other areas are accessible from within. External access is only foreseen for contingency.
SY-120	The Free Flyer shall provide 20 kW power for housekeeping (not including battery charging) and payloads
SY-121	The Free Flyer shall be able to survive loss of power generation for 1.5 orbits
SY-130	The Free Flyer shall be one-failure tolerant for normal equipment, two-failure tolerant for components with direct connection to human safety.
SY-140	The external platform shall allow installation of payloads for launch, if the launch loads do not exceed those in orbit
SY-150	The Free Flyer shall supply a cooling cycle temperature of 10-30°C

* SYS-090 became obsolete during the study and has been omitted.
**The ISPR standard is only used for volume / mass assessment. Applicable payloads still have to be compatible with the IBDM standard.

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of the to-be-designed Free Flyer, for it to be in line with assumptions being made for the Base Platform and therefore to fit into the overall Orbital Hub scenario (e.g. for the assembly phase or the required failure tolerance), was much more detailed and made it necessary to introduce a lot more constraints onto possible design solutions.

2.4 Cost estimation method

There are three major common methods to estimate the cost of a space system, each with specific pros and cons which make them more or less attractive during different phases of the project [10]:

1) Analogy-based: comparing to or deriving from existing, similar systems
2) Parametric: statistical data relations, based on historical data and experience
3) Detailed Bottom-up: define and sum-up the cost per work package from low to high level

The judgement of experts is of great importance for all of the approaches above to define realistic cost dependencies and also validate the obtained results as plausible. To assess the costs of the Orbital Hub hardware, two different approaches have been selected.

A first rough estimate for the development cost of the Base Platform has been conducted using an adjusted analogy-based cost estimate with the ISS as a reference. The ISS development costs have been primarily derived from [11]. They are assessed at around 35 billion $, which in combination with the overall station mass of 450 t led to a cost/mass ratio of 80 million $ / tonne. This value can be multiplied with the determined overall system mass of the Base Platform to obtain a rough order of magnitude cost estimation for the new platform. This relation can be reformulated to the following Equation (1), where C is the cost of the system and m is the overall system mass.

$$C_{OHub}\ [M€] = \frac{C_{ISS}}{m_{ISS}}\left[\frac{M€}{kg}\right] \cdot m_{OHub}[kg] \qquad (1)$$

In a next step, the results can be improved by incorporating additional available cost information, such as known procurement costs. This cost estimation approach has been selected to analyse the anticipated development cost already during the system design in the CE study. More elaborated cost estimation (in this case parametric) needs more time and the complete system layout and therefore this task at DLR is typically performed in post processing of CE activities.

The parametric cost estimation is based on a cost model developed at DLR in cooperation with AIRBUS DS which can be adapted to the specific study case. It uses a mass-related Cost Estimation Relationship (CER) on sub-system level involving all major components of the considered system. These relationships are used to calculate the development cost (incl. hardware) of each sub-system of the Theoretical First Unit (TFU) by the following Equation (2), where s is the single sub-system of module m, with its mass m_s and specific sub-system parameters A_s and b_s derived from statistics and experience of other comparable missions. It has to be stated that the TFU is a mathematical proxy only and does not contribute to the actual hardware cost. When the model philosophy foresees the development of a flight model tested on acceptance level, this so called FM1 would be equal to the TFU.

$$C_{s,TFU}\ [k€] = A_s\left[\frac{k€}{kg}\right] \cdot m_s[kg]^{b_s} \qquad (2)$$

Along with the escalation of this value to the current fiscal year using inflation factors, the cost model also considers the selected test model philosophy by a model factor (MF) and additional cost factors (CF) per model as well as for system level wrapping costs (i.e. project office and additional support equipment). The considered test models are:

- bread-boards (BB),
- engineering model (EM),
- structural test / qualification model (STM/QM),
- electrical test model (ETM),
- proto-flight model (PFM) and
- flight model (FM).

The assumed share of each cost contribution is again based on experience from former missions and incorporates a cost improvement curve for each recurring cost item, as visualized in Figure 1. The shown percentages are describing the cost ratio of each item always in comparison with the TFU (red bar). The introduced test matrix is used to control which of the sub-systems will be included to which extent into the single models by using values in the range from 0 (sub-system is not part of the model) to 1 (sub-system is included to full extent in the model). In a first step the cost factor for each sub-system (CF_s) is calculated using the selected CF and MF values.

$$CF_s = [MF_{BB} \cdots MF_{PFM} \;\; MF_{FM1}]_s \cdot \begin{bmatrix} CF_{BB} \\ \vdots \\ CF_{PFM} \\ CF_{FM1} \end{bmatrix}_s + CF_{s,ENG} + CF_{s,Tools} + CF_{s,O\&M} \tag{3}$$

Using this factor and adding specific wrapping cost factors, the development costs of a sub-system can be calculated from the TFU costs.

$$C_s[k€] = \left(1 + CF_{Mgmt} + CF_{PA}\right) \cdot CF_s \cdot C_{s,TFU}\,[k€] \tag{4}$$

The sub-system costs of the single modules are summed up and a module-specific cost-factor representing the AIT effort (Equation (5)) is used to complete the overall provision cost of the single modules.

$$CF_{AIT} = [MF_{BB} \;\cdots\; MF_{PFM} \;\; MF_{FM1}]_{m,AIT} \cdot \begin{bmatrix} CF_{,BB} \\ \vdots \\ CF_{PFM} \\ CF_{FM1} \end{bmatrix}_{AIT} \tag{5}$$

With this factor and the sum of the sub-system costs of the TFU modules, the AIT costs for one module of the system are calculated via Equation (6).

$$C_{AIT}[k€] = CF_{AIT} \cdot \sum_s C_{s,TFU} \tag{6}$$

The overall provision cost of one module C_m therefore is:

$$C_m[k€] = \sum_s C_s + C_{AIT} \tag{7}$$

The steps above are conducted for each module (m) separately, i.e. HAB, SM, DN and FF.

To assess the overall system cost, wrapping costs on system level are incorporated using respective cost factors for management, system engineering, product assurance and AIT (Equation (8)).

$$CF_{Sys} = \left(CF_{Mgmt} + CF_{Eng} + CF_{PA} + CF_{AIT}\right)_{Sys} \tag{8}$$

Absolute cost values coming from other models (e.g. software costs) or experience (i.e. for logistics) complete the cost calculation to estimate the final development cost (incl. hardware) of the system (Equation (9)).

$$C[k€] = CF_{Sys} \cdot \sum_m (C_m[k€]) + C_{S/W} + C_{Logistics} + \cdots \tag{9}$$

To avoid any overly optimistic cost estimation, the model reserves several margins on component level (i.e. component mass) and a risk margin on the cost calculation on sub-system level of between 5 % and 20 % depending on the components' and CERs' maturity.

In the course of the Orbital Hub study a proto-flight test philosophy has been selected, following the envisaged low cost approach. This means the first object put into orbit is the PFM and no actual FM is considered. The reason for this lies in the complexity of a human spaceflight system and the enormous costs of a full-qualification PFM model in addition to the actual FM. Thus, the FM factors in the equations above are put to zero.

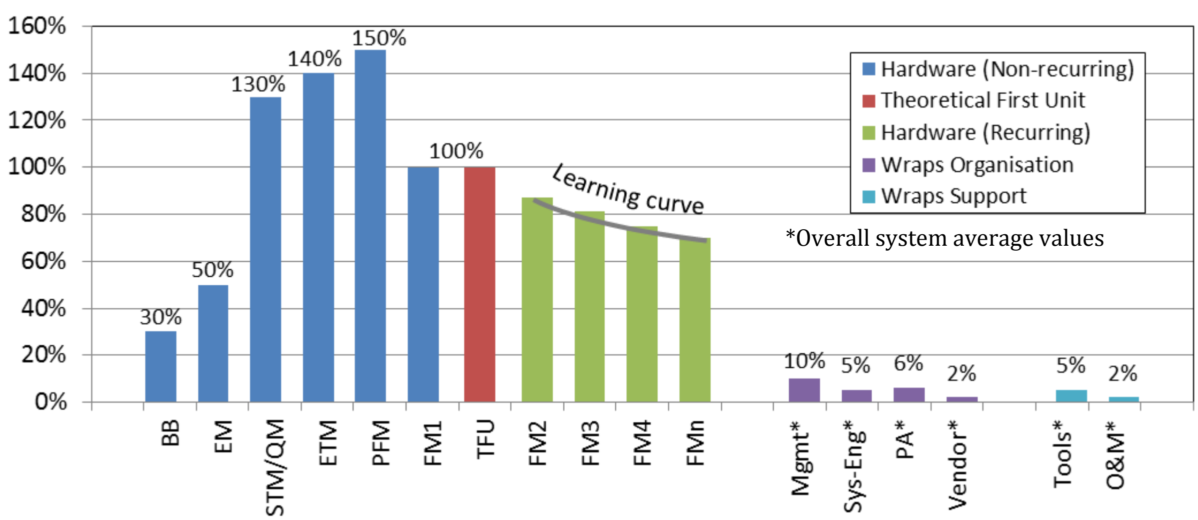

Figure 1: Cost distribution as basis for the parametric cost estimation including hardware matrix for testing and wrapping costs for organisation and support

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3 Orbital Hub in numbers

This chapter provides basic information about the elements of the Orbital Hub including short descriptions of their functionality and their main sub-systems and shows the main budgets for mass, power and estimated cost. [12]

3.1 Base Platform

The Base Platform is the crewed section of the Orbital Hub, which enables a continuation of human physiology studies in LEO, and accommodates experiments and activities which cannot be fully automated. The design of the Base Platform was elaborated in the first of two detailed design CE studies. The requirements set for the CE study can be found in Table 6.

