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LONG TERM SPACE PROGRAM SCHEDULING AND SYSTEM DESIGN OPTIMIZATION

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ABSTRACT

The human planetary exploration goal asks for both a strong technology development and a great scientific knowledge enhancement that can be achieved only through a rational and well tuned sequence of different highly related missions, from demonstrators up to scientific probes, in the framework of a limited resources scenario. Therefore the programmatic division has to face the hard task of producing a long term planning deeply connected with the technical design of each unit belonging to a multi-missions scenario. The paper suggests a possible tool to solve the long term space missions planning problem by working on the single mission preliminary sizing, while taking into account the complex constraint net, both in the design and temporal domains. Thanks to the proposed multi-objective optimisation the engineers are given a pruned and ranked solution space, to work on to refine the programmatic. The Evolutionary Algorithms have been selected to deal with mixed domains and get the globally optimal solution set on the time and in design alternatives search space. Appropriate preliminary models are proposed to deal with the criteria vector elements here assumed to be the most relevant for the problem. The architecture has been tested on the NASA Apollo program scenario. The obtained results are consistent with the real program and possible discrepancies helped better tuning the tool. Simulations for ongoing exploration scenarios, such as the ESA Aurora, are offered to highlight the benefits of the tool in identifying a set of optimal, preliminary plans. A critical discussion is also offered.

INTRODUCTION

Despite of the large number of systems launched so far, long term space programs for planetary exploration are still few. However a programmatic strategy - focused on the overall program return while assuming as control variables the design and allocation in time of each single mission as part of the whole - starts being considered as the key point for the future, to make the new rising programs of wide and methodical solar system exploration actually achievable. Tools and methodologies, successful for a single mission design, cannot cope with the increased complexity of a complete space program because of the added dimension of time: the classical design and scheduling disciplines have to be merged, giving rise to a wide set of multidisciplinary constraints from the logical sequencing constraint among different missions, up to the technology development spin-offs from the former to the following missions highly addressing their design chances. Technological design parameters are time dependent, the availability of a specific technical solution could depend on the success of a former mission to be designed and allocated in the same space program. Although a wide literature can be found on the scheduling and system design disciplines separately, works related to both of them can be hardly resumed.

Therefore, the work here proposed has to firstly faced the problem formalisation by selecting the most convenient criteria a program is judged on; secondly by identifying the variables the engineers together with the programmatic experts can work on to get a preliminary space missions path that make a far complex goal feasible; as a consequence the mapping from the variables domain to the criteria space has been defined; the set of both design and temporal/logical constraints have been identified and formalized according to the selected problem variables; finally, to prune the solution space according to the given criteria ranking an optimization procedure has been settled. It has to be noted that by moving the goal of the space system design from a single mission up to an entire program, the classical sizing variables become time dependent: as a clarifying instance it should be noted that the launch date has to be considered as a vector composed by each possible mission in the program launch event: each allocation in time of the vector elements is highly constrained by the technological and logical sequence those missions have among each others. It is worth noticing that each preliminary mission configuration is time dependent, because of a particular technology availability; a specific technology readiness for flight may depend on former planned mission design, and even flight success; a certain mission could turn out to be either infeasible or excessively expensive because of a insufficient technology readiness level, whereas it could fly more efficiently just being launched as soon as the adequate technological development is gained. Hence, depending on the missions allocation in time, the domain of the selectable technologies, for a given space system, is strongly influenced by the context generated by the missions selected to occur first; therefore, the configuration search space is planning dependent. The simultaneous search in the configuration and time domain, taking into account the two domains high coupling turns out to be the necessary approach to correctly formalize the long term mission plan.

In the followings the problem formalisation and the architecture to get the optimal planning set in terms of single mission in the program preliminary configuration definition is presented, according to the logical sequence already highlighted.

THE CRITERIA SET

The past and present space programs evaluation is almost always focused on at least one among the time horizon width, the technology development, the intrinsic risk and the costs [1,2,3]. Therefore those four quantities have been formalised in the tool as elements of the objective function vector to be fed in the optimization process: more specifically, the risk has been here interpreted as the level of uncertainty connected to the program. The user can freely select how many criteria to take into account for the evaluation, among the former set.

The scheduling horizon width criterion asks for no specific model, whereas the other objective functions modelling are presented in the followings.

