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A Modeling Framework for the Concurrent Design of Complex Space Systems

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The design of complex systems has become more and more articulated during the last decade, thus forcing radical modifications on the overall methodological approach. The authors developed a design methodology, which allows the user to design a particular category of complex systems usually called System-of-systems. This paper discusses the general framework to deal with the decomposition of a system-of-systems in its elements and sub-elements, to enable a faster and more effective solution of the problem, extending the applicability of the Concurrent Engineering paradigm to design phases that go beyond the preliminary/conceptual one. A hypothetical space exploration architecture, with a rover system, a lander system and an Earth-Moon transfer mission, have been implemented and discussed, linking the elements of this particular System-of-systems with a non-hierarchical decomposition approach and a multi-disciplinary feasible formulation.

Nomenclature

P	=	transmitter output power	[W]
P_{dB}	=	transmitter output power	[dB]
L_l	=	line loss	[dB]
D_x	=	antenna diameter	[m]
θ_t	=	half-power beamwidth	[deg]
L_{px}	=	antenna pointing loss	[dB]
G_{px}	=	antenna peak gain	[dB]
G_x	=	antenna net gain	[dB]
D	=	propagation length	[m]
L_s	=	space loss	[dB]
L_a	=	atmospheric loss	[dB]
E_b/N_o	=	bit energy to incremental noise ratio	[dB]
C/N	=	carrier-noise density ratio	[dB]
e_x	=	antenna pointing offset	[deg]
S/N	=	signal to noise ratio	[dB]
EIRP	=	effective isotropic radiated power	[dB]

Acronyms

ATLO	Assembly, Test, Launch and Operations
BER	Bit Error Rate
CDF	Concurrent Design Facility
CER	Cost Estimating Relationship
COTS	Commercial Off The Shelf
DTE	Direct to Earth
JPL	Jet Propulsion Laboratory
FOM	Figure of Merit
GUI	Graphical User Interface
MDO	Multi Disciplinary Optimization
NHD	Non-Hierarchical Decomposition
SEM	System Engineering Module
SOS	System of Systems
SSCM	Small Satellite Cost Model
STK®	Satellite Tool Kit
TRL	Technology Readiness Level
TWTA	Travelling Wave Tube Amplifier
USCM	Unmanned Spacecraft Cost Model

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I. Introduction

During the last decade, space systems and exploration architectures have become more complex and more articulated. The emergent behaviors arising from the interactions between the different involved elements and systems assumed an increased importance in the design processes implemented by space companies and agencies. For this motivation during the last ten years, the processes involved with the management and design of complex systems faced a radical modification. The Systems Engineering paradigm has been adopted and applied in order to pursue time and cost reduction by a parallelization of processes, while maintaining high quality standards. For what concerns the technical side, Systems Engineering is usually addressed as Concurrent Engineering. Most of the effort in applying Concurrent Engineering has been the development and utilization of the so-called Concurrent Design Facilities, CDFs. Due to their very nature the utilization of the CDFs looses predominance as the design phases advance from preliminary to detailed. For detailed design phases, every design team usually exploits self-developed tools or commercial ones to perform the analysis "*their own way*". The risk is the loss or reduction of communication between the design teams and more important, the loss of integration of the design processes of the various systems and elements.

In a previous paper[1], a concurrent design methodology and a tool that supports the user during the preliminary design phases of a spacecraft have been discussed. There, we identified a coherent system engineering process for the design of the subsystems of a satellite in a preliminary phase (phase 0/A), which emulates the design process that takes place in the already mentioned design facilities. A coherent system engineering process means that the subsystem models have been linked together so that each design activity has all the inputs available at the moment it is executed. The system-engineering process was implemented in a software called SEM, short for System Engineering Module. SEM has a Graphical User Interface (GUI), which allows the user to interact with the mathematical routines. The user can observe what a change of one or more design variables means for the outputs, as soon as he modifies these variables. The presence of hints and tips enhances the quality of the design; the user is guided through the whole design process, and provided with extra information that allows him to better understand the outputs of the analysis, and whether or not his inputs are appropriate for the analysis he is performing. SEM was verified and validated applying the design process to one of the CDF missions[32]. Our objective was to reproduce the main outputs of the CDF report. The results obtained by SEM were within 20% of the results obtained in the CDF. That was quite a good result if we consider that the margins given in the preliminary phases, for the more detailed design of the successive phases, are usually of the same order of magnitude.

Starting from the obtained results, we implemented a new design methodology, with a modified software architecture, able to support the concurrent engineering even during the advanced design phases, for the design of space systems whose complexity goes beyond the one of satellites systems. A more flexible and modular software architecture was needed to be able to extend the analyses to a complex system of a general nature. Further, we indentified the need of additional mathematical models[1] to enable the systems analyses from different perspectives. That is the main reason why in the current architecture we included, amongst others, also a mission phasing model and a mission cost model.

The main objective of this paper is to present the modeling framework in which we apply the design method describing the type of complex problems that are the target of the research and the approach we followed to decompose and solve it.

The remaining part of the paper is organized as follows. In section II, we describe in detail the modeling framework for complex systems and the class of problems used as a target for the design method implemented with the main assumptions. In section III, the first simple case study is described and the main assumptions explained. In section IV, a detailed example of the communication system and cost models is provided, while in section V we describe the verification and validation process of the developed models. In section VI some results obtained by using the modeling framework with a concurrent design methodology are provided. Finally, in section VII, conclusions and recommendations are given.

II. The System of Systems and MDO

The concept of complexity may be interpreted in different ways depending on the scientific branch to which it is applied. From an engineering point of view, a complex problem may be defined as one in which there are multiple interactions between many different components of a system or many different disciplines, whose aggregate activity is typically more than the simple interactions of the various parts. It is usually said that the system has emergent behaviors relative to the sum of the contribution of the parts.

Engineering problems, especially when dealing with systems design, are mostly concerned with predicting the behavior of the physical phenomena typical of the system of interest. The development of (mathematical) models able to reproduce a future behavior based on inputs, boundary conditions and constraints, is the fulcrum of the engineering activities. During the design process of a complex system, very often engineers are concerned in finding a solution that minimizes/maximizes some objective(s), e.g., measures of system behavior, resource utilization, risk, etc.

A large variety of terminology sets has been developed by companies and research centers to indicate the nascent and fast-evolving design branch that deals with complex systems. Through the present paper, we will often refer to the term "*System-of-Systems*", or its acronym SOS, indicating the complex system of reference.

Actually, in the literature it is not common to find a large consensus on one of the many definitions of the SOS. Therefore, we tried to provide an axiomatic definition, general enough to be shaped upon any particular problem and prone to be applied at any level of detail.

The axiomatic definition of an SOS is the following:

- ✓ *A system has elements*
- ✓ *The elements have attributes*
- ✓ *The elements are defined by relationships*
- ✓ *Each element is a system*

From the axiomatic definition it is clear that an SOS should have at least three decomposition levels: element level, system level and System-of-Systems level. Considering a three-level SOS decomposition we obtain a sliding scale between very-high level architecture analyses and very detailed systems analyses, see Figure 1. The type of information involved when ascending the decomposition tree goes from "*hard*" to "*soft*". The need of detailed and complete mathematical models decreases as the three-level window goes from the bottom to the top of the tree, and vice versa when it goes from the top to the bottom.

We already said that the SOS is a nascent paradigm in the scientific community; therefore, not much information is available. De Laurentis *et al.* describe an SOS design approach based on intelligent agents autonomously exploring the design space to find an optimum equilibrium between the design parameters[4, 5, 6]. The approach they use seems to provide interesting results identifying some feasible space exploration architectures. However, we believe that the workload needed to adapt the existing mathematical models to that kind of approach would be prohibitive, especially in a company environment. Therefore, we decided to pursue a different path. To face the problem in a structured way, we decided to re-use the experience gained by the scientific community in the development of a similar class of problem, the Multi-Disciplinary Optimization (MDO) problem.