The Base Platform, as seen in Figure 2, consists of three modules: the docking node (DN), the pressurized service module (SM) and the habitation module (HAB).

The DN, as suggested by its name, provides the interfaces for crewed and uncrewed vehicles to dock to the Orbital Hub. A cupola is implemented in the DN design, at the cost of a potential additional docking position, to provide crew members the opportunity to look out onto the Earth. Additionally, the DN houses communication and data storage components, a life support system and crew exercise equipment.

The pressurized SM provides the larger portion of the Base Platform's electrical power, the thermal control system, attitude and orbit control system, as well as a redundant life support system and crew waste management system.

Finally, the HAB module provides crew accommodations ranging from sleeping quarters to cooking facilities. The current design envisions the use of an expandable Bigelow Aerospace BA-330 module for the HAB. The BA-330 will be inflated with gas upon arrival on orbit, resulting in a radial expansion. The length of the module will remain the same. After inflation, the shell can be considered rigid.

Payloads and subsystems will be installed, facing outwards, in the main truss running the length of the habitat module. Astronauts will be able to pass through this truss into the SM, and will have access to the payload and subsystem racks from the back for maintenance and repair.

To facilitate crew movement, handholds will be installed on the outer side of the truss, along the entire length.

3.1.1 Technical solution

Crew:

The Base Platform is designed to accommodate a permanent crew of three astronauts, with the capability to support six for a limited duration, assumed to be at most one week, during crew exchange. The locations of the crew equipment (e.g. for cooking, dining, hygiene stations, toilet and exercising) have been optimized based on the current situation on, and lessons learned from, the ISS.

Although the Base Platform is crewed, regular extravehicular activities (EVAs) are not foreseen and the design aims to limit the need for such activities by avoiding externally-mounted components to the extent possible. Nevertheless, an EVA airlock is foreseen to allow for crew egress if necessary.

Payloads:

During the payload design study, approximate sizes for different experiments and test setups were defined with respect to the reference size of one International Standard Payload Rack (ISPR).

Of the different payloads which were developed, approximately four to five racks are integrated into the HAB. Specifically, the payloads relating to human physiology experiments, biology, radiation measurements, and additive and subtractive manufacturing will be located in the HAB. Additionally, technology demonstrations and some robotic experiments can be performed here.

Environmental Control and Life Support System

The Environmental Control and Life Support System (ECLSS) provides critical functionality for crew survival by managing the on-board climate, atmospheric gas composition, fire detection and suppression and water recovery.

On account of its importance, each of the three modules of the Base Platform contains an identical ECLSS which ensures redundancy. Depending on the current operational mode and crew size, the ECLSS duty cycle can be adapted and single ECLSS units can be activated on demand. During nominal operations, one of the ECLSS units will be operated continuously, while one of the remaining two will have a 50% duty cycle.

During crew exchange, when the Base Platform has to support six crew members for a limited duration of time, all three ECLSS units will be operated, whereas during survival mode only a single unit will be active.

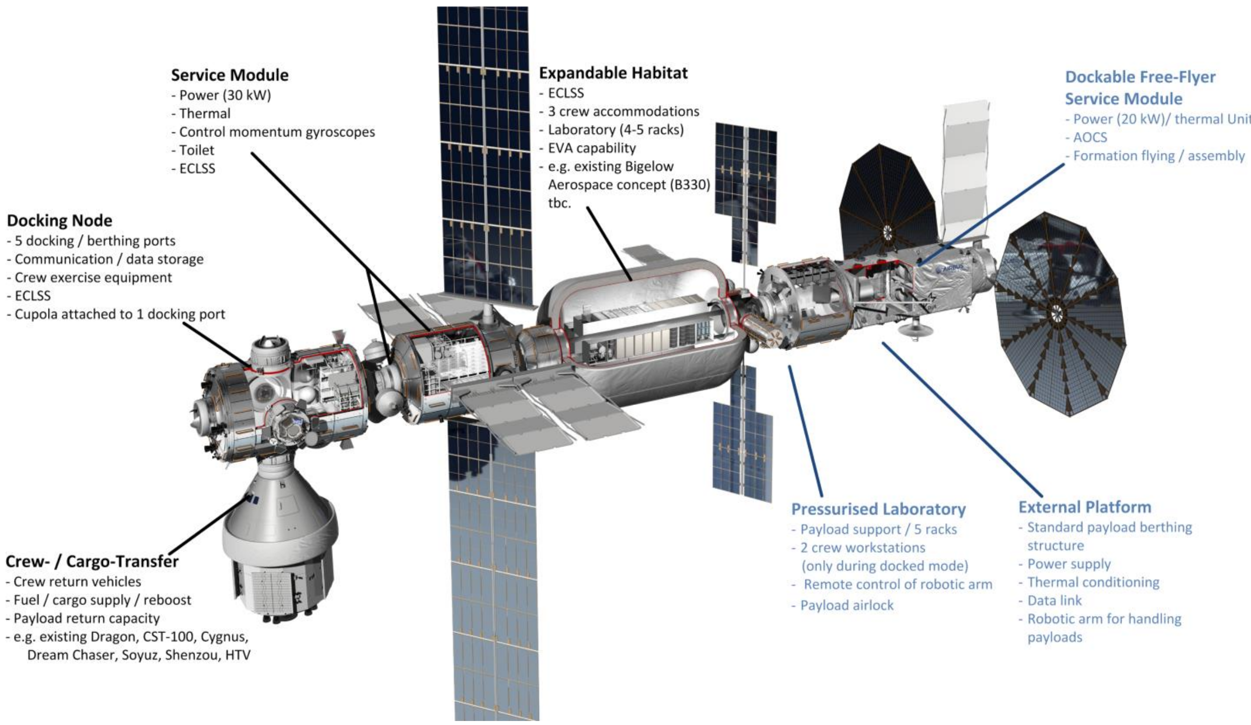

Figure 2: Sectional view and functional description of the Orbital Hub (artist's impression). The Base Platform of the Orbital Hub, consisting of the docking node, including a cupola, here docked by a crew vehicle, the pressurized service module and the habitation and base lab module, along with the emergency EVA airlock. The Free Flyer with the pressurized laboratory module, the external payload platform and the non-pressurized service module.

Data Handling & Onboard Computer

As the requirements imposed by the onboard experiments do not exceed the capabilities of the existing architecture for the ISS, the initial design takes this setup consisting of multiplexers/ demultiplexers (MDMs) and laptop computers as a baseline for further assessment in the future.
Further analysis is required to determine whether a cluster of easily replaceable computers could be a more suitable architecture than the MDMs. Especially when considering the effort related to maintenance and repair of the MDMs currently aboard the ISS, significant reductions in crew time might be possible.

Communication

The requirements on the communication system of the Base Platform were derived from the results of the payload design study. As a baseline design, the current configuration of the ISS is applied to the Base Platform, with an uplink of 25 Mbps and a downlink of 300 Mbps (Ku-band).

Three separate systems, with different frequency ranges, are integrated into the Base Platform to meet the varying functional demands. Specifically, the three systems are responsible for the following tasks:

- S-band: Command data, telemetry and audio
- K-band: Payload data and video
- UHF: EVAs and docking procedures

A promising option is the usage of geostationary relays systems as a useful supplement to the communication ways mentioned above to meet high data volume demands and continuous access. Such services as provided by e.g. TDRS or EDRS are assumed to be still existent at the considered point in time or replaced by a comparable service with similar capabilities, as to cover the increasing data volume by new (commercial) satellite constellations.

Additional optical communication capabilities are considered promising to accommodate increased payload data transfer requirements. These components have however not yet been included in the mass and power budgets.

Power

The following requirements were imposed on the design of the power control and distribution system:

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- The average electrical power generation should be 30 kW
- Maximum eclipse time is about 36 minutes for the selected orbit
- In survival mode, the batteries should provide sufficient electrical energy to power the station for two orbits

It is further assumed for survival mode that the solar power generation fails during an eclipse, such that the batteries start at a reduced charge state.

The system architecture is based on the current ISS design, with an assumed increase in efficiency and a number of simplifications where possible. A threefold redundancy is implemented in the primary bus. No redundancy is foreseen for the secondary bus, aside from double interface connections.

Thermal

The thermal system for the Base Platform has to ensure that conditions within the station are maintained within a range suitable for habitation.

An active system is implemented, where liquid coolant loops are used to transport heat to the station's radiators. The system is split into an external and internal loop, similar to the ISS, where the external loop uses ammonia as a coolant and the internal loop uses water.

Two radiators, with a total area of 90 m^2, are foreseen to reject up to 30 kW of heat. The radiators will be outfitted with rotation mechanisms, to ensure optimal heat rejection by tilting the radiators to avoid exposure to direct sunlight.