The technology development criterion

The technology development criterion gives a glance of the technology enhancement that a selected sequence of missions offers because of the design solutions selected for preliminarily define each of them; the missions time sequence, in fact, drives a specific technology evolution in time for each related discipline (control, thermal protection, power supply, etc). This criterion formalisation and evaluation is still an open point. In this work guidelines for its settlement have been resumed from the reported literature[4,5,6]. In particular the Technology Readiness Level (TRL) index concept, proposed by NASA has been here extended and applied to bridge the possible configuration solution domain and propagation in time with the technological development space[6]. The TRL is a quantification of qualitative classes a technology can belong too, depending on some predefined features. More specifically the criterion space is thought to be influenced by the following aspects to be considered while evaluating the sized missions possible allocation in time:

a) New technologies: percentage of innovative technologies selected in the project versus the whole domain. the higher it is the more technology areas are innovated in the program.
b) TRL step: sum of the TRL increasing offered by the technology history selected by the visited mission sequences: the higher it is the higher the quality of techonolgical evolution in terms of low risk and applicability
c) Confidence: number of innovative technology uses after activation (first utilization): the higher it is the more the innovative technologies are well developed in the visited time frame

The former quantities enter a specifically implemented inference motor to obtain the global Technology Development Index (TDI)**.**

The uncertainty criterion

The uncertainty criterion takes into account the risk connected to the hazards implicitly brought by the technological choices done to size each mission in the plan. The already available risk modelling techniques are here disregarded as they ask for numerous detailed inputs, not available in the very preliminary sizing phase of a space system[7,8]. At the long term planning level the missions to be scheduled are sized just in terms of configuration alternatives, with no sizing process; as a consequence, no figures are available for the risk computation that has to be accomplished by qualitative reasoning.

Two aspects are here considered: the uncertainty each single mission presents because of its own nature, and the effects of the propagation in time of any uncertainty inserted at some given instant in the plan by one of the allocated missions. These two aspects are treated sequentially: for the single mission uncertainty analysis a Failure Mode and Effects Criticality Analysis (FMECA) approach is used, whereas for the uncertainty propagation a logical tree analysis is accomplished. The most significant quantities here considered getting a final global uncertainty index are:

a) The innovation that each mission introduces.
b) The risk intrinsically connected to either dangerous missions or dangerous aspects of a mission: as an example, the aero-capture manoeuvre falls in the highly risky aspect
c) The complexity of each mission.

The models to map the problem variables into the former quantities have been designed. They are not here described in details for lack of space. For each mission a term of cumulated uncertainty is introduced to quantify the uncertainty propagation. The term is evaluated by taking into account:

a) The effects on the following planned missions of selecting an innovative technology for an "arrow" mission (later defined): the uncertainty level of all subsequent missions somehow constrained by the current arrow will be amplified.
b) The propagation of the local mission uncertainty level through the net of planned mission logically correlated to the current.

The final uncertainity index (UNCERT) is simply computed by aggregating the reported two aspects.

The economic resources management

The program cost can be interpreted as a limited resource to be managed while defining the mission scheduling. In this work the cost has been treated as a further criterion to feed the optimization loop. Both the total amount and the distribution over time are taken into account to judge the possible long term plans.

The cost modelling methods described in literature usually deal with a single mission class at a time, within a prefixed time window, that means a well defined technological context, at the time being of the evaluation process occurrence [9,10]. On the contrary, within the presented application the further dimension of time has to be part of the cost computation, as a whole space program on a several years time span has to be planned; a lot of care has to be paid in the selection of the best Life Cycle Cost (LCC) estimation methodology. The costs of various, uncertain and highly interconnected technological scenarios shifted in time have to be evaluated with a single cumulative index. Therefore the classical estimation methods fail because of the lack of detailed input information. An *ad hoc* model, focused on the most important aspects for the global economic resources analysis with limited need of detailed information has been developed. Specifically, the following macro-parameters, directly dependent on the problem variables, are defined to evaluate at the economic program effort from the very beginning of the sizing process:

a) Total expense index: it provides also the cost demand profile along the scheduling horizon
b) Mass configuration quality index for the mission sequence
c) Very expensive technology index (i.e. RTG)

The global index to be attached to a detected long term plan is computed by summing, properly weighted, the three former quantities.

The optimization architecture here proposed evaluates, for each visited set of given mission allocation in time, the following criteria vector:

$$\underline{Y} = [\text{horizon}; \text{TDI}(\underline{x}); \text{UNCERT}(\underline{x}); \text{COST}(\underline{x})] \quad (1)$$

The first together with the third and fourth criteria are here minimized while maximising the technological development.