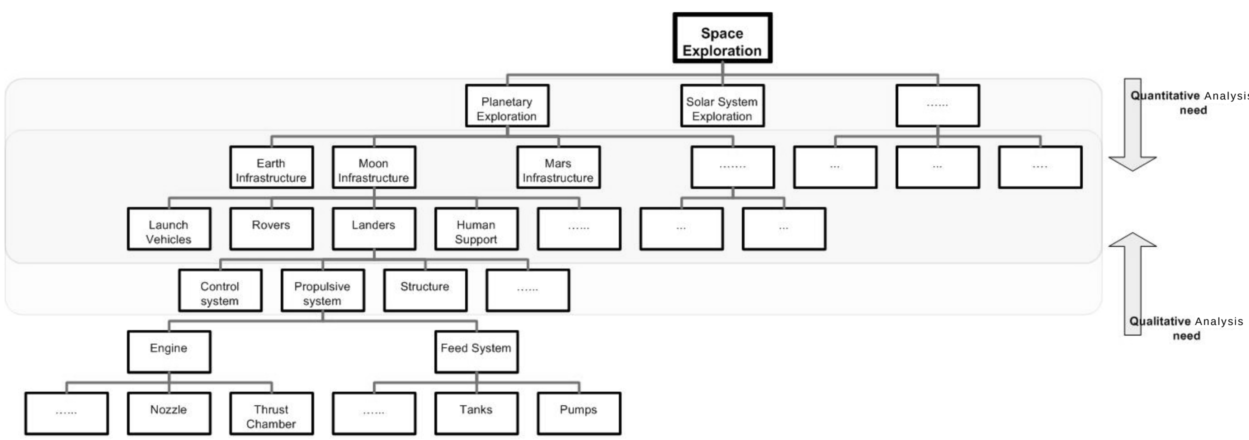

Figure 1: Space Exploration System of Systems Decomposition

In both complex and coupled systems, the design variables are shared by more than one discipline and very often, the output of one discipline is needed as an input for another discipline. Many solutions to this complex problem have been developed in the past years, all of them addressing the issues of problem decomposition (modeling) and problem formulation[7, 10, 11, 12, 15, 16], software architectures[8, 9, 13], and problem solution and optimization[14, 17, 18].

As the name suggest, MDO is a branch of system design, which mainly deals with enabling synergies between different disciplines to efficiently design a system. The System-of-Systems problem is conceptually different, by definition. The main concern is to concurrently design different systems/elements, whose design procedures may, as it happens in most of the cases, or may not involve multiple disciplines. The main differences and common aspects of the two problems can be found in Table 1.

Table 1: Comparison between the MDO and the SOS problem

	MDO problem	SOS problem
Multiple disciplines	Multiple disciplines are applied to the design of a single element/system	Every system of the SOS may or may not require more than one single discipline to be designed
Multiple elements	Usually not more than one	It is the core of the SOS problem. Several systems have to be designed concurrently
Mathematical Models	Level of detail depends on the objectives of the analysis	
Continuous Variables	Most of the MDO problems involve continuous variables. Classical Sensitivity analysis methods cannot be applied with discontinuities	In use mostly for lower-level elements analyses, where detailed mathematical models are available
Discrete Variables	Usually very few, dealt with ad-hoc optimization algorithms	Used for high-level elements (System or SOS level). Especially when different "*architectures*" have to be judged.
Optimization	Usually numerical techniques are applied, gradient-based or stochastic. The objective is to obtain the best possible solution: "*push-and-go*" techniques.	"*Push-and-go*" not applicable. The objective is to enable trade-offs: the human is in-the-loop.

We decomposed the SOS of the case study, described in the next section, with a Non-Hierarchical Decomposition approach, NHD. This means that every element of the SOS is able to exchange data with all the other elements. For what concerns the formulation, we decided to strive for a Multi-Disciplinary Feasible (MDF) approach. The MDF problem formulation foresees that for each combination of design variables generated by the optimizer a feasible solution must be obtained for the design of all the elements. Feasibility is obtained by iterating the element analyses until design-parameter convergence is reached. The feasible variable set, which is formed by the design variables only, is then used by the optimizer to calculate the values of the objectives and constraints.

The software architecture has been conceived to be single level. This means that there is a single optimizer on top of the system breakdown tree. In Figure 2, we show a schematic with the SOS decomposition and formulation, and software architecture approach.

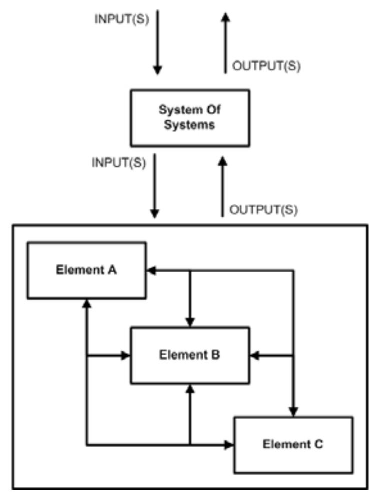

Figure 2: Single Level SOS architecture

III. Case Study: Space-Exploration Architecture

The SOS considered as case study is a space-exploration architecture. It is a hypothetical robotic exploration of the Moon composed of an Earth communication infrastructure, a launcher system, a robotic lunar rover, a lander and a module for the simulation of the Earth-Moon transfer trajectory. The mission considered for this particular application is simple, but realistic, and, more important, it is heterogeneous enough to test the concept of System of Systems. The developed analytical models are linked together as shown in Figure 3. The literature is not so generous with information regarding models of that type of systems. Only limited data on rovers and landers have been found[21, 22], but most of the information, equations, and empirical relationships for the design of the elements have been derived from other more general sources[23 - 30].

In Figure 3, the three levels of decomposition are outlined: the elements level, systems level and system-of-system level. The general input-output structure allows the user to select the levels of the design parameters, to select elements characteristics from databases and to design the mission phases, with operative modes and duty cycles, for all the systems of the scenario. The most important outputs are represented by the performances of the architecture and its systems and elements, and an estimation of the costs. The presence of a "*Mission*" block, that is not properly a system or an element into the system of systems architecture, shows its multifaceted nature; not only systems but also disciplines can be treated as elements in the SOS problem. The N^2 chart presented in Figure 3, is the result of a process of feedback reduction between subsystems and elements. As the reader can see it was not possible to eliminate all of them. This result was already known in advance: these kinds of problems are strongly coupled. It means that there are loops in the design process that cannot be eliminated by simply changing the order in which the elements are designed, or disciplines executed.

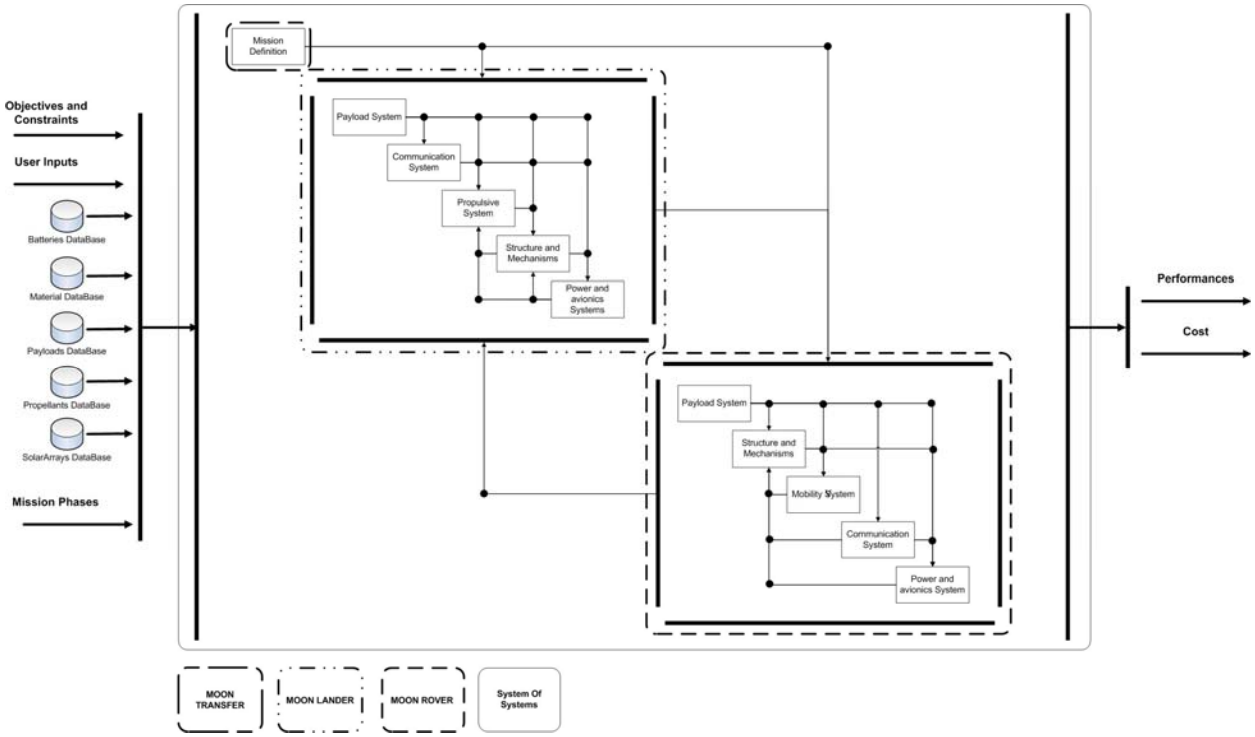

Figure 3: Robotic moon exploration architecture

To have a clearer impression of the implemented modeling architecture, in Figure 4 we show the details of the input/output structure for three of the blocks shown in Figure 3, namely the Structure and Mechanisms, Communication System and Power and Avionics System of the Rover.