AOCS / Navigation

As the Base Platform will be launched in separate sections (HAB, SM, DN) and then connected on orbit, each of the three sections requires sensors and actuators to accommodate docking of one section to another.

Furthermore, the orientation of the station will differ depending on the maneuver scenario. To accommodate this, both the HAB and the DN are outfitted with the necessary sensors (e.g. sun sensor, GNSS receiver and antenna) for attitude determination.

Attitude control of the station is done via the control moment gyroscopes (CMGs) installed on an adapter corridor between the SM and the DN. Additional thrusters are implemented on the SM to allow for rendezvous and docking during the initial station construction phase. These thrusters can later be used for attitude control.

Propulsion

The propulsion system is responsible for the initial rendezvous and docking maneuvers during the construction phase, as well as for maintaining the Base Platform's orbit and debris avoidance. The estimated orbit raising Δv-budget amounts to 93 m/s per year. Additionally, it is assumed that six debris avoidance maneuvers are required per year. Based on experience from the ISS, such a maneuver requires a Δv of about 0.5 – 1 m/s. The propulsion system also has to desaturate the CMGs. [13]

In nominal operations, either a visiting vehicle or the Free Flyer will provide the Δv required for orbit and debris avoidance maneuvers. However the DN will be capable of carrying out such operations for contingency cases.

3.1.2 Mass budget

During the CE study mass budgets were created for the different sub-systems. To account for the uncertainties early on in the design process, margins were applied at a sub-system level depending on the level of maturity of the design. A breakdown of the Base Platform mass according to sub-system is presented in Figure 3 for both the complete platform and for each module.

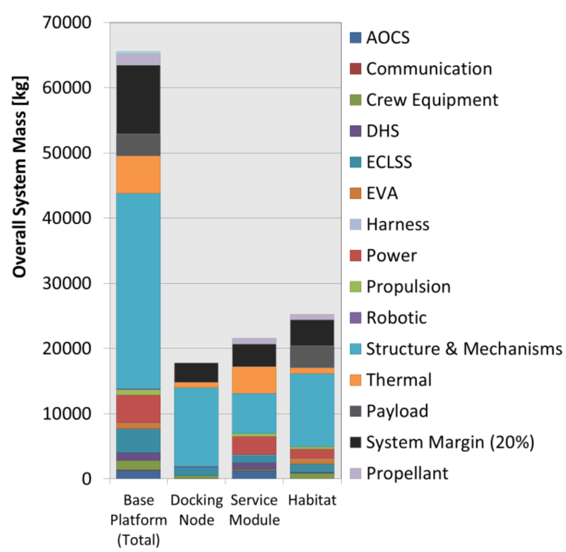

Figure 3: Base Platform subsystem mass contributions for the complete platform and per module.

A further 20% margin is applied on these system level budget values, which leads to an increase in mass of approximately 10 tonnes. The expectation would be that a significant mass reduction can be achieved later in the design as uncertainties are reduced. To accommodate the on-orbit assembly phase, it is necessary to include sufficient propellant in the initial launches of the HAB and the SM to allow for rendezvous and docking maneuvers, as well as station keeping until nominal operations commence.

3.1.3 Power budget

The overall power requirement of all the components on the Base Platform amounts to approximately 30 kW, including sub-system and system level margins.

A breakdown according to the different sub-systems can be seen in Figure 4. The graphs also include the power consumption of the components of the power sub-system itself, which are required to generate and distribute the power to the consumer. To ensure the provision of 30 kW, the solar panels and batteries have to be dimensioned under consideration of these losses. Therefore, based on the most power demanding mode (i.e. Crew exchange), the required amount of overall generated power of the Orbital Hub has been calculated as approx. 40 kW. Note that the graphs display power consumption values with sub-system margin, but without the additional system margin.

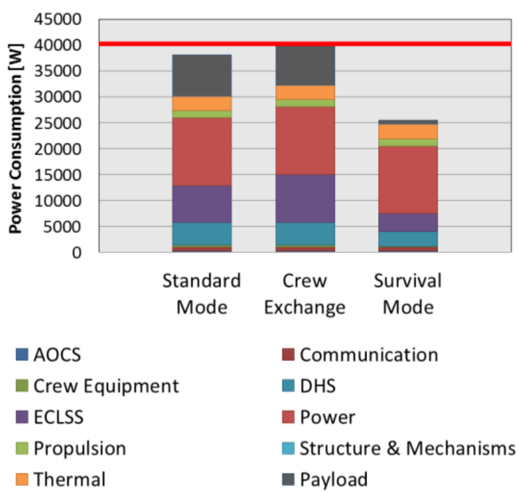

Figure 4: Base Platform power consumption per subsystem and maximum generated power (horizontal line)

The combined power required during survival mode is about 12.4 kW excluding the power subsystem losses. Including these losses, the originally generated power must be 25.5 kW as shown in Figure 4. During this mode, the majority of the payloads are shut down and the OBC and ECLSS are operated at reduced capacity. Additionally, some of the power available to the crew (e.g. for cooking) is reduced as well.

3.1.4 Cost

The first rough cost estimation of the Base Platform is done via analogy-based assessment. The selected reference architecture for the analogue based cost estimation is the ISS.

The ISS consists of approximately 44 modules (incl. truss segments, adapters and airlocks), with an average mass of about 10 tonnes per module.

A cost/mass ratio of 80 million $/tonne was previously stated for the ISS (c.f. 2.4). Applying this value, along with the estimated Base Platform mass of 63 tonnes, to Equation (1), an approximate cost of 5.1 billion $ is calculated.

However, the design of the Base Platform foresees the use of a BA-330 module which has already been developed by Bigelow Aerospace. As such, it is assumed that only the First Unit costs will need to be taken into account for the HAB, which would amount to 15-20% of the overall development costs.

This assumption would result in a reduction in the Base Platform development costs, down to 3.5 billion $. It should be noted that significant uncertainty exists with respect to the cost estimations as the values are based on analogue estimates.

Therefore, in post processing, a more elaborated cost analysis has been performed following the bottom-up approach explained in chapter 2.4.

The complete development of the first in-orbit hardware using a proto-flight model philosophy including wrapping costs for organisation and support sums up to approx. 2220 M€ based on fiscal year 2016, c.f. Figure 6. As can be seen from Figure 5, the HAB holds the biggest share of the development cost with the main contribution coming from the structure. This can be explained by the fact, that the cost calculation has been adapted for this position to represent the plan to procure a commercial expandable habitat for the initial cost offer. Depending on what other sub-systems will be included from the start in this module and how big the effort will be to modify, adapt and update the module towards the specific needs of the Orbital Hub, this cost estimation will need to be refined. For now, a pessimistic first estimation assumes that only the structure of the module will be purchased and all other systems need to be developed separately.

Additional to the technical development and testing of the modules, wrapping costs on system level have to be considered for project office and system engineering. Flight software development and additional costs for assembly, integration and testing of the complete system hold a non-neglible share of the overall system costs (c.f. Figure 6).

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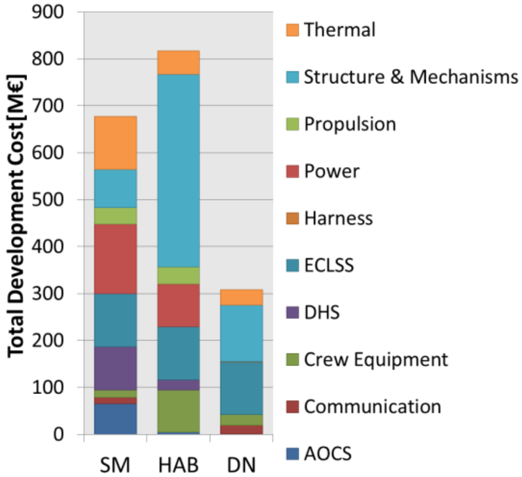

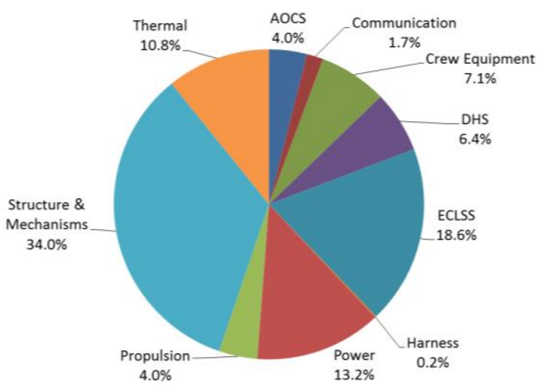

Figure 5: Total development cost by sub-system for the three modules in absolute values (top) and their cost share in the overall system cost (bottom) of the Base Platform

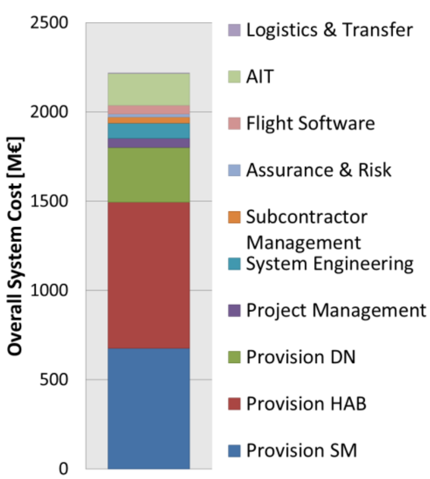

Figure 6: Overall system cost including module development and wrap up costs for organisation and support for the first proto-flight module of the Base Platform in absolute values in FY16 M€.

