SET, A SCENARIO EVALUATOR TOOL FOR SUPPORTING SPACE-EXPLORATION MISSION-ARCHITECTURE DESIGN

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The design of space-exploration missions begins with a mission statement that defines the ultimate goals of the mission itself. The mission-architecture defines, instead, how the mission will work in practice, and encompasses all the elements that will take part in it. It includes such issues as the synergies of manned and robotic resources, mission control, and the mission timeline.

The mission-architecture design activity is an iterative process in general aimed at the maximization of the cost effectiveness (or value) of the mission and minimization of costs. This is performed by successive comparisons and evaluation of the alternative generated mission architectures.

The Scenario Evaluator Tool (SET) is conceived to support the engineering team in the framework of the space mission design process. In particular, SET is a simulation software tool that allows building mission architectures with a significant reduction of development time and computational effort. The software allows the characterization, the comparison, and optimization of exploration scenarios and building blocks through a user friendly graphical interface. Each mission-architecture is characterized and evaluated on the basis of the mass budget of the building blocks, cost index and exploration capabilities. SET is general enough to allow the design of several space exploration scenarios for Gap-analysis studies (flexibility). Further, it allows the users to introduce new model libraries (expandability). This paper describes the main features and the potentialities of the simulation software. To show the working principle of SET, a hypothetical human space-exploration mission scenario has been developed and implemented. The results has been accomplished in the framework of STEPS (Systems and Technologies for the ExPloration of Space), which is a research project co-financed by Piedmont Region (Italy), firms and universities of the Piedmont Aerospace District.

I. INTRODUCTION

The mission statement defines what the mission needs to achieve, what the qualitative goals are, and why one shall perform the mission itself. The mission architecture defines how the mission will work in practice and all elements that will take part in it. It includes such issues as the synergies of manned and robotic resources, mission control, and the mission timeline. The mission architecture design activity is an iterative process aimed at maximizing the cost effectiveness (or value) of the mission. The target is reached searching the solution that maximizes benefits and minimizes costs and other negative effects. This is performed by successive meaningful comparisons and evaluation of the generated alternatives. Considering all the system combination of building blocks and functionalities allocation, a large number of possible solutions are possible and the process results a very demanding activity. Fig. 1 attempts to schematize the mission architecture design process. The analysis of the mission statements allows the definition of the main mission objectives that must be compatible with the technical capabilities, physical realities and available budget so that the activity can proceed. At this level, also potential partners can be identified, in order to recognize possible external contributions involving secondary mission objectives and first high level functional requirements, such as actions to be performed at the desired target site, number of crewmembers, system needed, etc. Once the mission objectives and constrains are known, the building blocks, consistent with orbits, trajectories and cost constraints, can be selected to develop all the potential mission concepts. The set of candidate architectures must be large enough to scan all possible combinations, resulting from major and minor variations, but also small enough to make the detailed definition and evaluation manageable. The list of options can be illustrated by a tree of alternatives where major variations are located at the root of the tree and minor variations are located at the extremities. There are several structured methods useful to develop all possible system combinations. The process to construct and prune a trade tree of available options is one of these. After the main systems drivers have been identified, this method consists in mechanically creating the list of all possible combinations of mission options reducing then the number of options to those that are actually feasible or even also reasonable. The concept-tree is the output of this crucial activity that must be performed with particular attention in order not to exclude solutions that at a first sight may seem non-optimal but that are actually optimal.

At this point, each mission concept must be subjected to qualitative and/or quantitative evaluations, taking into account issues such as mass, risk, cost and exploration performances. In order to perform these analyses, first of all the major system drivers that affect the main features of the building blocks have to be identified, then trade off analyses aimed at selecting the best solution have to be carried out. Generally, trade off analyses are performed for all those systems and subsystems where multiple options exist, as life support system, power generation, thermal control, propulsion, entry and landing systems, structures, environmental control EVA approaches, GN&C, layout, surface mobility approaches, science support, etc.. Moreover, also mission operations such as crew timelines, mission event sequencing and control, back up and emergency procedures, maintenance and repair, science activities, contingency approaches, communication methods must be considered to complete the analyses. The design process ends with an assessment of the cost effectiveness of each concept solutions, in order to identify the most promising alternative.

It is evident that the design process of a space exploration mission is a very demanding activity both in terms of time and computational effort. The process seems to be quite sequential and orderly but iterations are frequent as well as the simultaneous working on several steps of the process and at multiple levels of details.