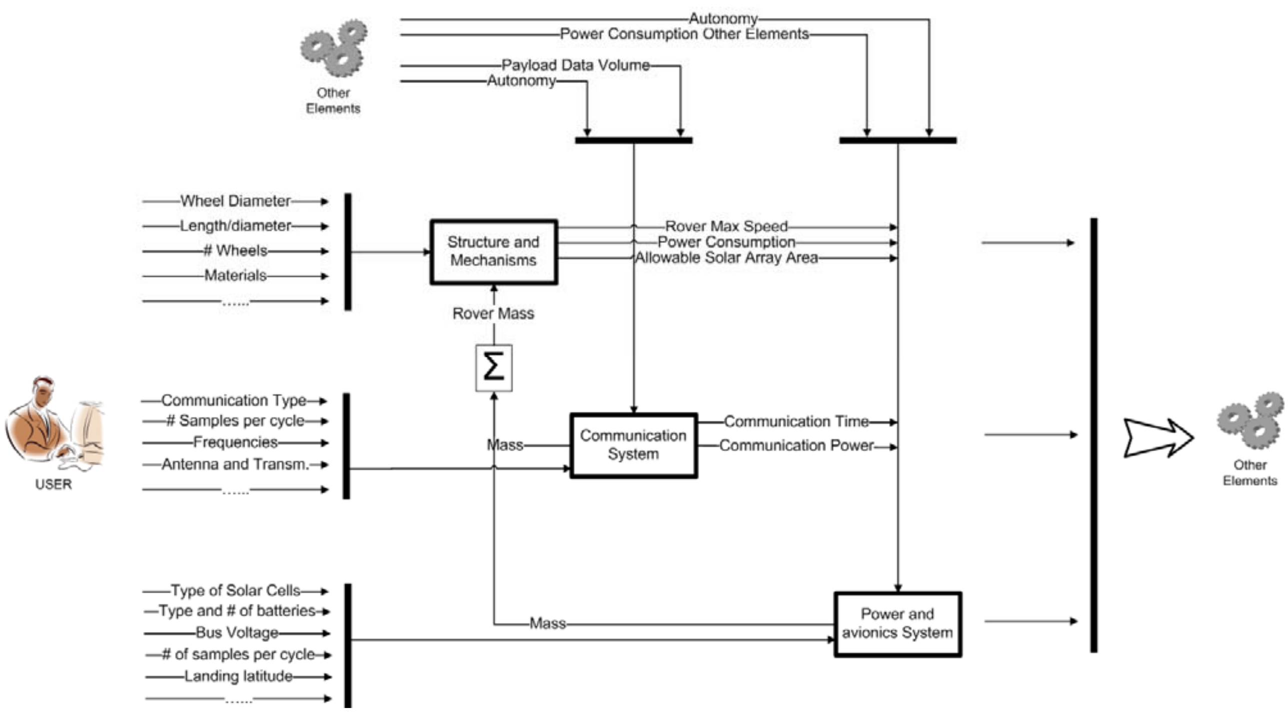

Figure 4: Detail of the robotic moon exploration architecture; structure and mechanisms, communication and power subsystem of the rover

For practical reasons not all the design variables of the Moon exploration architecture are presented. However, the most relevant design variables that affect the design of mission are shown in Table 2, Table 3, and Table 4, and the rationale behind the various possible architectures and the major expected outcomes of the analyses are described in detail.

Table 2: Earth-Moon transfer mission, model summary

Variables	Rationale
Type of Mission (discrete variables)	
LEO	The Launcher injects the system assembly into LEO orbit. The assembly provides the necessary ΔV for the Moon transfer, the mid-course maneuvers, the LLO circularization, descent and landing and attitude control.
GTO	The Launcher injects the system assembly into a GTO. The assembly provides the remaining part of the necessary ΔV for the Moon transfer, and the ΔV for the mid-course maneuvers, the LLO circularization, descent and landing and attitude control.
LTO	The Launcher injects the system assembly directly into a LTO. The assembly provides the ΔV for the mid-course maneuvers, the LLO circularization, descent and landing and attitude control.
Autonomy Level	Can be A1 or A3. It is related to the distance that the Rover is allowed to travel on the Moon's surface autonomously, before waiting for commands from an Earth control station (which requires time proportional to the data volume and inversely proportional to the data rate), and to the cost of the software needed for the two different levels of autonomy. In the first case the Rover is more autonomous and the software costs more.
# of samples per driving cycle	This value indicates the number of pictures/videos the rover has to take and send/store for each driving cycle; therefore before transmitting the data back to Earth/Lander when the maximum autonomy distance, set by the autonomy level, is reached.
Landing Latitude	It affects the way the solar rays impinge on the arrays' surfaces of the rover and the lander
Communication Architecture	
CROSSLINK	The Rover communicates with the Lander, which in turn communicates with Earth, both for telemetry and commands
DTE	The Rover communicates Directly To Earth and so does the Lander, both for telemetry and commands
Cost	
Systems TRL Design approach	Every system can have a Technology Readiness Level (TRL) that goes from 1 to 9. It affects its development cost. Two design approaches have been modeled, a typical and a low-cost one. The low-cost one foresees a much lower non-recurring fraction of the total cost if compared to the traditional approach.
Launcher	The launcher is selected from a database of available launchers. The selection is performed by an automate search of the cheapest launcher that allows the transportation of the assembly (its mass is the discriminator), according to type of mission selected.

Table 3: Rover system, model summary

Variables	Rationale
Rover Structure Wheel Diameter Proportionality ratios	The structure of the rover is modeled as a scaled version of the classical rocker-boogie[22] configuration. The main scaling parameter is the Wheel diameter but also Length-to-Diameter ratio, Suspensions height-to-Diameter ratio, obstacle-to-Diameter ratio, etc.
Payload Number and type of payload(s)	The payload(s) can be selected from a data base. The user can select all the necessary instruments with implications on payload mass, power consumption, and data volume for sample (if applicable).
Power Type of solar arrays and batteries Rover area-to-solar-Array ratio	The main output is the power available for the subsystems, the power consumption and the mass of the system, including harness.
Communication Command and Telemetry data rates Transmitter output power Antenna dimensions Transmitter type Losses Frequencies and modulations	The main output is the mass and the power required by the system, and the link budget, in uplink and downlink with Earth/Lander
Other Systems Variables	Mass and power of the thermal control system and mass and power of the computers, have been considered as a percentage of the mass and power of the whole system.

Table 4: Lander system, model summary

Variables	Rationale
Payload	
Number and type of payload(s)	The payload(s) can be selected from a data base. The user can select all the necessary instruments with implications on payload mass, power consumption, and data volume for sample (if applicable).
Power	
Type of solar arrays and batteries Lander area-to-solar Array ratio	The main output is the power available for the subsystems, the power consumption and the mass of the system, including harness.
Communication Command and Telemetry data rates Transmitter output power Antenna dimensions Transmitter type Losses Frequencies and modulations	The main output is the mass and the power required by the system, and the link budget, in uplink and downlink with Earth/Rover
Propulsion Type of propellant for main engines and attitude control thrusters # of engines, propellant tanks, pressurant tanks	The main output is the mass and the power required by the system.
Other Systems Variables	Mass and power of the thermal control system, mass of the structure and mechanisms, and mass and power of the computers, have been considered as a percentage of the mass and power of the whole system.

The software architecture has been implemented using the object-oriented programming language C++. The data exchange between elements is performed using XML data structures; the same structure is used to design the databases and the “mission phasing” module. The models of all the elements have been designed using the same structure of input, design process and output. The software architecture is extremely flexible, and built in a modular way. This means that the mathematical models of every element can be substituted / extended, providing the proper interfaces, without affecting the overall architecture. This also means that more elements can be added without major modifications to the code developed so far.

To understand the type of models implemented and the type of analyses that the user is able to perform with the proposed methodology, in the next section we describe the mathematical model of one of the elements of Figure 3: the communication system and the relative cost model.

IV. The Communication System and Cost Models

In this section we provide detailed information on the mathematical models that have been implemented to estimate the link budgets between the communication systems of the elements of the scenario, mass and power consumption, and the cost. The implemented equations can be used to estimate both the uplink and downlink budget, for all the elements of the scenario (i.e., rover, lander, Earth facility). The communication architectures that could in principle be established between different systems of a space exploration scenario are several and with different complexity level. However, at this stage of the development the user can only establish two communication architectures.

The first one is called DTE (Direct-to-Earth). In this case, there is a direct link of the rover with an Earth facility. All data are communicated directly to Earth. When the rover communication architecture is set to DTE, the one of the lander is automatically set to DTE as well, and the rover and lander do not communicate with each other. The second one is called CROSSLINK. In this case, the rover establishes a link with the lander, which in turn communicates with Earth.

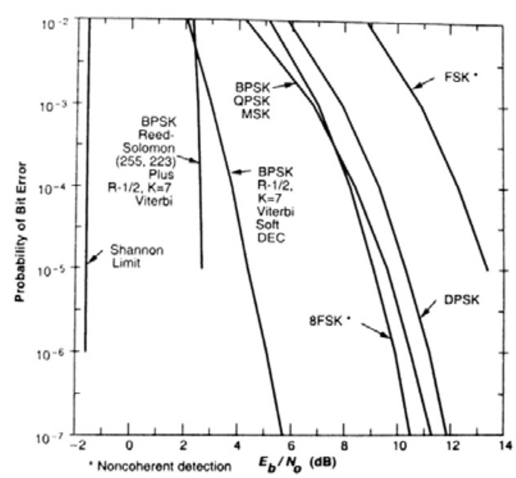

Figure 5: Bit Error Probability as function of E_b/N_o, ref. 23.