3.2 Free Flyer

The Free Flyer module is DLR's proposed answer to the user community's desire for a decoupleable platform to meet the requirements for undisturbed measurements under high microgravitation quality both for pressurized and unpressurized payloads.

The Free Flyer consists of three functional parts, each with dedicated purposes and design characteristics. These sections are the Pressurized Laboratory (PL), External Platform (EP) and Service Module (SM) as shown in Figure 2. It is intended to fly uncrewed in a safe formation to the Base Platform with an independent arbitrary attitude pointing (e.g. nadir for Earth observation or inertial for astrophysics) for periods of several months (e.g. 3 months) to perform its actual mission before it docks to the platform for a short service cycle (two weeks). During that time the Orbital Hub crew, supported by robotics and the included airlock, can reconfigure, stock-up and maintain the Free Flyer, as well as extract payload to be transferred back to Earth later on.

The PL is the Free Flyer's access point which the crew can enter when docked to the Base Platform (at any free docking port) or directly to a crew vehicle. This enables direct and quick maintenance or replacement of the internal experiments, and the external payloads before these are sent through the airlock. The EP represents the central part of the Free Flyer. Its main objective is to provide sufficient area and unobstructed field of views for the various assumed types of strawman payloads [12]. One main design decision during the CE study was to reject any complex deployable main structure for this purpose and to come back to a simple rigid rectangular truss structure covered with MLI, in close conformity with the ISS Integrated Truss Structure segments [14]. A 7-DoF robotic arm with heritage from the DLR DEOS project [15] in combination with a mobility unit on a circular rail around the structure is used to transfer the payloads from the airlock and to service the EP.

The SM of the Free Flyer accommodates all major bus sub-systems (power, attitude control, propulsion and thermal control). Its structure is an integral extension of the truss of the EP, using the same characteristics, allowing for an optimized transfer of the mechanical loads during launch. On the other hand this translates to the fact that it is unpressurized and therefore not directly accessible from the inside for the astronauts. This design decision has been taken during the study phase as there is no corresponding requirement for the SM to be maintainable. Thereby it has been accepted to reduce the nominal lifetime of the Free Flyer and to decommission it in case of a critical failure in the SM. EVA based repairing of main components which are accessible from the outside is still an option in contingency cases though.

The anticipated launch scenario foresees the Free Flyer to be put into orbit using a single launch e.g. considering an ARIANE 6-4 as baseline launch vehicle. The system mass and overall dimensions in launch configuration (c.f. Figure 11) are optimized according to this strategy.

3.2.1 Technical solution

Payloads:

The Free Flyer has two payload sections: one inside the PL, mainly for material science, and one for unpressurized payloads on the EP with multiple applications ranging from earth observation, astrophysics & -biology to technology demonstration. The PL accommodates 12 ISPRs in total (c.f. Figure 7), of which, in the baseline design, five are dedicated to strawman payloads. As the support functions of the PL (bus components, crew workstation etc.) only take up two ISPRs, the Free Flyer has enough spare racks for additional applications and upgrades if necessary. The EP meets the requirement of providing an area sufficient for ten JEM EFU equivalent big payloads and another 8 m^2 for smaller payloads. In total the EP provides approx. 38 m^2 for payloads on which 24 interfaces for big payloads and 8 for smaller payloads are distributed to create enough flexibility to satisfy the particular payload demands concerning e.g. position, viewing direction or FOV. The provided payload slots will be equipped as demanded by the (paying) customer and as allowed by the available financial budget, which is also driven by their operating cost. Not all positions need to be equipped necessarily, but offering a sufficient number of slots in different locations promises more flexibility and more frequent flight opportunities for different payload types. Additionally, not all payloads will be operated in parallel but could be (temporarily) deactivated.

ECLSS

The Free Flyer's PL is only meant to be crewed in such docked states during which the ECLSS functionalities can be provided by the docked platform. This allows for a streamlined and lean design with reduced complexity for the Free Flyer's dedicated life support system

Data Handling & Onboard Computer

Man-tended spacecraft in general require a two-failure tolerant control-system. [16] The Free Flyer is equipped with three hot-redundant computers used as central supervision and control instance. A Triple-LAN gigabit network as a back-bone for data exchange allows for e.g. real-time applications or video-streaming. A WiFi access point on the EP is foreseen for on-board payload data transmission.

The integrated data handling infrastructure of the Free Flyer contrasts the current ISS setup where system data, payload operations, high data transfer and video are handled via dedicated channels.

Communication

The Free Flyer is designed to communicate with the ground stations both directly and via the Base Platform as a relay. For this reason, the Free Flyer is equipped with the same three communication channels as the Base Platform with an increased focus on laser communication.

Power

The Power system has been sized based on two main requirements: an average demand of 20 kW during nominal operation, and the survival of the system despite a total loss of power generation for the duration of one orbit, when the Free Flyer is powered exclusively from the batteries.

Calculations show a necessary total solar panel area of 167 m^2. This high area demand requires an efficient design for the solar panel deployment to not contradictorily increase the vibration level on the Free Flyer due to a high span-width of the panels. The MegaFlex / UltraFlex circular deployable solar panels are a promising solution to this problem as, due to the sophisticated folding mechanism, it allows for big photovoltaic areas while still obtaining a small packing-volume, light mass and medium span-width [19].

For the Free Flyer Lithium Ion batteries are included to supersede the Ni-based battery cells originally used on the ISS. The selected battery type [19], in combination with the designed topology, provides enough energy storage for a complete power loss during two orbits.

Thermal

An active thermal control system (TCS) has been chosen to handle the generated heat and is designed in line with the Base Platform's setup.

The overall heat of the Free Flyer (including payloads) is transported to body mounted radiators and the deployable radiator wing (approx. 12 m^2 plus 25 m^2 surface area) for rejection into space. All

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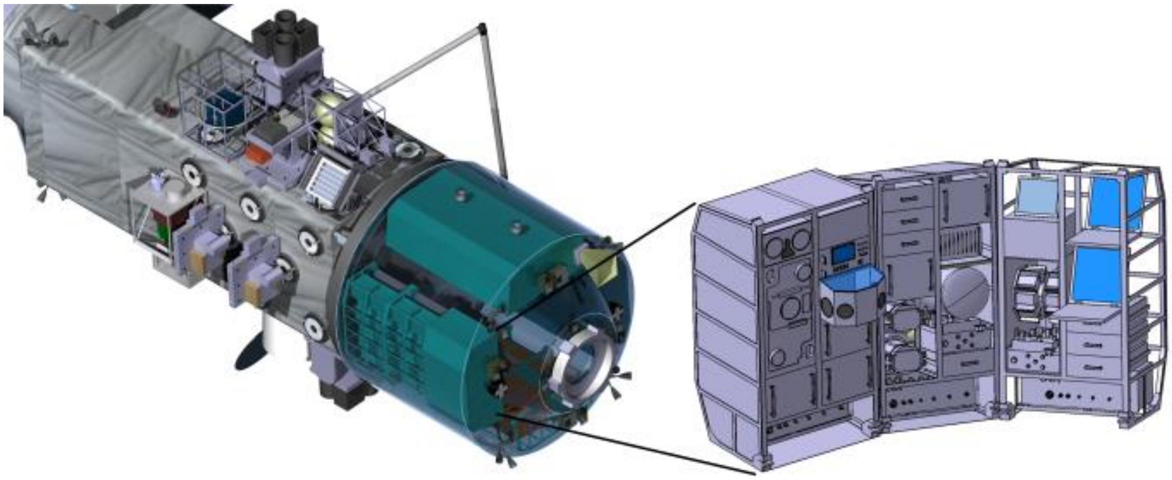

Figure 7: Free Flyer payload in the Pressurized Lab and on the External Platform

main components for the TCS such as pumps and tanks are located in the SM.

AOCS / Navigation

The AOCS components of the Free Flyer are selected in accordance to the Base Platform design. Thus, it is equipped with four Control Momentum Gyros (CMGs) and chemical reaction control thrusters as AOCS actuators. The CMGs are designed in accordance to ISS hardware but downscaled to the Free Flyer's specifications. They are active during the nominal mode whereas, during survival mode, the RCS thrusters are used for attitude control exclusively. Attitude determination is performed with GNSS during nominal operations and by star trackers during survival mode. Additionally, sun- & horizon sensors are used for coarse attitude determination. The navigation system for Rendezvous and Docking maneuvers is derived from the ATV design [20].

Propulsion

The propulsion system accommodated inside the SM is a hybrid between chemical thrusters for short impulsive manoeuvres (i.e. during rendezvous and docking, for debris avoidance and reaction control) and electrical thrusters suitable for longterm low-thrust applications such as disturbance (mainly atmospheric drag) compensation.