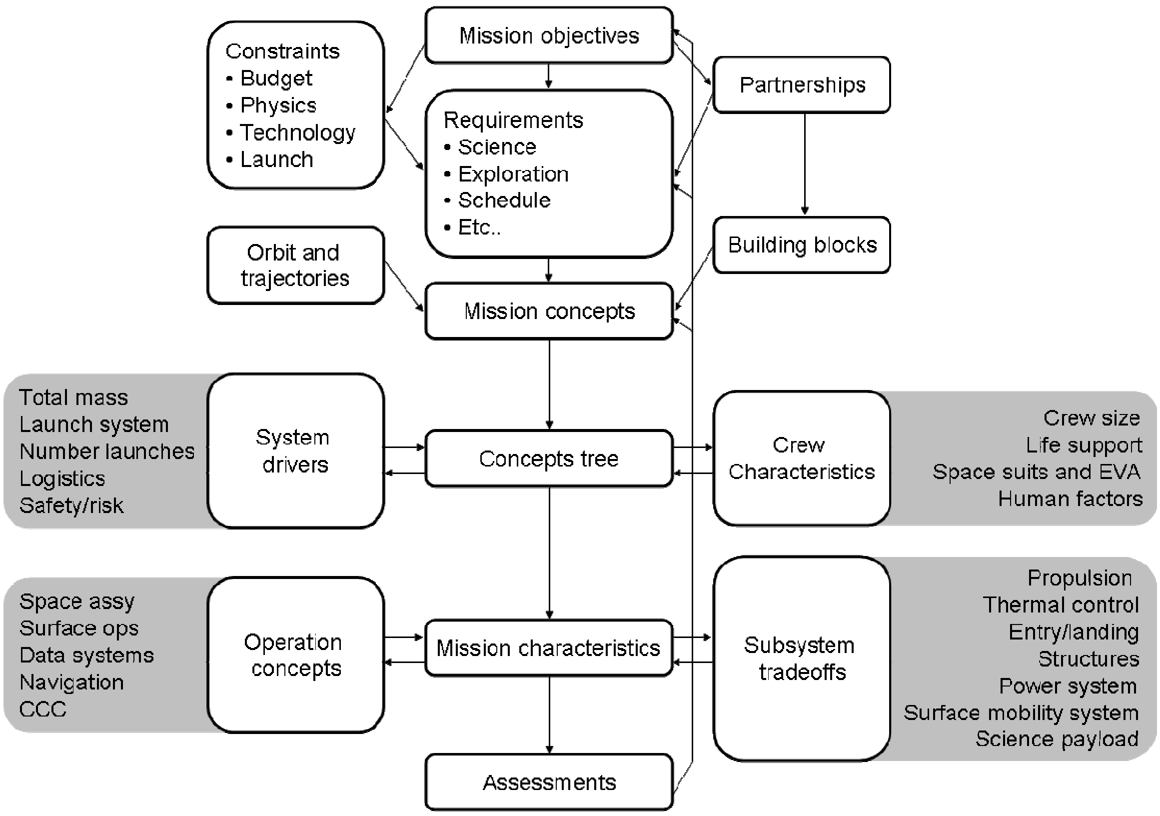


Fig. 1: Mission design process (ref [1])

With the intention of supporting the design team in the framework of the space mission design process, a simulation software tool has been developed. Scenario Evaluator Tool (SET) supports the design team in the framework of the space mission design process, allowing mission architecture definition and building block engineering with a significantly reduction of time and computational effort.

II. SET DESCRIPTION

The software allows the characterization, comparison and optimization of exploration scenarios and building blocks. The characterization of particular mission architectures is provided by evaluation and definition of the mass budget of the building blocks in the mission scenario, cost index and exploration capabilities. This information is then useful for the comparison of different solutions of the same problem. Finally the optimization is performed through a process of analysis of the effect of the main system driver on the performances. SET is implemented in Matlab and exports its results directly to the user through Graphical User Interface (GUI) and Excel file that can be used for post-processing analysis. SET is conceived in order to be applicable at several space exploration scenarios for Gap-analysis studies (flexibility) and allows introduction/customization of libraries to introduce new building blocks or to modify existent building blocks.

The Graphical User Interface has been organized in four main tabs, through which the user can provide inputs and access to the results, see Fig. 2. SET tabs are the scenario tab, the building blocks tab, the results tab and analysis tab. The scenario tab allows the user to specify the mission scenario and the mission architecture. Thus, the user selects the number of mission phases and the number and typology of building blocks that take part actively (the element performs an action during the specified mission phase) or passively (during a specified mission phase, the building block acts as a payload) to the maneuvers. The scenario description is completed by the selection of the starting and destination nodes. The nodes are positions in space intended as orbits around celestial body or surface locations. SET is provided with a database of nodes to which the corresponding values of delta-V to pass from one location to the other are associated. Nevertheless, the user can customize the default delta-V at any time via graphical interface.

Once the mission scenario has been described, the user shall provide the design input of the building blocks present in the mission scenario. The building blocks available in SET database are the Capsule, the Capsule Service Module, the Propulsion module #1, the Propulsion module #2, the Ascent module, the Descent Module, the Space Station Service module, the Space Station Node and the Space Station Integrated module. The detailed description of each module has been provided in ref. [2], [3] and [4]. Moreover, SET is provided with seven generic building blocks and two simple mass elements. Generic building blocks are characterized by the ratio between the inert mass and the total mass, by the specific impulse (Isp) and by the spacecraft typology. Mass elements are building blocks characterized by the mass and spacecraft typology. Both for generic modules and mass elements the typology of spacecraft that can be chosen includes Planetary Lander, Planetary, Manned Re-entry, Communication, Weather, Physics & Astronomy, Earth Observation, Lunar Rover, Manned Habitat, Unmanned Re-entry, Launch Vehicle Stage, Upper Stage, Liquid Rocket Engine - Lox/Lh, Liquid Rocket Engine - Lox/RP-1, Payload Fairing, Centaur Fairing. The typology of spacecraft is useful for the estimation of the building block cost.

The building blocks tab allows the user to specify the main building block design parameters. Once the user has selected the building block, the user is free to change the default design parameters. Since the software is integrated with concurrent design methodologies that allow the tool to perform sensitivity analyses and optimization processes (detailed description of such methodologies has been provided in ref. [3], [4] and [5]), in the building blocks tab, the user can also consider ranges of possible variation of the design parameters and the weighting factor necessary for the mission capability index definition. The weighting factor can be defined both for design parameters and performance parameters.