A. The uplink and downlink design process

The Bit Error Rate (BER) can be considered as a measure of the communication quality in case of digital communications. It is a measure of the likelihood that a received bit is not correct. This performance parameter can be derived from the carrier-to-noise density ratio, C/N, or from the bit energy to incremental noise ratio, E_b/N_0. The relationship between the BER and E_b/N_0 depends on the type of modulation chosen for the communication link, see Figure 5. With a certain required BER, and once the frequency-modulation technique is chosen, the required value for the E_b/N_0 can be obtained. This parameter is the most common Figure of Merit for the link budget, in case of a digital communication link.

The implemented design process is executed starting from the end. From an estimated output power of the transmitter, provided as first guess by the user, thanks to the environmental losses and antenna performances (transmitting and receiving antenna), the E_b/N_0 and the margin relative to the required E_b/N_0 can be computed. Indeed, the E_b/N_0 is considered the most relevant Figure Of Merit regarding the communication subsystem. The following relationships are sequentially computed in the process. Every subsequent relationship needs the output of the previous ones, and the inputs from the user (where indicated) to be executed.

The first input provided by the user is the transmitter power, $P[W]$. From the value in W, we obtain the value in dB as follows:

$$P_{dB} = 10\log_{10}(P) \tag{1}$$

The transmitter-to-antenna power loss (line loss L_l $[dB]$), is another input parameter from the user; it is the loss that occurs from the transmitter to the antenna.

The transmitting antenna diameter D_t $[m]$, or the half power beamwidth θ_t $[\deg]$, must be given as input by the user as well; those two parameters can be derived from each other thanks to the following empirical relationship[23]:

$$D_t = \frac{21}{f_{GHz}\theta_t} \tag{2}$$

where f_{GHz} is the frequency of the link in GHz. The antenna transmits half of the power within a certain angle, through the main lobe. This angle is called the half-power beamwidth; it is a direct indication of the gain that the antenna can provide. The larger the beamwidth, the lower the gain.

The receiver antenna may not be located at the center of the transmitter antenna's main lobe so that some gain losses occur. The antenna pointing offset e_t $[\deg]$ is a parameter that indicates the offset of the antenna's mechanical mounting (or directional control) with respect to the desired direction. In the developed model the antenna pointing offset is estimated by the user at the beginning of the process. Based on the antenna pointing offset the transmit antenna pointing loss can be computed[23], L_{pt} $[dB]$:

$$L_{pt} = -12\left(e_t/\theta_t\right)^2 \tag{3}$$

The peak transmit antenna gain, $G_{pt}[dB]$, is the ratio of the effective aperture area of the antenna and an hypothetical antenna considered to be isotropic $\left(\lambda^2/4\pi\right)$, ref. 23:

$$G_{pt} = 10\log_{10}\left[\left(\frac{\pi D_t^2\eta}{4}\right)\left(\frac{4\pi}{\lambda^2}\right)\right] = 10\log_{10}\left(\frac{\pi^2 D_t^2\eta}{\lambda^2}\right) \tag{4}$$

The wavelength $\lambda[m]$ is calculated from the frequency and the speed of light, c= 299,792,458 m/s:

$$\lambda = \frac{c}{f} \tag{5}$$

The net transmit antenna gain, $G_t\ [dB]$, is the peak transmit antenna gain minus the pointing losses[23]:

$$G_t = G_{pt} - L_{pt} \tag{6}$$

The Effective Isotropic Radiated Power, EIRP$[dB]$, of the transmitting antenna can now be computed as follows[23]:

$$EIRP = P_{dB} - L_l + G_t \tag{7}$$

The EIRP usually represents the Figure of Merit for transmission systems (e.g., the rover antenna in case of downlink, the ground-station antenna in case of uplink, for a DTE architecture).

From the propagation path length, $D\ [m]$, we can calculate the space loss[23], L_s:

$$L_s = 10\log_{10}\left(\frac{\lambda}{4\pi D}\right)^2 \tag{8}$$

The space loss is the free-space attenuation between the antennas. This represents the main source of noise, but there are more noise sources that may be taken into account: atmosphere attenuation, polarization loss, attenuation by rain. Those loss sources depend on the frequency used for the communication and usually represent only a small percentage of the total loss, if compared to the space loss.

The atmospheric loss, L_a, can be divided into two main categories: one that takes place in the ionosphere and another one in the troposphere. The ionosphere effects are pre-dominant for low frequencies but negligible for frequencies of the order of MHz and onwards. The tropospheric effects can be considered predominant, and among them, the attenuation is the one that can cause most of the problems in the communication link. In Figure 6, we observe the attenuation due to the atmosphere at zenith, as a function of the frequency. The model has been derived from ref. 23.

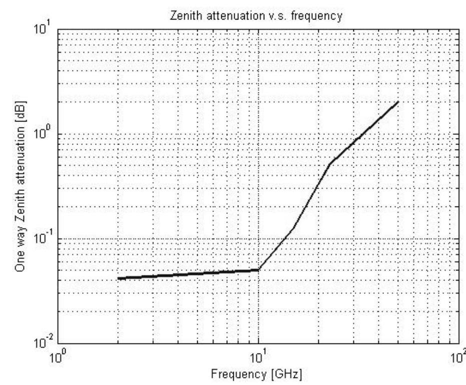

Figure 6: One way Zenith Attenuation v.s. frequency, adapted from ref. 23.

The attenuation from the rain is a function of the frequency as well. The attenuation prediction is usually based on semi-empirical statistical models that take the rainfall statistics into account and transform those into rain attenuation. Those models developed by the International Telecommunication Unit, ITU, provide the rain attenuation as a function of the frequency, probability of rain occurrence, ground station location and satellite elevation angle.

In Figure 7, we observe the rain attenuation predicted with the Crane model, for the northern part of the U.S. This model shows that the rain attenuation is significant for frequencies above 8 GHz; in the worst case, the rain attenuation is around 40 dB. This value is around 15 % of the usual space loss.

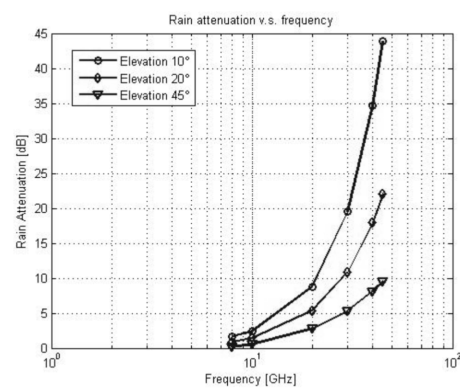

Figure 7: Rain attenuation v.s. frequency, function of the elevation angle. Crane model for a rain climate typical for the northern U.S, adapted from ref. 23.

The loss for polarization mismatch for large ground antennas may be estimated as 0.3 – 0.6 dB, ref. 28.

For the receiver system, we need the antenna diameter, the half-power beamwidth and the pointing offset as well. The antenna diameter and the half power beamwidth are linked to each other thanks to the same empirical equation mentioned before, equation (2). The antenna peak gain, $G_{pr}\ [dB]$, pointing loss, $L_{pr}\ [dB]$, and net gain, $G_r\ [dB]$, of the receiver antenna, can be calculated with the same equations as used before: namely equations (4), (5) and (7), respectively.

In addition, for the receiver system, we must consider some noise sources; the antenna noise and the receiver noise give rise to the so-called system noise temperature. The higher the temperature, the higher the noise the system will experience. In literature, we may find some values for the system-noise temperature, as a function of the frequency range, see also Table 5.

Table 5: Typical system-noise temperature in satellite communication links, in clean weather[23]

	Downlink			Uplink	
Frequency range [GHz]	0.2	2-12	20	0.2-20	40
System Noise Temperature [K]	221	135	424	614	763

The temperature increase is proportional to the rain attenuation, $L_{rain}\left[dB\right]$, and the temperature of the rain droplets, estimated as 290 K . The system temperature increase is then[23]:

$$T_{rain} = \left(1 - 10^{\left(\frac{L_{rain}}{10}\right)}\right) T_{droplets} \tag{9}$$

Given the system-noise temperature and the temperature increase due to the rain, we are able to calculate the sensitivity of the receiving station[23], $G_r / T_s \left[dB\right]$:

$$G_r / T_s = G_r - 10 \log_{10}\left(T_s + T_{rain}\right) \tag{10}$$

To calculate the performance of the entire communication link we will now calculate the actual E_b / N_0 value and we compare it with the required one. Expressing everything in dB, we calculate the E_b / N_0 as follows[23]:

$$\boxed{E_b / N_0 = EIRP - L_{pr} - L_{pt} - L_s - L_a + G_r + 10\log_{10}\left(k\right) - 10\log_{10}\left(T_s + T_{rain}\right) - 10\log_{10}\left(R\right)} \tag{11}$$

In equation (11), k is Boltzmann's constant, $k = 5.67051\ W/m^2 K^4$, and R is the data rate given as input at the beginning of the design process.