THE PROBLEM VARIABLES

The high level variables from the scheduling problem point of view are clearly represented by the space missions themselves. The schedulable mission domain is here considered as finite and discrete. Therefore, although certain flexibility on the missions' category is maintained, they do not represent the main working variables. While the first evaluation criterion in eq.(1) clearly depends on time, a nested dependence on the allocation of the given mission on the temporal axis can be identified in those criteria being strictly related to the selected technology for accomplishing the on-board subsystems tasks, even if at a very rough level of definition. Therefore, being the mission fixed the search space is moved towards the technological alternatives to answer the preliminary sizing of each of the mission in the program, as follows:

- The time span to get the final program goal: the launch date of each mission to be allocated in the program fills an n-dimensional control vector (n=no. of missions); that vector undergoes the logical constraint set, imposed by the user, about the sequence requirements of the set of missions to be scheduled.
- The high level system configuration: the technological solution to preliminarily define the probe\s devoted to actuate each mission represents the added degrees of freedom of the problem: an m-dimension vector is attached to each mission in the program and it gives the

proposed technological solution for each on-board subsystem; a discrete domain is defined for such a class of variables. A set of constraints is given to guarantee the systems feasibility and the technology readiness level for flight.

As already mentioned, although the selection in type and number of the missions to be considered, in the program seems representing the main set of d.o.f. to reduce the dimension of the problem to be treated their have been considered settled by the user, in terms of maximum number, type and objectives. A classification is offered on the basis of the Aurora Programme[1]:

- Milestones: missions strongly connected to the others through time constraints; once selected by the designer from a given pool, they can be removed from the program no more
- Arrows: missions with no time constraints; they are selected by the user at the beginning but the solution process can remove them from the schedule during the problem solving process.

Those missions are identified by their modules configuration: their logical subunits which do not necessarily coincide with the physical subparts that will constitute the spacecrafts. At this level of research it is more interesting to emphasize the draw-backs that a mission produces in terms of technological acknowledgment and scientific achievements. According to these two aspects the possible presence of two distinct but identical modules has no influence on the solution score. To better clarify consider a mission that needs two identical "landers" to execute a certain phase: the problem formalisation takes care of just one of them. The systems logical subunits, as well as their task assignments, are derived from an analysis of the spacecraft operations. This automatic process will be explained later in the paper. In the following the search domain is deeper detailed.

The time variable

Two different time dependences are here taken into account for each mission: the time span dedicated to the design and integration accomplishment, and the operative phase lifetime. The launch time that fixes the mission allocation on the temporal axis, is here selected as the sole explicit temporal variable: the time span devoted to each project phases is computed as percentage of a given reference time partitioning for the project evolution, according to the mission complexity. The mission lifetime is obtained by both the inputs given by the user in terms of mission objectives and the mission analysis, strictly connected to the propulsion technique proposed by the tool for the visited mission. Constraints coming from the technology availability of specific key devices at the launch date, and from possible requirements imposed by different missions in the plan bounds the actual search domain for that variable.

The configuration variables

The spacecraft configuration comprehends both the technological solution adopted to answer each functional task of the probe and the capabilities that a spacecraft has to possess to accomplish its specific mission phases. The first part is here addressed as the "subsystems" set, while the second aspect is named the "abilities" set; the capability of landing on a planetary surface, the autonomous navigation performance belong to the abilities class.

While the set of subsystems here considered does not differ from mission to mission, the abilities vary depending on the task that a specific module has to accomplish.
To comprehend as more scenarios as possible, the abilities taxonomy has been driven by their relationship with the already identified control variable set:

a) Internal abilities: purely free variables part of the variable vector (i.e. landing)

b) Subsystem dependent abilities: they do not belong to the variable vector, but they activate the presence of dedicated subsystems domain to be included in the mission definition; as an example, the "auto rendez-vous" ability contributes to turn to active the search on the domain of the guidance subsystem (GNC)

c) External abilities: they intervene on the constraint set possible enlargement as they can impose further time constraints on the mission: it could be necessary to wait for a specific date in to acquire a specific technological knowledge to make the mission feasible

From the technological point of view two different classes of constraints can be identified, intervening on the configuration variables: the actual availability of the technologies selected for every subsystem at the date the mission design starts; the task-dependent domain to be visited for the configuration solution; the electric propulsion, for example, cannot be part of the alternatives for the configuration definition of a planetary ascending module.

Technologies availability

As already highlighted, the timeframe is highly connected with the configuration alternatives through the technological readiness at the mission launch date. Therefore the proposed launch date vector drives the search domain definition for the technological aspects, and the configuration selection constraints the possible launch date. That strong dependence has to be modelled to successfully deal with the proposed scheduling problem driven by the missions preliminary design. More specifically, the technologies time dependence has been classified as follows:

a) Ready technologies: they are available since the very beginning of the planning horizon.

b) External-developing technologies: they are widely applied in space systems, therefore their development can be considered independent from the considered space program; their first application in the context of interest can be scheduled starting from what is foreseen by the technological context.

c) Internal-developing technologies: they are hardly ever applied in missions different from those inserted in the visited program, therefore, their readiness for flight relies on their application history within the space program itself.