Once the all the inputs concerning the mission scenario and the building blocks have been provided the user can access to the results through the results tab and analysis tab. Although the results tab is an output tab, the user can still select some mission scenario features. In particular, the user can select the number of launches and which building blocks are launched with the launcher #1 or #2. Once all the inputs have been provided the tool shows all the results. The results tab provides the user with information about the mass budget of each building block, the total mass launched in orbit, and eventually the cost of the building block, launch and global mission. Finally, the software provides the user with information about the mission capability index and mission cost-effectiveness (or value). All the mass results are provided in kilograms and all the cost information are provided in millions of dollars.

Obviously the mission capability index and the mission value are dimensionless entities.

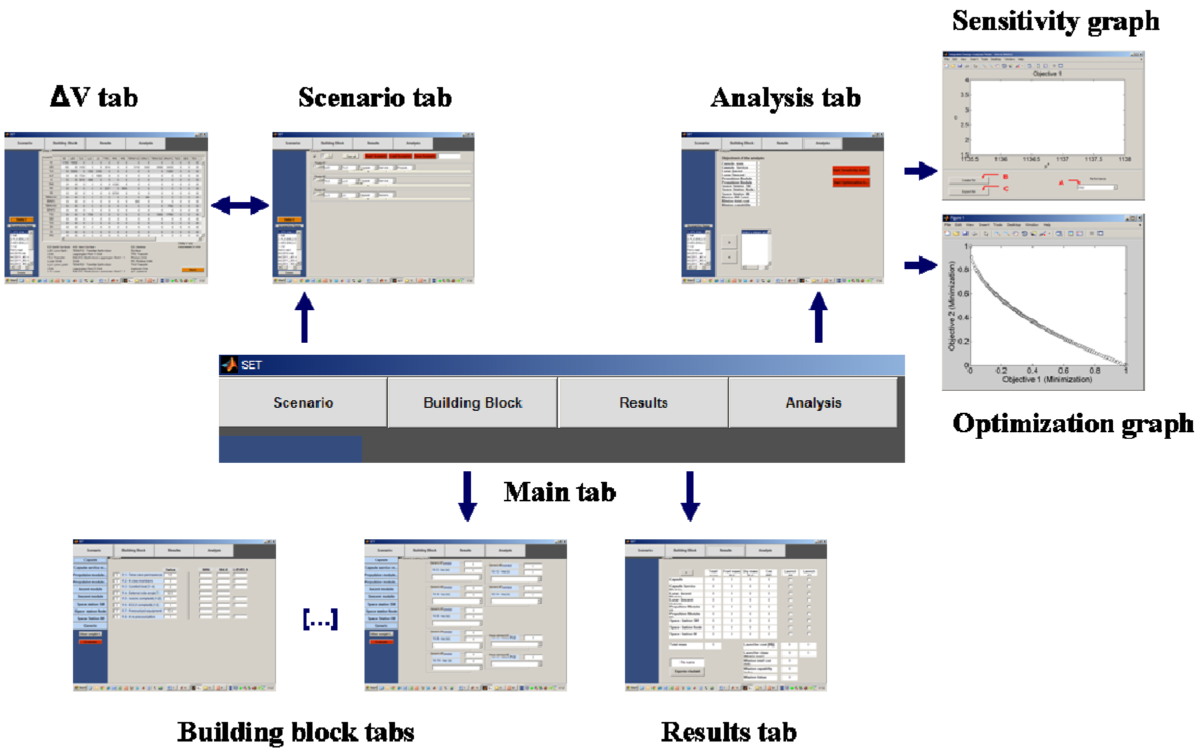


Fig. 2: SET Graphical User Interface

The method implemented to estimate the building-blocks cost is based on the Advanced Missions Cost Model (AMCM) proposed by NASA, ref, [6], [7]. This cost model is a parametric model suitable for manned space systems and useful to estimate development and production costs of the spacecraft. The AMCM is not only based on the mass, but it takes into account also the type of system (manned habitat, manned re-entry, planetary lander, etc.), the level of design inheritance of the system, the level of programmatic and technical difficulty anticipated for the new system, and the total number of units that will be produced. The cost model is based on a database of more than 260 programs, ref. [7]. The equation used to estimate the cost is the following:

$$C = \alpha Q^{\beta} M^{\Xi} \delta^{S} \varepsilon^{(1/(IOC-1900))} B^{\phi} \gamma^{D} \quad [1]$$

where the cost regression coefficient α is equal to 5.04839 x 10^{-4}, β is equal to 0.594183076, Ξ is equal to 0.653947922, δ is equal to 76.99939424, ε is equal to 1.68051x 10^{-52}, ϕ is equal to -0.355322218 and γ is equal to 1.554982942. The IOC is the year of Initial Operating Capability and for space systems. This is the year in which the spacecraft or vehicle is first launched. Q is the development and production quantities of the system expressed in equivalent unit, while M is the dry mass of the system in Pounds. The parameter S is the *Specification*. It designates the type of mission that is going to be flown (e.g., planetary, physics and astronomy, Earth observation). The parameter B is the system's block number, which represents the level of design inheritance. It is equal to 1 if the design is completely new while it is equal to 2 or more if the design is derived by an existing one. Finally, D is a qualitative assessment of the relative programmatic and technical development and production complexity of the element. It may range between -2.5 (design extremely easy) to 2.5 (design extremely complex).

The launcher cost model is based on a database of about fifty current launch vehicles, ref [8]. It estimates the launch cost on the basis of the launcher payload mass. The statistical survey shows that the higher is the launcher payload mass, the higher is the launch costs.