The chemical propulsion system is equipped with four main engines in the stern of the Free Flyer with 400 N thrust each and 24 RCS thrusters with 220 N each distributed along the bow and the stern with heritage from ATV`s and Orion Service Module`s reaction control system [21], to provide sufficient agility during the Base Platform's assembly phase and formation flying. The bi-propellant tanks are dimensioned to be refuelled multiple times and with a capacity of approx. 760 kg of bipropellant are sufficient for one complete free-flying phase including rendezvous and docking manoeuvres and safety margins [13].

For the electrical propulsion system two types of thrusters from the RIT series have been selected (RIT 10 EVO and RIT 20). To fulfil the required operational thrust range of 10-130 mN and ensure redundancy, clusters of four of each thruster type are included at the stern of the Free Flyer. The electrical propulsion system is estimated to have a consumption of approx. 660 kg of Xenon over the entire lifetime of 15 years, of which half can be stored in the tanks, leading to one necessary refuelling. Currently, in-orbit refuelling of high-pressure Xenon tanks is an unsolved problem though. If this is still true by the time the Free Flyer will be realized (current timeframe is 2025) solutions range from exchangeable tanks using robotic means, to On-Orbit Servicing or a reduction of free-flying durations and, correspondingly, payload capabilities.

3.2.2 Mass budget

The overall system mass incl. all recommended strawman payloads has been collected in the common data model during the CE study. The results reflected in Figure 8 show a discrepancy between the allowed launch mass of 19 tonnes and the total mass incl. payloads of 27 tonnes. To meet the mass requirement coming from the single launch scenario using ARIANE 6, the payload mass during launch has to be reduced to a maximum of 1.4 tonnes to reach a final launch wet-mass of 18.7 tonnes incl. 20 %

system margin (c.f. , Figure 8 right). This means, the Free Flyer will be equipped, after launch, with additional payloads provided by transport vehicles in order to reach full operational state and the maximum allowed in orbit mass. Exchange of payloads with dimensions exceeding the IBDM capabilities (e.g. telescopes) would be done by robotic hand-over between transport vehicle and external platform.

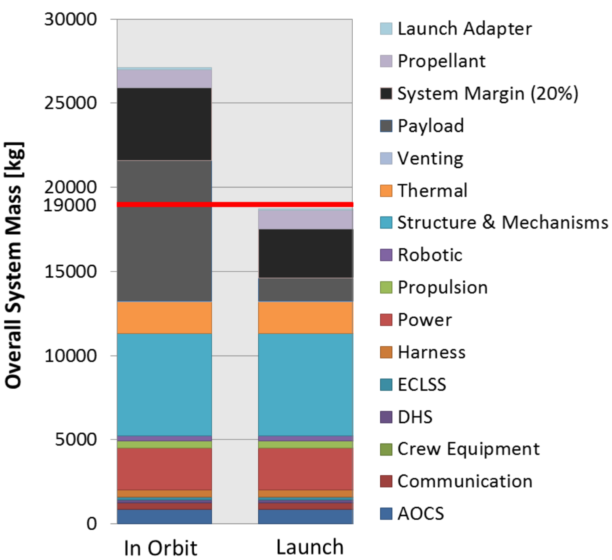

Figure 8: Overall system mass contribution by subsystem for comparison between expected in-orbit mass with all strawman payloads included (left) and the launch configuration with reduced payload mass (right) including maximum launch mass of selected launcher (horizontal line)

3.2.1 *Power budget*

Two main power modes have been introduced for the Free Flyer to separate between nominal operation (Standard Mode) and a contingency case (Survival Mode) in which the nominal power level cannot be obtained due to e.g. a failure in the attitude control resulting in a misalignment of the solar panels wrt. the sun vector and thus a reduced power input from the photovoltaics. The maximum assumed duration of a complete power generation loss is 1.5 orbits during which the complete system has to survive only by means of stored energy from the batteries. Therefore, similar as for the Base Platform, in the Survival Mode all unnecessary components are switched off (i.e. there will be no payload operation) to reduce the power consumption to a minimum which still guarantees the survival of the system. Main energy sinks in Survival Mode are the power sub-system itself (mainly losses), thermal control, data handling and communication. AOCS and propulsion performance is reduced to a minimum which still allows prevention of tumbling and a return to sun-pointing. The electric propulsion system is switched off completely and only the chemical thrusters are assumed active for short maneuvers. Figure 9 shows the power consumption during these two modes and also highlights the nominal average power provided by the photovoltaics of 27.44 kW which exceeds the expected consumption during Standard Mode also with all payloads being active.

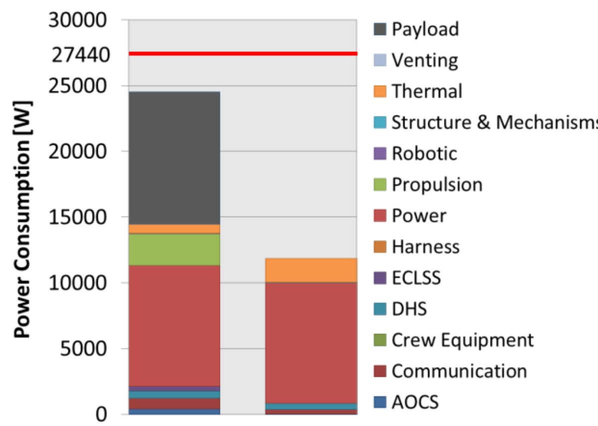

Figure 9: Overall system power consumption for the two power modes with absolute values of the sub-system's average power demand including maximum generated power (horizontal line)

3.2.2 *Cost*

Following the bottom-up methodology explained in chapter 2.4, the costs of the Free Flyer have been estimated for the complete development of the first in-orbit hardware, using a proto-flight model philosophy, including wrapping costs for organisation and support. The overall system cost sums up to approx. 530 M€ based on fiscal year 2016, c.f. Figure 13. As can be seen from Figure 12, the SM holds the biggest share of the development cost. This is understandable, as it accommodates the most critical sub-systems, which partly require new developments to improve on their low TRL. In particular the power sub-system, with the heavy batteries and huge solar panels, has a big impact on the cost when using the mass driven CERs. The structure & mechanisms cost, with the rather low TRL level of the foreseen common rotary ring mechanism in the rear part of the Free Flyer, is also prominent in this cost distribution. Those two sub-systems also hold the biggest share in the overall system cost, which, when compared to similar

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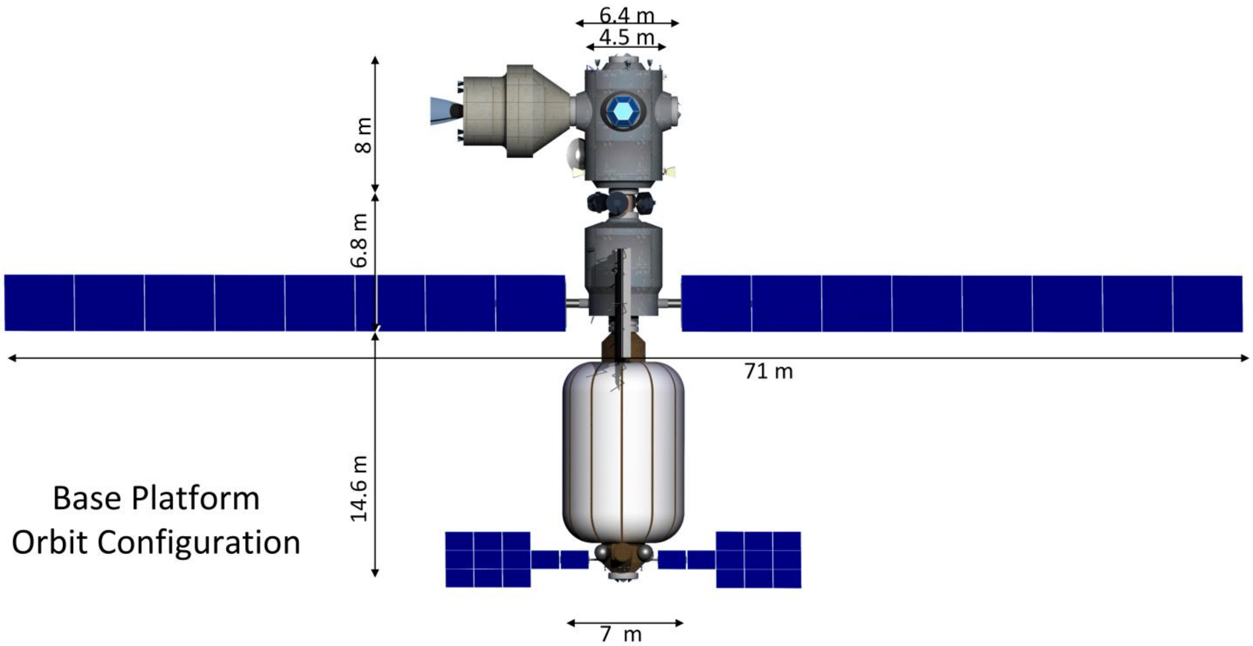