From this value of E_b / N_0 , we may calculate the carrier-to-noise density ratio[23], C/N_0 :

$$C/N_0 = E_b / N_0 + 10\log_{10}\left(R\right) \tag{12}$$

This value may be used to estimate the S/N ratio for analog modulations.

Subtracting between 1 and 2 dB for implementation loss from the E_b / N_0 , we can calculate the margin between the required E_b / N_0 and the calculated one. If this margin is below the rain attenuation value, with some safety margins (3 to 4 dB), then the design process will be iterated again, modifying some of the design parameters values provided at the beginning of the process itself. The design-parameter values can be modified according to two different strategies: automatically when an optimization routine is enabled, following the principles of the optimization being performed, or manually when the user is interested in a single design-point evaluation.

At the end of the design process, the user has an estimate of the link budget between the rover and the ground station (the same will be between lander and ground station and between rover and lander, with the proper boundary conditions). Antenna diameter and transmitter power output are the parameters that influence the mass and the power of the complete system the most, and the cost as a consequence.

B. Mass and power estimation

To estimate the mass of the antenna, and mass and power of the transmitter(s), for a given power output and given frequency range and bandwidth, we work with data collected by the ESA equipment database[31]. In literature, we did not find any numerical relationships linking the antenna geometrical characteristics to its weight, or numerical relationships linking the frequency and the power output to the mass and the power of the transmitter.

Only Wertz *et al* provide some other data relative to classes of antennas[23]. From those data, we could derive a relationship that links the aperture area of the antenna to its mass. We can estimate an average density of 12 – 13 kg/m^2 . Therefore, we obtain an estimated value for the mass of the antenna multiplying the aperture area by the average density.

For what concerns the transmitter mass and power estimation, we tried to pursue a similar approach. In the official databases[31], not so much information on transmitters is provided. In Figure 8, we show a graph that presents the trends of transponder mass and power as a function of the power output. A distinction has to be made on the type of transmitters. TWTA is the acronym of Traveling Wave Tube Amplifier; it is the classical amplifier tube, usually used for analog communications. Solid-state amplifiers have been developed in the recent years. Those are amplifiers based on printed circuits, capable of giving the same performance in terms of power output, that the TWTA provides with much less mass, much less volume and higher power consumption.

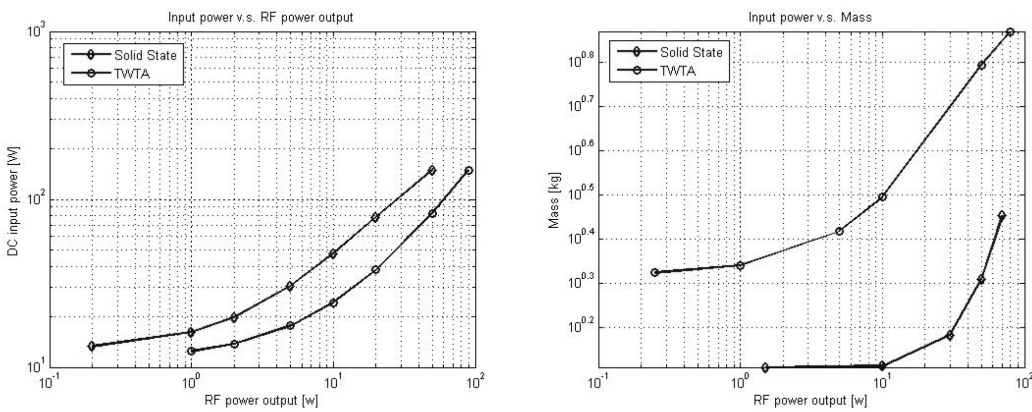

Figure 8: Satellite transmitter power and mass v.s. RF power output, adapted from ref. 23

C. Cost Model

Determining the cost of a space system, to be intended as the cost of the entire program needed to build all the subsystems and the elements, and to support the mission, is becoming more and more important. In general, the cost of a system depends on its size, design complexity, involved technology (new or proven), operative life, program schedule, risk tolerance, management and size of the organizations involved[24].

The cost of a space program is not something usually advertised by companies or organizations. It is almost impossible to find publicly available information about the cost of systems, and it is even worse in the case of sub-systems.

Table 6: Rover Cost Breakdown, adapted from ref. 21

Subsystems and activities	Cost [%]
GNC	10.21
Power	19.46
Structures	26.26
Thermal	6.77
Telecom	11.99
TT&C-C&DH	9.48
S/W	15.82
Test-Beds	11.17
Cabling	-
Payload	46.59
ATLO	10.87

The only source of data regarding rovers' cost is given by Wilson *et al*., who provide a cost breakdown for fifteen rover designs developed at JPL[21]. In Table 6, the cost breakdown of a rover is shown. The percentage of the cost is normalized over the cost without Payload, ATLO and Test-Beds, therefore on the Rover Bus only. The cost percentage of payload, Test-beds and ATLO is computed as a percentage of the Rover Bus cost. Using 15 data points to estimate the cost of a rover is probably not the best approach considering the reliability of the results. However, in Wertz *et al*. almost the same number of data to develop the Cost Estimating Relationships (CERs) they represent has been used[24].

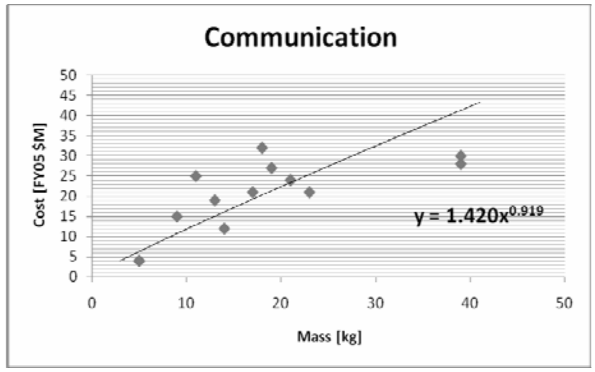

Figure 9: Communication System, Cost Estimating Relationship

To fit the data, a Linear Least-Squares method has been used, with linear combinations of linear and non-linear functions of the performance parameter, which in this case is represented by the mass of the system. Each function has been selected in such a way to maximize the so-called *coefficient of determination* R^2, used as a *goodness-of-fit* indicator. In Figure 9, we show the CER interpolated for the Communication System cost. Since we were not able to find any information about the cost of the lander, we decided to adopt a bottom-up approach. The idea is to use the Unmanned Spacecraft Cost Model[23] (USCM), adapting the cost of every single subsystem as a function of the relative performance parameter linked to the cost via the CERs. Therefore, the Cost Estimating Relationships presented in ref. 23 have been used to complete the cost model developed using the data from ref 21. For what concerns the rover cost model, the equations have been weighted as a function of the standard error computed with respect the original data. Concerning the lander, the used equations are those of the USCM. In Table 7, we show the CERs relative to the Communication System. The equations have been adapted to the Fiscal Year 2010, and the cost is expressed in million dollars. The parameter *X* represents the mass of the Communication System. The Technology Readiness Level (TRL) of a certain element or group of elements is considered in the Heritage Factor (HF), which affects the non-recurring costs only.

Table 7: Communication System Cost Estimating Relationships.
*From Figure 9; cost unit FY10 M$. † From ref. 23, cost unit FY10 M$. HF is the Heritage Factor.

Cost Estimating Relationships [FY10 M$]	Standard Error [%]
$y = \frac{1.25}{1.099} HF \cdot 1.420 \left(X \right)^{0.919} {}^{*}$	27.5
$y = \frac{1.25}{1000} \left(HF \cdot 545 X^{0.761} + 635 X^{0.568} \right)^{\dagger}$	41

The cost of a space system is largely dependent on the way the program is managed rather than the system itself. In ref. 24, we read that "*how we do something is more important that what we do*", if referred to the cost of what we do. As already said the aspects that strongly affect the cost, that are not related to the procurement of hardware or to the construction itself, may be identified in launch, ground stations, operations, infrastructures, support personnel, amount of documentation, meetings, analyses, tests and reports, mentality and decision making process within the design team. Based on this information, we are able to identify a *traditional* approach and a *low-cost* approach to the design of a space system. The two approaches differ, because in a *low-cost* approach the paradigm is completely changed, and there is a small-team mentality. The requirements are traded rather than accepted as given, and the schedule is compressed: there is less time to spend money. The design margins are wider, and the non-space qualified as well as COTS components are preferred to the standard ones or to components with a low Technology Readiness Level. Wertz *et al*. develop a Small Satellite Cost Model, SSMC 8th version[24]. We decided to implement this model as well, for the user to capture the effect of the design process on the cost.