The cost effectiveness (or Value, V) of a space mission can be calculated by dividing the system global functionality (f) by its cost (C).

$$V = \frac{f}{C} \quad [2]$$

The system global functionality (f, see Eq. [3]) can be obtained by the sum of each system performance (P) multiplied by a weighting factor. The weighting factors (α_1, α_2, …, α_n) indicate the relative importance of the system functions/performances.

$$f = \alpha_1 P_1 + ... + \alpha_n P_n \quad [3]$$

SET has the capability to simulate and evaluate various scenarios as well as the capability to apply optimization techniques. The optimization activity can be performed through the Analysis tab. To perform the sensitivity or optimization analyses the user has to select the objectives of the analysis to be minimized (building block mass, total mass launched and mission total cost) and to be maximized (mission capability index). Also the mission architecture can be selected as parameter of the sensitivity or optimization processes. In this case, the mission architecture shall be previously implemented and saved in the database. The process will be useful to identify the best mission architecture(s) according to the objective chosen.

Once the sensitivity and/or optimization analyses have been completed, SET shows the outputs in graphical way.

The sensitivity analysis exploits the method of Morris to determine the subset of input factors having important effects on the model output, ref. [9]. The method has been introduced and presented in ref. [4]. It is based on the so-called *elementary effect*, which is a measure of the sensitivity in the form of incremental ratios, i.e. an approximation of a local derivative within a finite interval of variation of the variable:

$$d_i(\mathbf{x}) = \frac{\left[y(x_1, \ldots, x_{i-1}, x_i + \Delta, x_{i+1}, \ldots, x_k) - y(\mathbf{x}) \right]}{\Delta} \quad [4]$$

As such, the elementary effect is a local measure of sensitivity. However, in the method of Morris, the final value attributed to the sensitivity of each design variable is obtained by averaging several elementary effects and their absolute values are computed at different points of the input space, ref. [10]. In Eq. [4], Δ is the width of the step in the i^{th} dimension of the design region that has been considered to compute the incremental ratio. To compute the sensitivity measures for all factors, the design region is fractioned into a grid of dimensions $k \times P$, where k is the number of factors and P is the number of levels in which every dimension is subdivided. The influence of a factor is determined by computing several elementary effects (the number of elementary effects is indicated by R) at points randomly selected from the grid. The value of Δ is defined as a multiple of $1/(1-P)$.

The method of Morris provides two qualitative measures of sensitivity, namely the mean μ and the standard deviation σ of the elementary effects.

$$\mu = \sum_{i=1}^{R} d_i \Big/ R \quad \sigma = \sqrt{\sum_{i=1}^{R} (d_i - \mu)^2 \Big/ R} \quad [5]$$

Large values of μ indicate that a factor has a prominent overall influence on the output. Large values of σ, instead, are the result of interactions of the factors with other factors or non-linear effects on the output. An alternative measure of the parameter μ was introduced by Campolongo et al. in ref. [11] to avoid misleading results with non-monotonic models. Indeed, computing the mean of the elementary-effect distribution in a non-monotonic model may cause some effects to cancel each other out. The alternative figure μ^*, computed as the mean of the distribution of the absolute values of the elementary effects, provides a more reliable measure for ranking the factors. This measure presents the drawback of losing the sign of the effect. However this information is available by the analysis of μ, which comes at no extra computational effort.

$$\mu^* = \sum_{i=1}^{R} |d_i| \Big/ R \quad [6]$$

The computational cost of the method of Morris is linear with the number of factors, equal to $R \times (k+1)$. A thorough description of the method of Morris and its implementation is provided in the original work of the author, ref. [9]. Saltelli et al. and Campolongo et al, respectively in ref. [10] and ref. [11], describe instead the implementation of the method with an alternative measure of the mean. This method is very effective and computationally cheap in identifying factors with an overall contribution to the determination of the variability of the results obtained with the simulations.

The output of the sensitivity analysis is a chart with the indication of the values of μ^* and σ for each parameter.

The multi-objective optimization technique that has been implemented is aimed at finding a set of good compromises, i.e. trade-offs, rather than a single optimal solution, by optimizing all the objectives of a given problem simultaneously. The set of solutions is usually found using the Pareto-optimality concept. A solution is defined to be Pareto-optimal or non-dominated, if there is no feasible solution for which one can improve a single objective without causing a degradation of at least one other objective. According to the Pareto-optimality concept, a variables vector a is said to dominate another vector b in a maximization problem with N objectives, also written as $a \prec b$, if and only if the following relationship holds:

$$\forall i \in \{i,\ldots,N\}: f_i(a) \geq f_i(b) \wedge \exists j \in \{i,\ldots,N\}: f_i(a) > f_i(b) \quad [7]$$

The set of non-dominated vectors, plotted in the objective space is defined as the Pareto front. The MOEA/D (genetic algorithm) method has been utilized for computing the Pareto front of the multi-objective problem because of its convergence speed, accuracy and solution diversity characteristic. It is based on the decomposition of the multi-objective problem into a number of scalar sub-problems and on their simultaneous optimization. Consider for instance a two-objectives (f_1 and f_2) problem. The transformed scalar optimization problem can be formulated as the optimization of the functional $F = \lambda_1 f_1(x) + \lambda_2 f_2(x)$, where λ_s are coefficients subject to $\sum \lambda_i = 1$, and x is the vector of variables. This weighted-sum approach allows generating a set of N different Pareto optimal vectors by using N different weights combinations. The output of the optimization process is a graph showing the Pareto front calculated by means of the analysis.