Figure 10: Base Platform main dimensions in orbit configuration

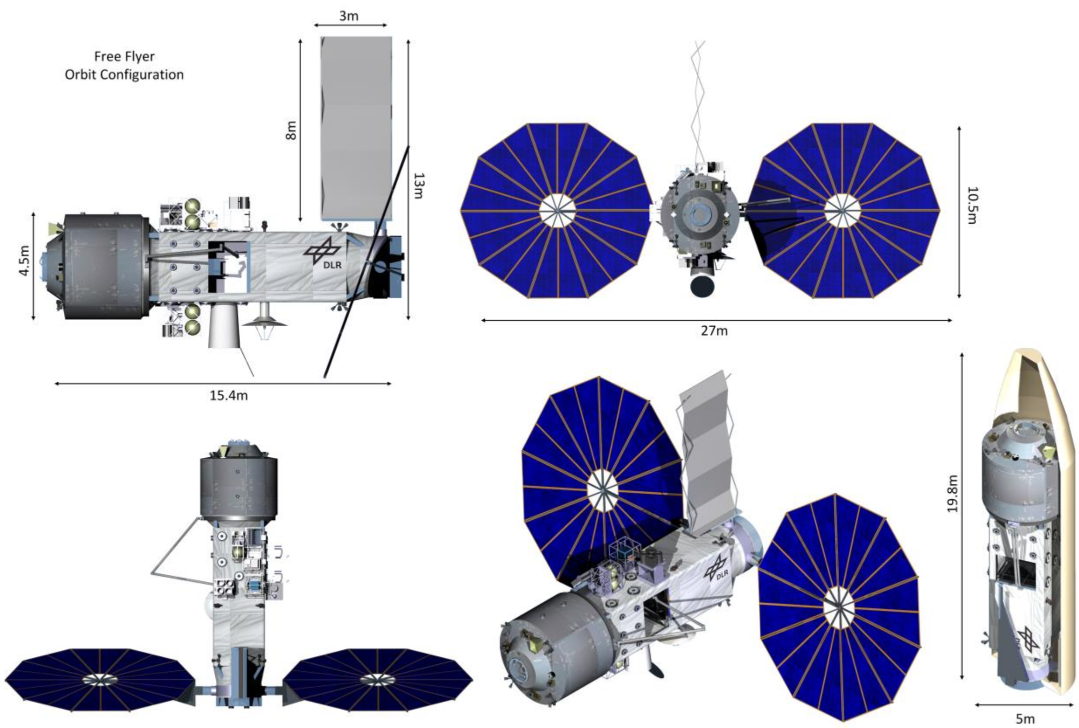

Figure 11: Free Flyer main dimensions in launch and orbit configuration

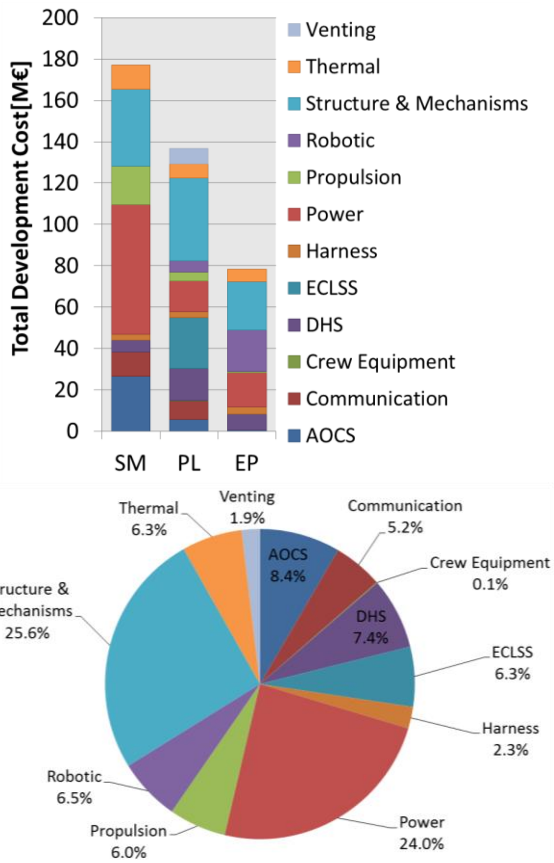

Figure 12: Total development cost by subsystem for the three modules in absolute values (top) and their cost share in the overall system cost (bottom) of the Free Flyer

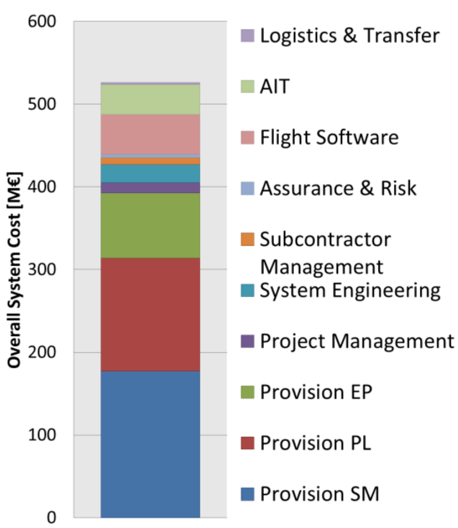

Figure 13: Overall system cost including module development and wrap up costs for organisation and support for the first proto-flight module of the Free Flyer in absolute values in FY16 M€.

studies, is a reasonable result. The cost share for the ECLSS system (approx. 6%) is rather low in comparison to other man-tended space systems, which can be explained by the fact that the Free Flyer is only equipped with reduced ECLSS capabilities and relies on the respective docked vehicle's life support system for full functionality.
In line with the results from the Base Platform bottom-up cost calculation in Chapter 3.1.4, Figure 13 visualizes the estimated overall system cost for the provision of the first Free Flyer.

3.3 Orbit selection and launch scenario

For the mission analysis of the Orbital Hub scenario an ISS-like orbit of 51.6° inclination and a reference orbit height of 400 km are assumed. On the one hand, this orbit offers a coverage of 95 % of the world's populated area, which is an advantage for the Earth Observation applications, and on the other hand allows for subsequent utilization of the well-developed ISS ground station network and launch infrastructure. Additionally, as it is foreseen to have the Free Flyer coexistent with the ISS during its first mission, no fuel-expensive inclination change manoeuvers would be required to dock with the ISS.

As described throughout the technical description of the Base Platform and the Free Flyer, the single modules are foreseen to be inserted into orbit separately on subsequent launches. With the decommissioning of the Space Shuttle, the capability to transport complete modules into LEO and assemble those by robotic means got lost, without the plan to be replaced by a comparable system in the foreseeable future. Therefore, any new modules for ISS or future platforms need to have the capability to perform rendezvous manoeuvres with the platform at least until a point within the range of a supporting robotic arm to be grabbed and berthed to the existing platform. Thus, fundamental sub-systems need to be included within the modules to support these transfer phases.

The Base Platform of the Orbital Hub concept is planned to be assembled without the assistance of the current ISS. Additionally, it relies on the existing European know-how on automated rendezvous and docking from ATV and the assumption that this key technology will be available also for future visiting vehicles, which in turn makes a robotic arm for berthing obsolete.

To streamline the assembly phase, the strategy is based on only one active part, i.e. the Free Flyer. It will be the first element in orbit and subsequently performs rendezvous with the other passive modules, which only have minimal keep-alive and

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attitude stabilization functionalities. Thereby, the Free Flyer collects the single modules one after the other and merges them to the final platform configuration. Only after these steps are completed and the functionality of the Base Platform is ensured, will the first crew arrive. This, together with the mass and volume of the modules leads to the following possible launch scenario:

1) Free Flyer (e.g. Ariane 6-4, Proton, Atlas V, Falcon 9, H-II)
2) Habitat (e.g. Delta IV, Proton, Falcon Heavy)
3) Service Module (e.g. Ariane 6-4, Proton, Atlas V, Falcon 9)
4) Docking Node (e.g. Ariane 6-4, Proton, Falcon 9, H-II)

3.4 Operation scenario

The flight plan pictured in Figure 14 is one possible scenario for the operation of the Orbital Hub concept.

Starting from the envisaged mission duration aboard the base platform of 6 months per crew with overlapping times for handover, a launch and return schedule has been derived both for crew vehicles and cargo supply. The Base Platform's DN provides five docking ports, of which one is permanently occupied by the Cupola. The visiting vehicles have been distributed over the available ports also considering their docking capabilities. The download capability, required by several payloads, is assumed to be covered either by suitable cargo vehicles or by the use of available unused mass on the crew return vehicles. For example, the Dragon V2 for crew return offers up to seven seats [22], which in this scenario with a crew size of three astronauts, would not be completely exploited. The free capacity could also be used for additional cargo up- and download, which would release the requirements on the cargo supply missions. It has to be stated that the pictured selected systems are only one potential solution. The concept aims to be open for alternative combinations of other existing or future visiting vehicles (e.g. SNC Dream Chaser for cargo download).

Even though the Free Flyer is capable of being connected to the DN, in nominal operation it is foreseen to dock to the HAB's docking adapter in flight direction and stay there for servicing and maintenance for approx. two weeks (depending on required effort) before departing for an approx. three month free-flying campaign. This scenario would lead to three payload operation cycles per year for the Free Flyer.