D. Subsystem Analysis

The user is allowed to set many of the design parameters mentioned in the previous subsections, as shown in Figure 4, Table 3 and Table 4. Besides the type of transmission band and the type of modulation, the most relevant parameters that the user can set are the transmitters' output power, diameter and efficiencies of the antennas (transmitting and receiving), uplink and downlink data rates, and the system TRL. In Figure 10, we show the trends that the model captures and the typical trades that the user is able to perform using it. We can clearly see that the link budget (between the Lander and the Earth facility) depends on the antenna diameter and the transmitter output power according to a logarithmic law. This means that the gain in performance of the communication subsystem decreases as the antenna diameter increases and the transmitter output power increases. The cost increases as the antenna diameter increases. We see that the power output also affects the cost. This is due to the fact that as the output power required increases, the transmitter mass increases as well, according to the model shown in Figure 8.

Typical trades are usually performed with cost limitations, minimum required link budget, minimum and maximum antenna dimensions, due to technological limitations, and maximum output power. The objective of the designers is usually to minimize the cost while meeting the performance requirements.

In this particular example the type of trades that the user is able to perform, at subsystem level, is shown. The interesting aspect of the modeling framework is that trade-offs, or, more in general, the study of the effect of a set of variables on a set of performances, can be performed even at a higher level, and also among variables belonging to different subsystems, thus for cases in which there are no clear mathematical relationships available, but only implicit coupling effects. A clear impression of these types of results is provided in the following section, together with few hints on the design method used to obtain the results described exploiting the modeling framework.

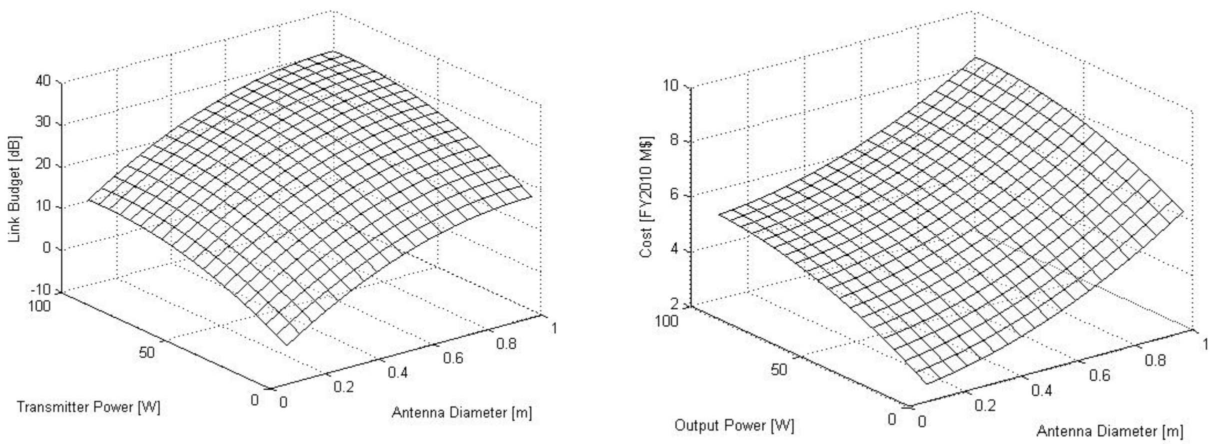

Figure 10: Link Budget (left) and Cost (right) as a function of Transmitter Antenna Diameter and Transmitter Output Power

Data rate = 256Kbps; HF = 0.2; Receiver Antenna Diameter = 4m. TWTA transmitter type

V. Verification and Validation

With the verification and validation process, we intend to demonstrate that the mathematical models developed for the communication system provide reliable results.

The verification has been performed checking that the implemented equations provide correct outputs given certain known inputs. The book of Wertz *et al.*, ref. 23, has represented the main source of test problems and exercises for the verification of the equations. In the discussion about the design of a space mission, through the whole book, he designs his own space mission in detail: *Firesat.* Firesat has been used as the main benchmark for verifying the implemented equations.

The validation procedure, instead, has been carried out by evaluating of the performance of the model compared to the performance of Satellite Tool Kit, STK®, a commercial software developed by AGI which allows the user to perform link-budget evaluations amongst other.

The communication architecture reproduced in STK is composed by the following main elements:

- Earth Facility for transmitting and receiving
- Lander communication infrastructure
- Rover communication infrastructure

In Figure 12, the STK settings for the Rover-Lander communication link are shown. STK computes the link budgets of the communication channels as a function of time. Depending on the position between the Earth and the Moon and on the line-of-sight between the facility on Earth and the Lander on the Moon, the link budget evolves with time. A typical output that STK provides is shown in Figure 11. The *x* axis represents a time scale, while on the *y* axis the link budget in dB is plotted. As we can see, there are periods in which the antennas are in view and periods of time in which there is no line of sight. The parameter $^{Eb}/_{No}$ increases as the facility on Earth, or the antenna on the Moon, rises above the horizon; it is more or less constant for the period of time in which the two antennas are on a line of sight, and then it decreases again as the two antennas approaches the horizon relative to each other. The methodology we developed is not able to provide the users with such detailed data on the link budget as a function of time, since the orbital geometry between the Earth and the Moon, is not modeled. However, we show that, considering only the central part of each access period and taking an average value of the parameter $^{Eb}/_{No}$, the methodology is able to provide very precise data. In this section we only show the results of the validation of the communication link established between the Lander on the Moon and a facility on Earth. In particular, the uplink is established between a transmitter on Earth and a receiver on the Moon Lander, while the downlink is established between a transmitter on the Moon Lander and a receiver on Earth. In Figure 13 and Figure 14, we show the comparison between the performances of our tool and STK® in the estimation of the downlink and uplink budget. The FOM is the link budget, $^{Eb}/_{No}$, plus the receiver implementation losses. In those figures we show the trends of the Link Budget as a function of antenna diameter, transmitter power output and data rate, with the results obtained with STK at some design points. The figures clearly show that the implemented model is perfectly capable of identifying the trends of the link budgets, with different settings of the design variables that influence it. Few decibels of discrepancy can be found, especially when the down-link is considered. Those are to be attributed to the assumptions made when developing the model, especially on the Earth atmospheric attenuation of the signal and on the mission geometry figures of merit.

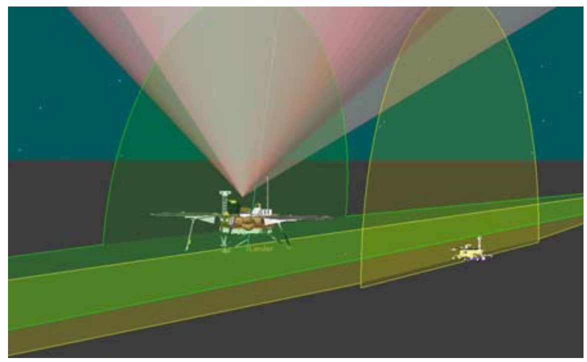

Figure 12: Communication Infrastructure on the Moon, STK®. Yellow shadow: Rover-Lander field of view. Green shadow: Lander – Rover field of view. Red shadow: Lander – Earth Facility field of view

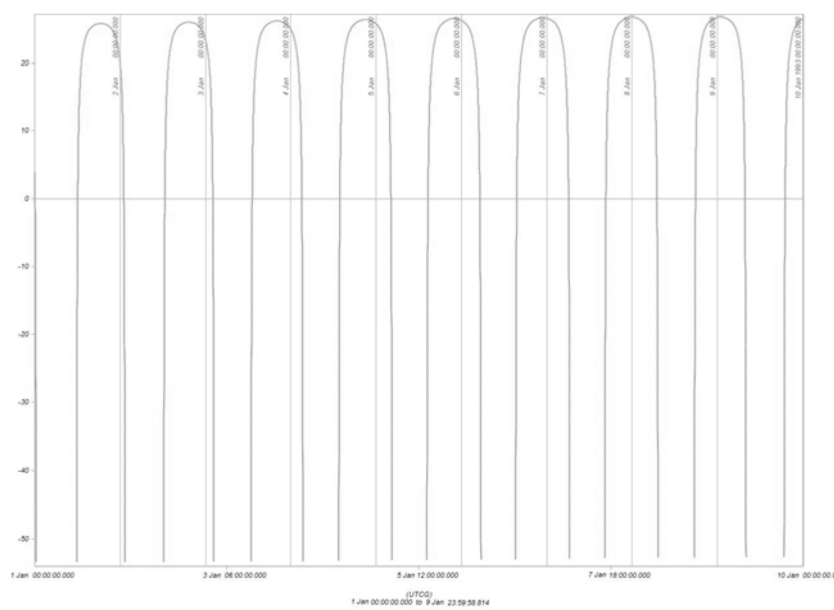

Figure 11: STK® typical link budget graphical report

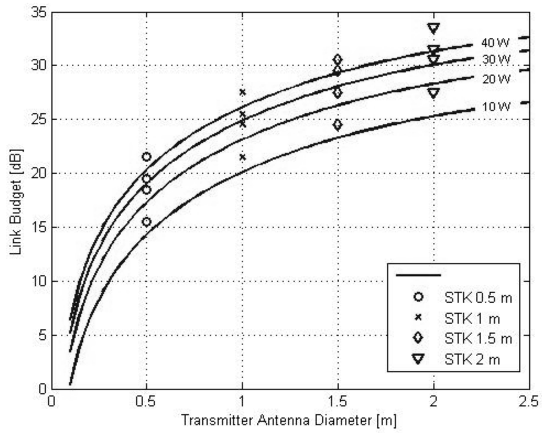

Figure 13: Lander – Earth Link (Down Link)
Data Rate = 256Kbps; Receiver Antenna Diameter = 4m