III. EXAMPLE

III.I Reference exploration scenario

In order to give an example of SET utilization and of its potentialities, the software is applied to an hypothetical exploration scenario of the Cis-lunar space. The software will be utilized to provide a cost assessment of the reference exploration scenario. The cost assessment will provide an estimation of the cost of each single building block and the cost spreading throughout the entire Cis-lunar outpost lifetime.

The reference exploration scenario envisages the deployment of an outpost in Low Lunar Orbit (LLO). The outpost consists of a man-tended free flyer, which is periodically visited by the crew and logistic vehicles. We assume that the time between 2 crew visits is six month, while the logistic mission is performed one time per year. The assumed lifetime of the outpost is 10 years. At midlife (5 years), the extension of the outpost capabilities is foreseen. A further inflatable module is attached to the outpost and provides it with the capabilities to support a permanent crew up to 1 year. Periodic logistic missions are foreseen to support the outpost every 6 months.

Considering the hypothesized exploration scenario, the building blocks identified are listed in Table 1.

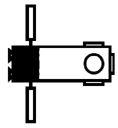
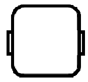
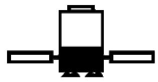
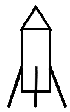
Description	Acronym	Symbol
Capsule	CAP	
Service Module	SM	
Outpost	OP	
Inflatable module	IM	
Logistic Vehicle	LV	
Transfer Stage	TS	
Launch System	LS	

Table 1: Description of the main building blocks

The capsule (CAP) is the vehicle capable of transporting and housing crew from Low Earth Orbit (LEO) to Low Lunar Orbit (LLO). The Service Module (SM) is an unpressurized system that provides the capsule wih propulsion, power and other supporting capabilities. The outpost (OP) is the orbital infrastructure that allows extended autonomous free-flying and supports a crew of 4 people up to 4 weeks in the Cis-lunar environment. At midlife (5 years) the outpost is extended by a inflatable module (IM) that increases the habitable volume and provides the outpost with the capabilities to support a permanent crew of 4 people up to 1 year. The logistic vehicle (LV) provides the orbital infrastructure with logistic support. It provides the outpost with pressurized and unpressurized cargo every 12 months. The transfer stage (TS) is a propulsion module that gives the necessary thrust to leave Low Earth Orbit (LEO) and inject the payload into the LLO. Finally the launch system (LS) allows the launch of the systems in orbit.

The detailed description of the capsule, service module and transfer stage analytical model is presented in ref. [2]. The description of the outpost and launcher model is reported in ref. [4].

The outpost is initially conceived to support the crew members up to 1 month. Nevertheless, after 5 years of operative life, a mission to extend the outpost performances in terms of crew permanence is envisaged. The outpost extension is achieved thanks to a further module able to provide the outpost with additional habitable volume and high closure ECLS (Environmental Control and Life Support) functionalities. Since inflatable systems have an higher Volume/Mass ratio than conventional space structures, the additional module consists of a primary internal rigid structure that supports the external flexible structure. The primary structure is cylindrical with two docking ports at the extremities. The first one allows the docking of the inflatable module with the outpost. The second one allows the docking of visiting vehicles or accommodation of the airlock. The flexible structure consists of a multilayer skin that maintains the internal pressure and provides the system with thermal and micrometeoroid penetration protection. The internal configuration of the module envisages two floors where astronauts find crew quarters and can perform experimental and/or research activities. The thermal control system collects heat from internal equipments and atmosphere and through a heat exchanger transfers it to the outpost. Passive thermal control is provided by MLI integrated in the flexible skin. The electrical power system essentially allows power distribution and illumination. The life support system consists of an oxygen recovery system, a fire detection system, an air circulating system and crew accommodation. The crew accommodation includes a galley system, a personal hygiene system, recreational equipments, sleep accommodation and crew health care equipments. In order to meet the requirement of protection from GCR (Galactic Cosmic Rays), equipments and consumables are located on the outer diameter of the shell. To protect from SPE (Solar Particle Events), a crew quarter area is envisaged inside the rigid structure where the shelter protection provided by structures and equipments have been considered sufficient. The external envelop of the inflatable module consists of a cylinder with a diameter Φ equal 7 m and a length l equal to 7 m. The estimated mass is 20 tons.

The logistic vehicle provides the outpost with logistic support in cis-lunar space. In particular the system provides pressurized and unpressurized cargo. The system concept derives from Automated Transfer Vehicle (ATV) but it has been adapted to the deep space environment. It consists of a service module and a cargo carrier. The service module has propulsion capabilities, power generation, storage and distribution as well as thermal control, data management, and communication capabilities. The cargo carrier provides the payload (2 tons) with a pressurized environment and docking capabilities. The propulsion system of the service module provides the spaceship with orbit transfer capability. Like ATV, the propulsion system of the logistic vehicle consists of four main engines plus 28 smaller thrusters that ensure attitude control. The propellant tanks are pressurized by helium stored in two high-pressure wound carbon fiber tanks and the adopted propellant is Monomethyl hydrazine fuel and Nitrogen tetroxide oxidizer. Four GaAs solar wings, which are made up of 4 panels each and are able to rotate, provide the spaceship with the electrical power. The solar array components are ATV derived but utilize new and more efficient solar cells. The solar wings are installed at 22 deg one from the other. The passive thermal control is provided by Multi Layer Insulation material that covers all surfaces exposed to space. The active thermal control is provided by body mounted radiators which dissipate the exceeding heat generated by avionic equipments. The thermal control system exploits HFE-7000 series as coolant to collect and transfer the heat load from avionics to radiators.