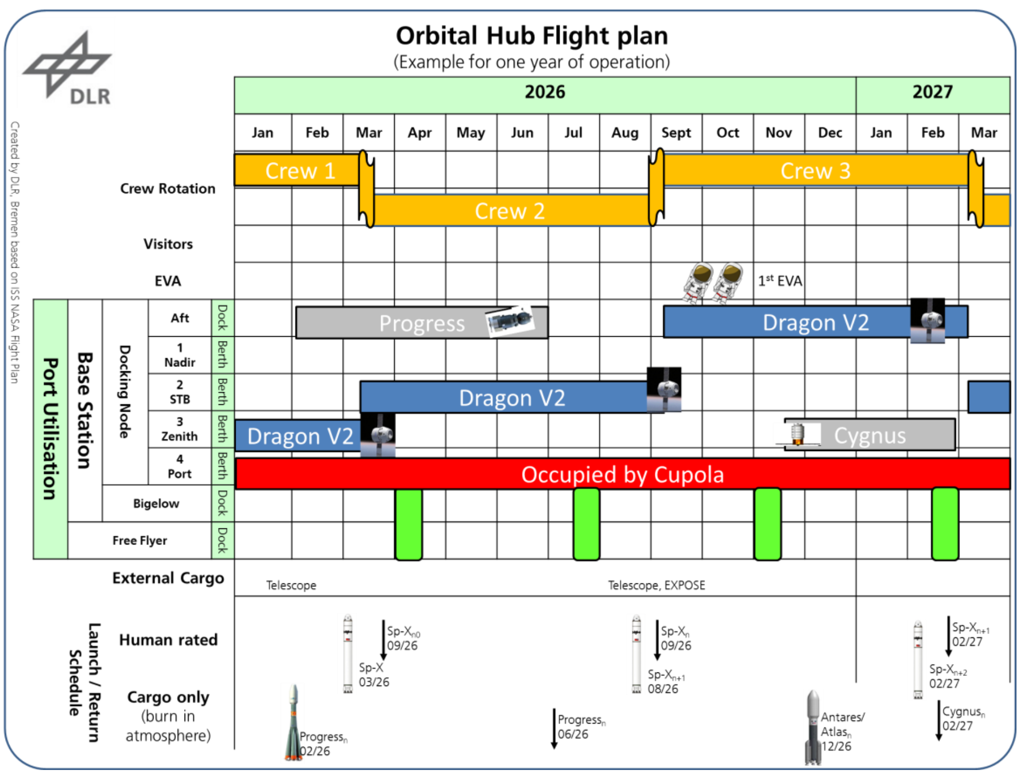

Figure 14: Exemplary flight plan for the Orbital Hub for one year of operation

During nominal operations, the DN will be forward in the direction of flight. However, orbit raising of the station will be done, primarily, by crew/cargo vehicles attached to the DN, which requires that the HAB is forward in the direction of flight. In the case where no vehicle is docked, the DN thrusters will be used for orbit adjustment. The EVA activity in Sept. / Oct. is shown as one exemplary contingency case and is not part of the nominal operations.

3.5 Operation cost

Aside from the development costs, the recurring operating costs based on the assembly strategy and the described yearly flight plan have been estimated. The setup and operating costs are illustrated in Figure 15. The Year 0 costs cover the complete development costs, operating costs for one year, four cargo launches (180 M€ each) for the respective modules and one crewed launch.

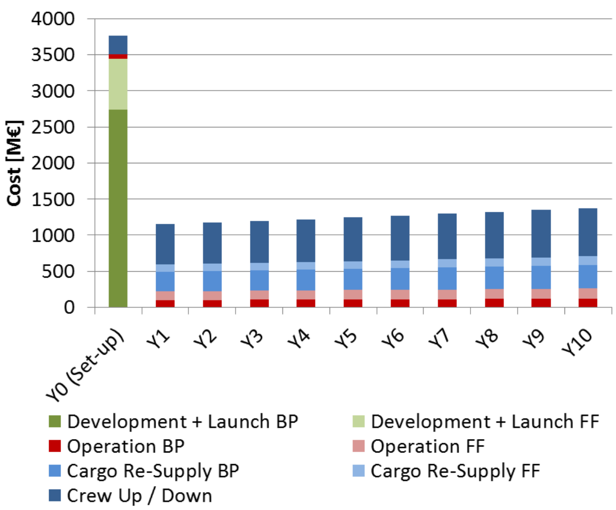

Figure 15: Orbital Hub cost estimation including cost for operation and supply missions

For subsequent years, a total of two crewed launches (280 M€ each) and two cargo launches per year were assumed. Additionally, 220 M€ per year was assumed for mission operations including astronautical activities. Not yet taken into account were costs associated with the on-board utilization, payload development and additional cost for enhanced ground-network usage (e.g. via TDRS/EDRS). These points are especially related to the demands of the single payload provider / customer. Depending on the actual business model of the platform, these costs could be shifted to the actual paying (commercial) customer and are not considered as part of the running cost of the platform itself. The single cost estimations are based on best-engineering guesses derived from current Ariane 5 and ISS operation cost.

An inflation rate of 2% per year was applied to estimate the total costs of the Orbital Hub after 10 years, resulting in approximately 16.4 billion € at an average of 1.5 billion € per year.

4 Discussion

The Orbital Hub, as the result of the two design studies, is a complete concept of a small modular LEO platform with extended capabilities thanks to the included Free Flyer for payloads with specific requirements. The concept shall be assessed on several different aspects in the following to evaluate it and compare it to similar designs.

<u>*Comparison to existing designs*</u>

In comparison to the ISS, the Base Platform is significantly smaller but provides all necessary functionalities for a permanent crew. With its 65 t the mass of the Base Platform equals only about 15 % of the current in-orbit mass of the ISS and the electrical power of 30 kW is approx. a quarter of what is available on the ISS. A coarse comparison of these numbers with the timeline of the construction phase of the ISS shows that the Base Platform (mass, power and functionality wise) is best comparable to the development state of the ISS in 2000, when the first permanent crew arrived. Back then, the ISS consisted of the first three pressurized modules (Zarya, Unity and Zvezda) plus the first truss element with a total mass of 60 t and 17 kW of electrical power. With regard to the provided functionalities it is equivalent to the Base Platform: crew living, life-support, propulsion, power supply, attitude control and docking ports. This comparison supports the essential assumptions of the Base Platform design as plausible and the first mass break-down as a good approximation. For the difference in the power value it must be noted that in this early ISS phase no power-hungry experiments have been conducted aboard the station. With an according duty cycle, the average power consumption of the payloads inside the Base Platform is approx. 8 kW. A big difference between both platforms is the expandable habitat module which, thanks to the technological advances, provides much more room for the crew and experiments than in the Russian ISS modules.

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The Free Flyer is designed based on the technology and know-how from mainly Columbus and ATV for the pressurized part and the docking maneuver, as well as the Kibo Exposed Facility and the ISS Truss for its unpressurized section. The launch wet-mass of the Free Flyer (19 t) is comparable to a fully loaded ATV (approx. 20 t) and once in complete orbit configuration with 25 t it resembles the Kibo module including Exposed Facility (24 t, excluding external payloads). However, the Free Flyer is a new kind of system with very specific characteristics and requirements which makes it hard to find relevant examples for a direct comparison of performance and budgets.

Operations

New concepts for operation and maintenance have been incorporated into the design to further reduce the operational cost of the platform. One important point was the requirement to reduce the usage of EVAs as far as possible.

The reliance on autonomous systems and avoidance of EVAs for operation and assembly reduces costs and risks. EVAs need extensive preparation and planning and are always a risk for crew safety, due to the involved radiation, technological obstacles and the risk of failure with limited back-up and fallback capacities.

Autonomous systems remove stress and workload from the crew and likewise reduce the workload for ground base operation teams, if they work reliably and do not require additional supervision from ground or from the crew, thus reducing the operational costs associated with the station. This means, that critical external components need to be located and designed in such a way that they can be maintained or replaced by robotic means. In the Orbital Hub, one example of this was the positioning of the maintenance-prone CMGs externally on an adapter between the SM and DN to make the components reachable by accordingly equipped visiting vehicles or a robotic manipulator on the Base Platform.

On account of the experience with crew operations which has been gained from the ISS, there is significant potential to improve on existing crew accommodations during the further development of the Orbital Hub.

The Orbital Hub design aims to utilize proven technologies and designs and incorporate lessons learned from the ISS, in order to reduce the required amount of maintenance and repair work. Consequently, more crew time can be dedicated to scientific experiments and commercial activities, utilizing the experiment payloads installed in the HAB module.

Modularity approach

Concerning modifications or successive updates of the platform, as has been done for the ISS by heavy use of EVAs, the Base Platform of the Orbital Hub follows a different approach. In fact, it is not foreseen that it will be a growing platform with more and more modules being permanently attached to it, but rather it should be the central node for multiple, differently equipped, visiting vehicles (e.g. multiple instances of the Free Flyer or similar vehicles) for collaboration and resource sharing as it is foreseen in the DLR long-term vision of a "Space City" in LEO. [28]

Size reduction

One further advantage of the presented design is the reduced size in comparison with ISS and at the same time the separation in crewed and uncrewed portions. The reduced size along with the designed autonomy results in lower costs and launch and operation efforts.

It also leads to earlier benefits. With three launches the base can be fully set-up allowing the complete exploitation of its capabilities. ISS assembly was started in 1998 and only in May 2009 the first 6 person crew came onboard, doubling ISS' crew size. The reduced size of the Orbital Hub also eases the governance structure.