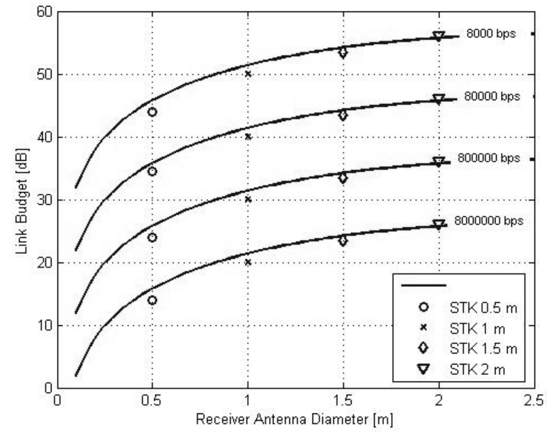

Figure 14: Earth – Lander Link (Up Link)
Transmitter Output Power = 500W; Transmitter Antenna Diameter = 4m

VI. System of Systems Analysis using the Modeling Framework

To show the potentialities of modeling a System of Systems according to the described framework, a hypothetical design session has been created with the simple objective of maximizing the distance traveled by the rover system on the surface of the Moon while minimizing the costs.

The method used to exploit the mathematical models is based on the utilization of the factorial design technique. A factorial design is a set of planned simulations of the mathematical model of interest that allows the study of the effect of a set of design variables on a set of performances or objectives. The design variables values are varied from a minimum to a maximum level, accurately set by the user, in such a way to simulate the model with all the possible combinations of design variable levels, or a fraction of it. Indeed, a special class of factorial design called Orthogonal Array has been used to obtain the results presented later in this subsection. The Orthogonal Arrays developed by Dr. Taguchi[19], allows an efficient experimentation of the design space by substantially reducing the number of required simulations to obtain the design-variable effects on the performances. Further, the SoS analysis with the Orthogonal Arrays has been coupled with the analysis of variance technique for the determination of factor importance, factor prioritization and sensitivity analysis. The advantages of using orthogonal arrays to plan the experiments are that the results coming from the experiments are valid over the entire experimental region spanned by the control factors, albeit with limited computational effort. Further, the method is deterministic, which translates into repeatability of the simulations and thus traceability of the results. Continuous or discrete variables may be used in the methodology without any major complication, which is particularly useful when dealing with architectural configurations of a complex system. An example, referring to the space exploration problem described in this section, may be the communication of a system directly to Earth or via a relay system in space. Those are two completely different architectures that may be defined by an architectural variable such as "*type of communication*".

More on the utilization of the factorial design and Orthogonal Arrays technique for an efficient utilization of the SoS models, coupled with the analysis of variance, can be found in ref. 2 and ref. 3. In ref. 19 and ref. 20 standardized orthogonal arrays are provided; for the example shown in this subsection an L27 orthogonal array has been used. In Table 8, we show the settings for the selected design variables and the performance parameters we will observe. The number of design variables taken into account is not so large for practical reasons. Indeed, the objective is to show the possibility to systematically analyze the effect of design variables belonging to different elements of the SoS architecture on the performances and the interactions between them.

Table 8: System of Systems design (27 design simulations)

Design Parameter	Low level	Mean level	High level
Type of Mission	LEO	GTO	LTO
Rover Wheels Diameter [m]	0.2	0.4	0.6
Rover Autonomy level [-]	A3	A3	A1
Rover # of Samples per cycle [-]	1	3	5
Lander # of Engines [-]	1	3	5
Lander type of propellant [-]	N2O4-MMH	O2-RP1	F2-N2H4
Performance Parameters			
Mission Cost [-]			
Rover Max Travelled Distance [m]			

The design settings presented in

Table 8 are the result of two previous design iterations that involved the rover system alone and the lander system alone. The results show that the telemetry data rate, the diameters of the antennas and the power output affect the performances of both the rover and the lander, in terms of mass, thus cost and, concerning the rover, maximum travelled distance on the Moon's surface. However, we decided to leave the design parameters related to the communication systems of the rover and the lander out of the simulation. It is common practice to design the communication system in such a way to meet the link budgets requirements (i.e., an adequate margin in downlink and uplink); there is usually no reason to target a link margin above the minimum threshold, besides some contingencies. For this motivation, and with the objective of keeping the number of design variables low to be able to best explain the principles behind the design methodology, we set the communication systems design parameters in such a way to meet the requirements before starting with the full system of systems design iteration.
The results shown from Figure 15 to Figure 18 have been obtained by factorial analysis[20] on the results obtained from the experiments plan shown in Table 8. For every experiment a certain value of the performance is obtained, so that at the end of all the experiments we will obtain a performance vector $\overline{y} = \left[y_1, y_2, ..., y_n \right]$, with *n* equal to the number of experiments, which in this case is *27*. The average effect of a factor *A* on a performance *i,* for instance, can be studied as follows:

$$A_{-1}^{i} = \frac{1}{m}\sum_{c=1}^{m} y_i\big|_{A=-1} \qquad A_{0}^{i} = \frac{1}{m}\sum_{c=1}^{m} y_i\big|_{A=0} \qquad A_{1}^{i} = \frac{1}{m}\sum_{c=1}^{m} y_i\big|_{A=1} \tag{13}$$

In (13) we read that the average effect of a factor *A* on the performance *i* can be computed as the average over the number of levels of the factor *A*, which is m in this case, of the sum of all the experiments in which the factor A was respectively at *low*, *medium* and *high* level.

In Figure 15, we read that the maximum distance travelled by the rover on the surface of the Moon is affected by all the design parameters taken into account, with different relevance for all of them. With an increasing number of samples per driving cycle, the data volume increases, and so does the time needed to communicate, given a certain data rate. The result is that the maximum travelling

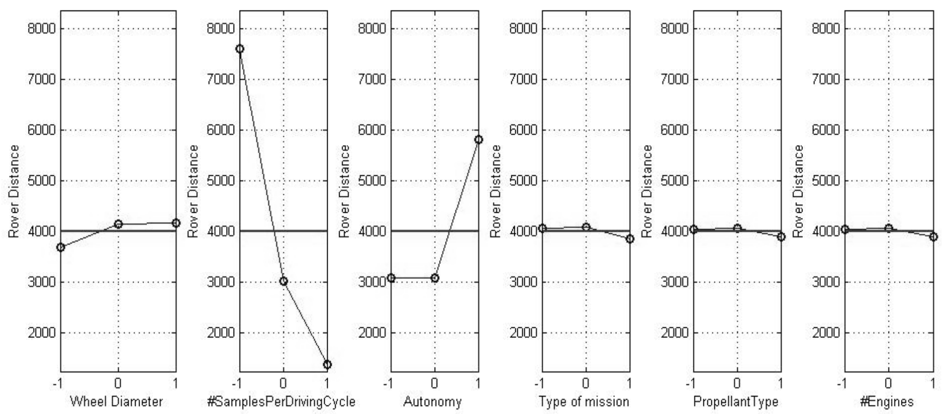

Figure 15: SOS simulation, Rover Travel Distance main factor-effects

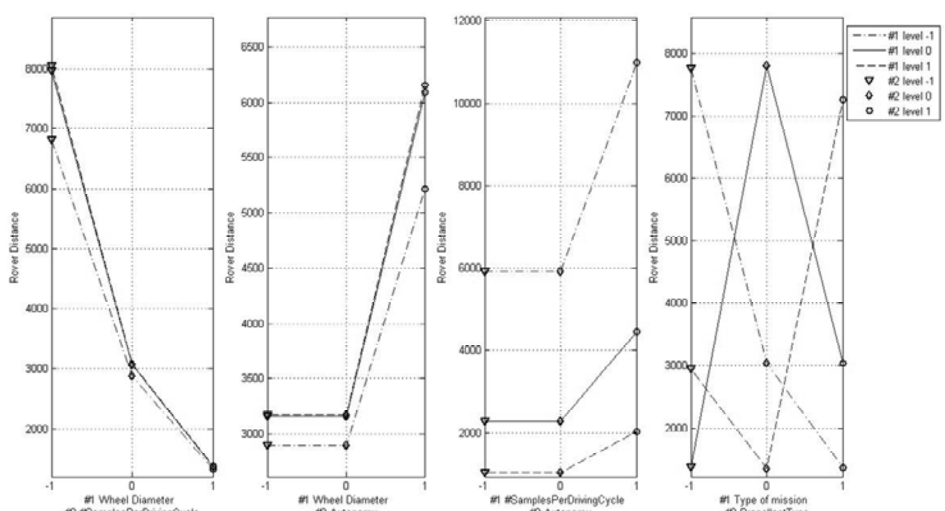

Figure 16: SOS simulation, Rover Travel Distance interaction effects

distance decreases. The autonomy level is responsible for the maximum allowed distance that can be covered before communicating with Earth (through the lander or not, depending on the communication architecture). With increasing autonomy of the rover the maximum distance travelled on the surface of the Moon increases as well, given the maximum mission duration of 14 sidereal days. The wheel diameter also affects this performance parameter because, as can be observed, with an increasing rover diameter the maximum allowable speed for the rover increases as well. The type of mission, propellant type and number of engines for the lander, do not have a relevant effect on the distance travelled by the rover.