The logistic vehicle has been modeled with a generic building block model. The generic building block model takes into account the ratio (δ) of the inert mass (m_i) and the total mass, which is the sum of the inert mass, the fuel mass (m_{fuel}) and the payload mass ($m_{payload}$):

$$\delta = \frac{m_i}{m_i + m_{fuel} + m_{payload}} \qquad [8]$$

The mass of fuel is calculated using the rocket equation: the ratio of the spacecraft mass after (m_{after}) and before (m_{before}) the maneuver is proportional to the delta-V (ΔV), to the specific impulse (Isp) and to the gravity acceleration (g_0):

$$\frac{m_{after}}{m_{before}} = e^{\frac{-\Delta V}{Isp \cdot g_0}} \qquad [9]$$

Two main mission nodes are considered: Low Earth Orbit (LEO) and Low Lunar Orbit (LLO). All mission architectures begin by launching the building blocks in orbit (LEO or HEO, High Earth Orbit). Then, since the outpost shall be located in the LLO, transfer maneuvers are performed to reach the correct orbit. In Fig. 3 a schematic of the Outpost deployment mission architecture is shown. As reported in ref. [4], the best mission architecture to deploy an outpost in LLO foresees the utilization of a transfer stage that performs the TLI and LOI maneuvers prior to be discarded. Considering the obtained result, for the outpost deployment mission we refer to the same mission architecture: the OP and the TS are inserted into orbit by the launcher. Once in orbit, the systems perform the TLI and LLO orbit insertion maneuvers, in a docked configuration. The maneuvers are performed by the TS. Once the LLO orbit insertion maneuver is completed the TS is discarded.

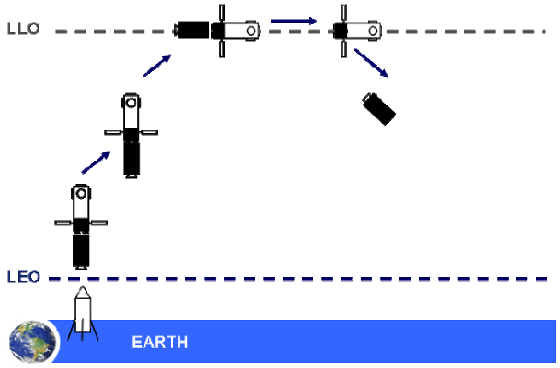


Fig. 3: Outpost deployment mission

Once the outpost has been deployed in LLO, the crew and logistic missions start. Fig. 6 shows the mission architecture considered for the crew visit mission. The described mission architecture has been obtained, after an activity of sensitivity analysis and multi-objective optimization. Three mission architectures have been considered. The first one (mission architecture “A”) envisages that the TS performs the TLO injection and LLO insertion maneuvers prior to be discarded. The SM will provide direct return on Earth. The second one (mission architecture “B”) envisages that the TS performs only the TLO injection prior to be discarded. The SM will provide LLO insertion and direct return to Earth. The third architecture (mission architecture “C”) envisages that all necessary maneuvers to reach LLO and return to Earth are performed by the SM.

The sensitivity analysis has been performed with the intention of identifying the design variables that mostly affect the mission total cost. The design variables that have been considered are the crew size, the comfort level, the specific impulse of the SM, the specific impulse of the TS and the mission architecture. The results show that the service module specific impulse, the capsule comfort level, the mission architecture and finally the capsule crew size are the design variables with the greatest influence.

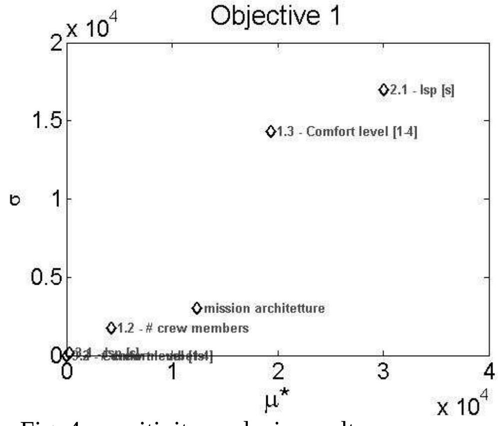


Fig. 4: sensitivity analysis result

On the basis of the sensitivity analysis results, a multi-objective optimization analysis has been performed, considering only the most affecting design variables, i.e. service module specific impulse, the capsule comfort level, the mission architecture and finally the number of crew members. The objectives of the optimization are the reduction of costs and the increase of human transportability, i.e. the ability to transport as many astronauts as possible with the maximum comfort. Fig. 5 shows that an optimal single solution that maximizes transportability and minimizes the cost does not exist. On the contrary, there are many system configurations that are characterized by different values of cost and transportability but for witch the global system value is the same. It is worth remembering that the choice of the system configuration cannot be performed only on the basis of technical issues but it must take into consideration also programmatic, technological and political issues. Within the considered design variables, only the mission architecture can be chosen on the basis of technical issues. In fact, all solutions on the Pareto front are obtained for the design variable at level 1, i.e. the mission architecture A (Fig. 6). The other design variables are chosen considering technology already developed in Europe. For example the specific impulse of the service module has been chosen equal to 315 s as that of ATV. The same specific impulse has been chosen for the LV so that commonalities and synergies can derive from the development of the two building blocks.