The separation into two parts, one with crew and one without, allows unperturbed experimentation, which has been a drawback for ISS operations.

The size of the current station leads to perturbations, as only the center of mass is in a true micro-gravity environment. All other parts of the station are – from an orbital mechanics view – perturbed as their radial distance from Earth differs from what is required by their orbital velocity. Effectively ISS is subject to tidal forces [27]. A smaller size results in reduced effects. And the parted station is very small compared to ISS.

The Base Platform has a total length in the current configuration of 26 m, the free Flyer of 15 m, vs. 74 m of ISS along its flight axis (108 m perpendicular to that, along the solar array truss) [29] reducing tidal effects significantly. Actual values depend on the orientation of the station, but the distance of the center of mass is relevant.

The situation is depicted in Figure 16 in a highly simplified manner for visualization of the basic principle, where r is the distance of the station's center of mass from the barycenter of the orbit, r' the distance of the furthest point from the barycenter and *l* the length of the orbital structure.

Assuming the difference between these two distances is:

$$\Delta r = r' - r \tag{10}$$

$$\Delta r = \sqrt{r^2 + l^2} - r$$

and with the definition of the gravity force as depending on the square of the distance between the two masses [27]:

$$F = \frac{K}{r^2} \tag{11}$$

where K contains the two involved masses and the gravity constant. These are summarized here to focus on the interesting parameter r.

Assuming that the difference between the two forces is:

$$\Delta F = F - F', \tag{12}$$

and with Eq. (10) it can be derived that:

$$\Delta F = K \left(\frac{l^2}{r^2 (r^2 + l^2)} \right) \tag{13}$$

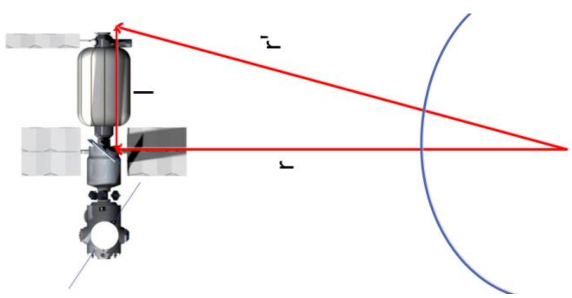

Figure 16: Illustration of the gravity-gradient situation of an orbital structure, here the designed Base Platform.

Assuming the characteristic length of ISS to be the parameter L and as depicted before that in case of the Base Platform the characteristic length is about 1/3 of that of ISS it can be seen that the effect on the presented design is about 10 % compared to ISS:

$$\Delta F_{base} = K \left(\frac{\frac{1}{9} L^2}{r^2 (r^2 + \frac{1}{9} L^2)} \right). \tag{14}$$

With L being very small in comparison to the orbital distance of several thousand kilometers, it can be simplified to:

$$\Delta F_{base} \approx K \left(\frac{\frac{1}{9} L^2}{r^4} \right). \tag{15}$$

In case of the Free Flyer the characteristic length is approximately $1/5\ L$, i.e. Eq. (6) becomes:

$$\Delta F_{base} \approx K \left(\frac{\frac{1}{25} L^2}{r^4} \right). \tag{16}$$

This means an improvement of factor 25 of the Free Flyer's gravity-gradient perturbations compared to ISS.

Furthermore, the removal of moving parts, e.g. training equipment, ventilation components, toilets, etc. from the experimentation area through usage of the uncrewed Free Flyer results in even less perturbations.

__Technology heritage__

The Orbital Hub design includes tested technology from existing comparable space systems, especially from the ISS program, with improvements due to new technologies where applicable. This on the one hand has the advantage that the design is based on realistic assumptions, but it also leads to a reduced development effort and hence reduced development time and cost once the concept will be taken to further stages.

One example is the Free Flyer PL's structural design and internal setup, which is based on the existing Columbus module with a shortened length due to a reduced number of required included ISPRs.

The successful ATV is another important guideline for the technical design. To perform automated rendezvous and docking manoeuvres with the Base Platform, the PL's in-flight front surface is equipped with multiple sensors based on hardware from the ATV program to re-use its control concept. The same accounts for the RCS thrusters.

This is one reason why it is seen as plausible to conduct the first Free Flyer mission in combination with the still existent and operating ISS within eight years.

__User applications__

The design of the Orbital Hub has been driven by the user community from the beginning of the project. The unique combination of man-tended base and the decoupleable payload platform creates an optimized setup for environmental and operational conditions for the payloads. The platform aims at appealing to both scientific as well as commercial users by providing important constraints, which increases the attractiveness for the development of new space-born applications. The proposed platform provides long-term experiment or observation programs to ensure planning reliability, frequent exchange and flight opportunities for the users' payloads and clear interfaces/resources w.r.t. data, power and environmental control.

While the payloads inside the crewed platform are foreseen to focus on human physiology, the Free Flyer is designed as multi-purpose payload platform.

The continuous compensation of drag forces by the Free Flyer's electrical propulsion system creates a high quality microgravity environment (up to 10^{-6} g) with decreased disturbances and vibrations through the absence of humans and the reduced structure size, which is important for e.g. material physics.

The Free Flyer's variable attitude (i.e. possibility to change between nadir pointing for Earth Observation applications and inertial pointing for astronomy) is an added feature in comparison to the ISS and could also attract users which normally would rely on specialised satellites to launch their payloads.

Generally speaking, the Orbital Hub concept combines the capabilities of a crewed platform (maintenance, exchange, return-capability and sophisticated operations for the payloads) with the known benefits of a satellite mission (pointing, microgravity). In contrast to a satellite, the Free Flyer is open to accommodate various types of payloads at the same time, to maintain them, and it gives the possibility to exchange them after their operational lifetime. Especially for technology demonstration applications, this could be an important argument to prefer the Free Flyer solution.

Cost analysis

The first estimation for development costs of the Orbital Hub hardware shall be compared with the most current numbers of the ESA budget to get a feeling for the plausibility of a realistic implementation of the scenario. The first cost analysis proposes a total development cost of the Orbital Hub (Base Platform plus Free Flyer) of approx. 2800 M€. This equals more than 50 % of the overall ESA budget of 2017 [25] and therefore despite the low-cost design approach is unlikely to be feasible as an all-European project. However, considering cooperation with other space-faring nations with interest in human spacecraft in low earth orbit and commercial partners from industry, the Orbital Hub scenario seems to be a manageable endeavour. The Free Flyer has been designed to also be self-sufficient and could be realized as first in-orbit hardware to dock and cooperate with the existing ISS design. Its estimated development and provision costs are within the limits of the ESA budget assigned to human spaceflight and robotic exploration [25] and could, especially with support from industry partners, be seen as a realistic first step.

Future exploration road maps

The ISECG Global Exploration Roadmap [2] as well as the derived ESA space exploration strategy [26] both explicitly mention small commercial and governmental LEO platforms, also after the currently envisaged operational phase of the ISS, for the exploitation of human-tended infrastructures, for technology demonstration and for the preparation of crewed missions beyond LEO. Additionally, ESA stresses the importance of "user-driven space exploitation" and the increasing influence of commercial partners. Thanks to the direct involvement of both potential users and industry partners in the design process of the Orbital Hub scenario it fits well into the near-term exploration strategies of the international human spaceflight community. Key technologies for deep-space exploration as indicated by ESA [26], e.g. robotics, on-orbit rendezvous and docking, and astronaut related technologies, are important aspects of the Orbital Hub scenario and therefore it is a perfect platform for the demonstration of these capabilities.

5 Outlook

After the analysis of lessons learned from the ISS, the user demands, and the technical design of the Orbital Hub scenario as described in this paper, this concept proved a promising solution with high potential for future LEO activities. The operational scenario has been designed on qualitative level but needs further analysis wrt. e.g. the following points:

- optimal free-flying durations and experiment exchange frequencies for optimal output concerning economic and scientific aspects
- orbit maneuvers timeline for the optimization wrt. design driving factors such as fuel-consumption, maneuver duration and generated payload data
- required time to exchange payloads from the Free Flyer to confirm the assumptions regarding the duration of docked operations

Currently a lot of work is conducted to include this solution, proposed by DLR, as a whole or as single modules (e.g. only the Free Flyer or single Base Platform modules), into the exploration road maps of both industry partners and institutions on international level. This leads to the question of a possible role share for the development and operation of the platform which needs to be answered both on technical but also on political level.

6 Conclusion

In this paper the complete design process of the Orbital Hub scenario is described. Starting from the request for a concept for a future LEO platform formulated as a loose idea, over the selection of strawman payloads and the evaluation of the most promising answer, to the specific user demands and derived system and mission requirements until the actual detailed technical design of the involved modules. The followed process was strongly depending on and characterized by the use of concurrent workshops and studies involving an interdisciplinary team including users, domain experts and engineers, as well as experienced astronauts for first-hand experience, to create an optimized, consistent and realistic concept.

The resulting designs of the Orbital Hub (consisting of Base Platform and Free Flyer) have been described on sub-system level, and main budgets for mass, power and development cost have been given together with a brief description of a possible operational scenario.

An assessment of the pros and cons of the key elements of the design and a comparison to the current ISS are given. Additionally the design has been put into context of current budgets and exploration road maps.

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