The interactions between the design variables can be clearly seen in Figure 16. The fact that the lines are not parallel is due to the presence of synergistic and anti-synergistic effects. A synergistic effect is present when the improvement of a performance given the variation of a design parameter is enhanced by the variation of another parameter. An anti-synergistic effect is the exact opposite.

Let us consider, for instance, the interaction between the wheel diameter and the number of samples per cycle. We read that with the wheel diameter that increases (going from dashed line to solid line), in average the maximum distance travelled by the rover increases, in accordance with the results presented in Figure 15. The increase of the rover travel distance with the wheel diameter is mitigated by the number of samples per cycle to be collected. This means that the benefit of having a set of larger wheels is less important when the number of samples per cycle to be collected is high. They have an anti-synergistic interaction. The same type of rationale can be captured when looking at the remaining blocks of Figure 16. In the case of the interaction between the type of mission and type of propellant, we conclude that the advantages or disadvantages have to be studied case by case, due to the strong anti-synergistic effect between the two design variables.

Table 9: Best parameters settings

Design Parameter	
Type of Mission	LTO
Rover Wheel diameter [m]	0.4
Rover Autonomy level [-]	A1
Rover # of Samples per cycle [-]	1
Lander # of Engines [-]	1
Lander type of propellant [-]	F2-N2H4

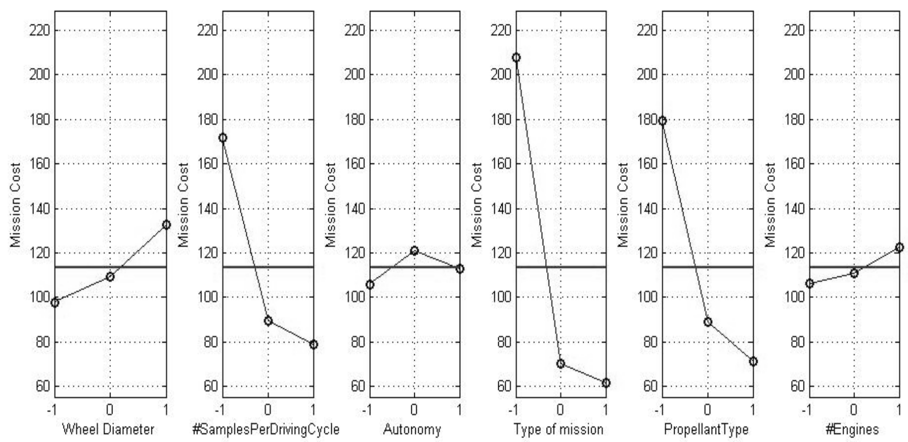

Figure 17: SOS simulation, Mission Cost main factor-effects

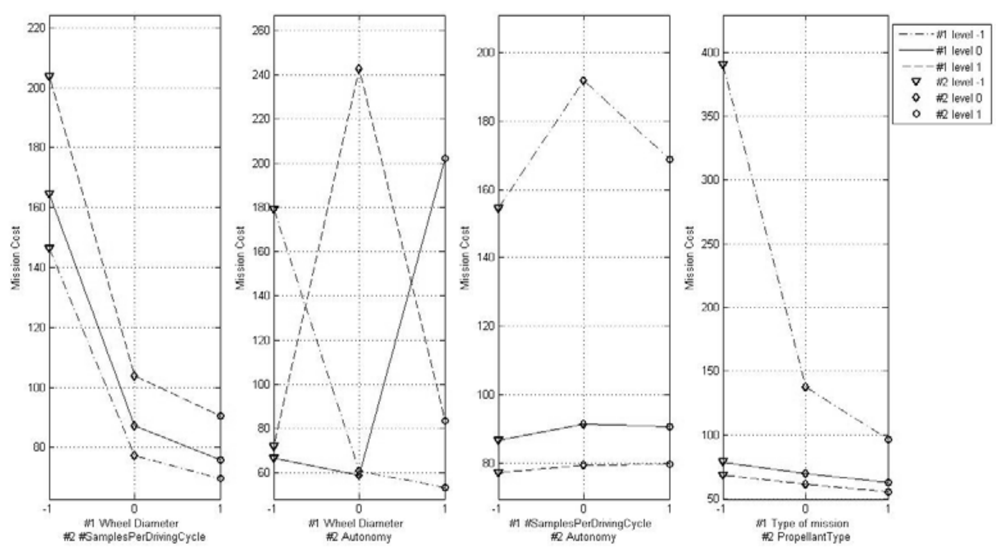

Figure 18: SOS simulation, Mission Cost interactions effect

In Figure 17, we present the factor effects on the estimated mission cost. The cost comprehends the rover cost and the lander cost. As we can see, in this case the most relevant factors that affect the cost of the mission are the type of the mission and the type of propellant. This is directly linked to the fact that the smaller the ΔV that the assembly has to provide during the mission, the smaller the mass of the propellant and of the lander, thus the lower the cost. Also the wheel diameter partially affects the cost. It is due to the fact that a more massive rover is considered more costly by the implemented model and the rover mass increases with the rover wheels diameter. The number of samples per driving cycle affects the rover power due to the fact that the samples must be sent to Earth through the communication system, which absorbs power and that while communicating the rover does not move, saving energy. There is thus a strong interaction between the number of samples per driving cycle, the power subsystem and the rover autonomy, as can also be observed in Figure 18. These phenomena lead to the trends reported in Figure 17. The autonomy, in turn, is affected by these interactions, and that is the motivation for which the performance with Autonomy at level -1 and level 0, which correspond to the same settings as shown in Table 8, is not constant. The impossibility of discerning interactions and main effects is commonly called "*confounding*". Confounding must be dealt with care, and it is a common risk arising when using orthogonal arrays. In Figure 18, the interaction effects of the design variables for the mission cost performance are shown. Analyzing the trends of Figure 15 and Figure 17, we are able to predict the best combination of parameters which allow the minimization of the cost and maximization of the distance travelled by the rover on the surface of the Moon. In Table 9 the best parameters settings are reported.

VII. Conclusions

In this paper, we described a modeling and analysis framework for the concurrent design of complex space systems. The objective of the research was to obtain a general framework to deal with the decomposition of a complex system in its elements and sub-elements, to enable a faster and more effective solution of the problem. The complex problem of interest has been addressed as System-of-systems. In section III and section IV we provide the basis to understand the type of the mathematical models developed and implemented, and the way they have been linked together. In particular we adopted a NHD approach with a MDF problem formulation. The case study of interest is a hypothetical robotic mission to the Moon, with a rover, a lander, and a transfer mission Earth-Moon. All the mathematical models have been verified, most of them have also been validated. In section V we provided some details on the validation of the models for the communication system. The implemented communication system model has been compared with the performances of commercial software, STK®, allowing us to conclude that it is suitable for the estimation of the link budgets for an interplanetary communication architecture.

The framework we developed is a backbone, which enables elements, systems and System-of-Systems analyses in a highly integrated design environment. The mathematical models have been linked together in a modular and flexible way, thus enabling the communication between the various architectural elements by only providing the correct interfaces, irrespectively of the complexity of the models that are implemented in the architecture.

The design methodology based on fractional factorial design (i.e., orthogonal arrays) implemented to use the modeling framework showed its potentialities of capturing main effects and interaction effects information, showing it in a graphical form, allowing the design team to make more informed decisions during the trade-off process. The possibility of analyzing inter-elements and inter-systems interactions is very important at system and System-of-Systems level, because it provides information usually covered in the interactions coming from the coupling of the elements and of the subsystems between each other, thus not clearly expressed by mathematical relationships. In the future, further investigation on the confounding effects arising from using orthogonal arrays is strongly advised for a better understanding of the physical phenomena to describe a particular system.

This flexible and modular approach to the modeling of the System-of-Systems problem may pave the way for implementations that go beyond the particular application presented in the paper, also for more advanced design phases of a complex system in a concurrent environment. Different and more complex models can be added to the software framework, to complete or substitute the models already developed, in order to perform design analyses with the desired level of detail.

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