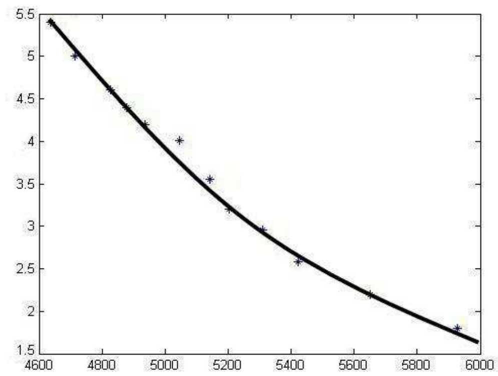


Fig. 5: Multi-objective analysis result

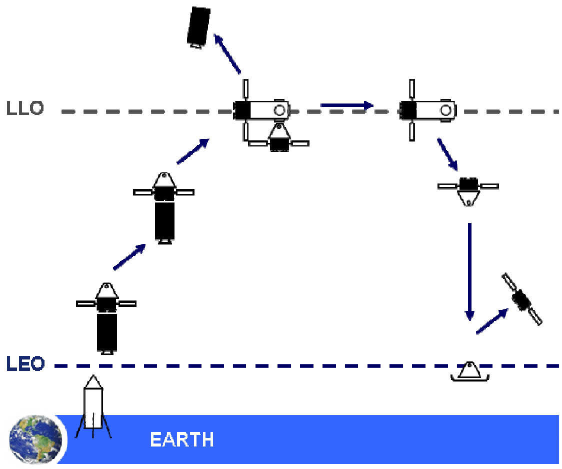


Fig. 6: Crew mission

Fig. 7 shows the mission architecture for the logistic mission. The LV is launched in HEO orbit by the launcher. It performs autonomous resonance transfer strategy to reach and dock to the outpost in LLO. In case the LV docks to the outpost before crew arrival, it remains docked in dormant mode. After crew arrival, it remains docked to the outpost for all the time necessary to cargo unloading/loading. Then the LV, previously filled with waste, undocks and performs disposal maneuvers that put LV in an orbit without long-term effects. The crew mission lasts until the scheduled conclusion.

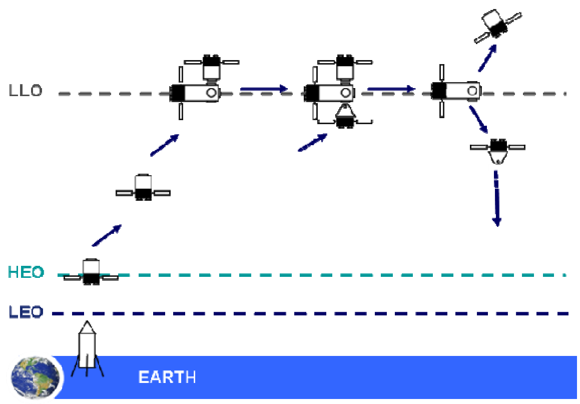


Fig. 7: Logistic mission

Fig. 8 shows the hypothesized mission architecture for the delivering of the inflatable module. The inflatable module, docked to TS, is injected in LEO orbit by the launcher. The TS performs the transfer orbit injection and arrival maneuvers. Once in proximity of the outpost, the TS performs the R&D (Rendezvous&Docking) maneuvers prior to be discarded.

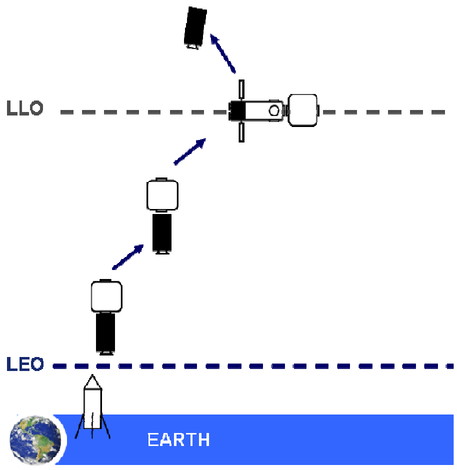


Fig. 8: Inflatable module delivering

III.II <u>Results</u>

The described architectures have been implemented within SET tool. Through SET interface, each architecture has been implemented in the scenario tab and saved, the design parameters of each building block have been set to the chosen value in the building block tabs. Table 2 shows for each building block the main performance parameters and the total mass that has been calculated thanks to SET. Since the model of the launcher does not allow estimating the total mass of such system, the launcher total mass has been omitted.

Building block	Performances	Mass [t]
Capsule	Crew members: 4 Crew permanence: 15d	10.4
Service Module	Isp: 315 s; ΔV: 1300 m/s	10.8
Outpost	Crew members: 4 Crew permanence: 28 days Comfort level: average	19.4
Inflatable module	High closure ECLS	20
Logistic Vehicle	Cargo: 2000 kg Isp: 315 s Delta-V: 690 m/s Resonance transfer strategy Transfer time: 3m÷~1y	12.1
Transfer Stage (Outpost deployment mission)	Isp: 451,5 s ΔV: 4500 m/s	82.2
Transfer Stage (Crew mission)	Isp: 451,5 s ΔV: 4500 m/s	91.5
Transfer Stage (Inflatable module delivering)	Isp: 451,5 s ΔV: 4500 m/s	83.7
Launch System (Outpost deployment mission)	Class: 100 tons	-
Launch System (Crew mission)	Class: 110 tons	-
Launch System (Logistic mission)	Class: 12 tons	-
Launch System (Inflatable module delivering)	Class: 100 tons	-

Table 2: Building blocks performance and mass

Table 3 shows the estimates of the development and production costs of each spacecraft obtained through the cost model previously presented and integrated within SET. Costs are expressed in millions of dollars (2004$). Other than the cost of a single unit Table 3 shows the total cost to produce all units necessary to ensure the outpost support for its entire lifetime. Obviously, the bigger is the number to be produced (#), the lower is the production cost of each single unit because development costs are distributed on the entire fleet. Thus development and production costs of the capsule and service module are spread on 15 units, development and production costs of the logistic vehicle are spread on 10 units, and finally development and production costs of the transfer stage are spread on 17 units. In the latter case, the assumption is that TS is sized to support the crew mission, which envisages the maximum amount of fuel, whereas in the other missions it is filled with a lower quantity of fuel.

As an assumption, 2025 has been assumed as the date in which the spacecrafts (outpost, capsule, service module, logistic vehicle and transfer stage) are first launched. The inflatable module will be launched in the 2030. The difficulty factor represents the level of programmatic and technical difficulty anticipated for the new system. The considered value is an average value for all systems, except the inflatable module. The inflatable module is the most costly building block, as technical difficulties have been assumed high because of the low TRL of inflatable systems.

The logistic vehicle is the least costly system because of the assumption that it is an ATV design evolution: the level of design inheritance has therefore been considered high with respect to the other systems.

Building block	Cost [M$]	#	Total cost
Capsule	1253	15	18801
Service Module	537	15	8055
Outpost	2394	1	2394
Inflatable module	5040	1	5040
Logistic Vehicle	532	10	5323
Transfer Stage (Outpost deployment mission)	1588	1	1588
Transfer Stage (Crew mission)	1588	15	23820
Transfer Stage (Inflatable module delivering)	1588	1	1588
Launch System (Outpost deployment mission)	478	1	478
Launch System (Crew mission)	521	15	7815
Launch System (Logistic mission)	103	10	1030
Launch System (Inflatable module delivering)	485	1	485
Total scenario cost [M$]			**76417**

Table 3: Development and production cost of the building blocks

Fig. 9 shows graphically the spreading of the costs on annual basis for the entire Cis-lunar outpost lifetime. The first year is the most expensive because the outpost shall be deployed and supported. Then the annual cost decreases because only crew and logistic mission are foreseen. The annual cost increases again when the inflatable module shall be deployed. Nevertheless, since the outpost is then able to support a crew up to 1 year, crew rotating missions are reduced, thus allowing a general decreasing of the annual cost.

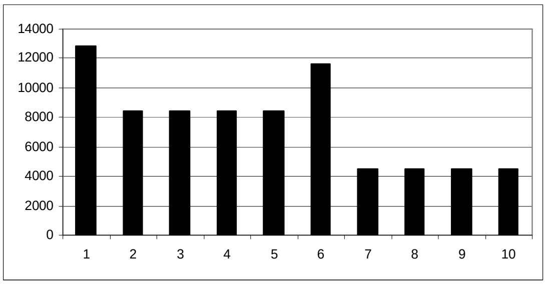


Fig. 9: Cost spreading above the entire Cis-lunar outpost lifetime

IV. CONCLUSIONS

The paper presents a simulation tool (SET) useful to support designers and decision makers in the framework of the space mission design process, allowing mission scenario and architecture definition and building block engineering with a significantly reduction of time and computational effort. The software allows the characterization, comparison and optimization of exploration scenarios and building blocks. The characterization of a specific mission architecture is given in terms of building blocks mass budget, cost index and exploration capabilities. The comparison and optimization analyses are performed on the basis of equivalent possible solutions. SET has been conceived in order to be applicable to several space exploration scenarios for Gap-analysis studies. The Gap-analysis is an assessment of gaps between the current state and the future state of a system or process and it is the starting point for the implementation of a system improvement process. In particular the Gap-analysis is a structured process that, considering space missions, allows identifying gaps between existing technologies and technologies needed to complete a space exploration mission. In this framework, the Gap-analyses are aimed at answering to questions such as: What is necessary to complete a mission? Where it is necessary? When it is necessary?

Considering the reduction of economical resources, the costs of space programs and projects have become more important. For this reason, main space agencies have proposed and continue to propose studies concerning new exploration scenarios and enabling technologies to investigate more efficient solutions. Thus, it is necessary to investigate new system design that accounts for cost, particularly for large-scale effort. SET has been conceived to help decision makers perform this investigation, reducing the time of preliminary assessment and trade off analyses between new system configurations.

After the description of the tool, in order to provide example of SET utilization and potentialities, SET has been applied to an hypothetical exploration scenario of the Cis-lunar space. The exploration scenario envisages the deployment and support of an orbital space infrastructure in LLO. Main purpose of the study was to define a mass budget and to perform a cost assessment of the entire lifetime of the outpost.

All building blocks of the exploration scenario have been introduced and described and the associated mission architectures have been presented.

The crew mission architecture has been obtained after an activity of sensitivity analysis, to identify the design variables that are the most relevant in the determination of the cost and the mission-functionalities, and after an activity of multi-objective optimization performed only with the important factors. The activity provided the more suitable mission architecture and the set of optimal design-factor levels thus allowing the design and sizing of the building blocks present in the mission scenario.

The logistic mission architecture and inflatable delivering mission architecture were aimed at increasing the delivering efficiency. The mission architectures were initially selected after a pre-design assessment performed by the authors.

The results have been obtained implementing the exploration scenario within SET. The post processing of the results has allowed to show graphically the cost spreading on annual base for the entire Cis-lunar outpost lifetime. The results show that although the cost of development, production and delivering associated to a permanent crewed space station are higher than a man-tended facility, the cost of logistic support decreases. A final consideration shall be performed on the obtained cost values. These shall be considered as indicative values that are more suitable for trade off analyses amongst similar system configuration or to understand a general trend. In fact the costs of space system are very difficult to be predicted mostly because of the limited number of space vehicle developed and the limited information available in literature.

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