According to each given class, a technology can be taken into account for flight as soon as the qualifying tests occurred. The first application to a real space mission is here intended as a qualifying test, letting the technology step forward in its TRL scale[6]. The task to validate new technologies is here left to the "arrow" missions, interpreted as technological demonstrators missions: even not yet ready technologies can be selected for their configuration, to increase the specific technology confidence level and to let it be exploitable by milestones. Minimum time spans for the acquisition\analysis of the arrow mission results, as well as a demanded study time period to contain both the risks and the costs related to the tests are taken into account.

The already mentioned TRL index quantifies the technology readiness level, according to some given rules stating specific events occurrence that partly models the technology time dependence:

- "ready technologies": TRL = 9
- "external-developing technologies": TRL <8; TRL= 9 is accomplished at fixed dates derived by the scientific context
- "internal-developing technologies": TRL=8 is obtained as soon as an arrow mission selects that technological solution; subsequent utilizations both by arrow and milestone missions lead the technology to TRL 9.

It should be noted that the adopted formalization scheme offers the chance to deal with various, widely different, scenarios: the user can choose the missions, the subsystems classes, the abilities and the technologies domains during the pre-processing phase. Moreover, due to its modularity, it is possible to extend, update and refine quickly these domains. Hence the domains low level description is left to the specific applications.

THE PROPOSED ALGORITHM

The long term space program scheduling and through the system design optimization can be formalized as the minimization of the criteria vector in eq.(1), for which the $\underline{x}$ vector of decision variables, is time dependent. The $\underline{x}$ vector can be partitioned to better highlights the temporal dependence $\underline{x}_{ti}$, and the either internally or externally developed technologies $\underline{x}_c$, $\underline{x}_d$ in the space program itself:

$$\underline{x} = \{x_{t1}(t),\ldots,x_n(t),x_{c1}(t),\ldots,x_{cp}(t),\ldots \\ x_{d1}(t,\underline{x}_t,\underline{x}_d),\ldots,x_{dq}(t,\underline{x}_t,\underline{x}_d)\}$$

$$n = \text{no. missions};\ t \in [t_{start}, t_{end}]_{\text{sched horizon}} \qquad (2)$$

Within the time domain, the optimization is constrained by the milestones' temporal sequence requirements and the possible external abilities, that act on different phases of various missions, and the new technologies activation schedules that happen depending on the missions allocation in time itself:

$$\begin{cases} \underline{g}(\underline{x}_t) = \{g_1(\underline{x}_t),\ldots,g_s(\underline{x}_t)\} < 0 \\ \underline{h}(t,\underline{x}_t,\underline{x}_d) = \{h_1(t,\underline{x}_t,\underline{x}_d),\ldots,h_v(t,\underline{x}_t,\underline{x}_d)\} \le 0 \end{cases} \qquad (3)$$

By dealing with a multi-criteria optimization problem a set of optimal solutions is eventually detected. The user is in charge of selecting the most promising long term plan among them. As the uncertainty connected to the information is not taken into account, the environment is said to be deterministic. It has to be underlined that the time-dependent quantities are here treated as discrete variables; therefore the problem reduces to a combinatorial optimization. In this context the classical approaches to solve multi-criteria combinatorial problems cannot be successfully applied because of the huge number of variables and the complex constraints net the solution must be consistent with[11]. To cope those difficulties, and to catch a set of possible global optima running the tool once, the Genetic algorithms (GA) technique has been here selected. In fact, among the different benefits this option can offer, GAs are particularly appropriated for mixed domain optimizations, as no information on the gradient is asked for; they don't car of the search domain dimension; they can deal with complex multimodal hyper-surfaces, by exploiting their capability to avoid being trapped in local minima thanks to the population-based approach; they can even work with code-variables and, they provide, in the multi-criteria framework a set of optima. This last characteristic is really profitable, according to the designer, as a further degree of choice, in a restricted, more manageable domain, is still left to the expert.

The idea that supports the GAs is to emulate the natural selection process in such a way that those individuals, representative for the possible problem solutions, which posses emerging features, marked by an index strictly connected to the criteria vector evaluation, would survive and transmit their genetic patrimony to step forward the global optima area.

A survey of GA-based techniques applied to MO problems is available in literature[12]. It is worth noting that the objective functions in eq.(1) are not-commensurable. Not to deal with delicate scaling techniques the dominance approach, according to the Pareto definition is here applied to detect the global front. The front is, basically, a trade-off surface, made of all those solution vectors I the criteria space that do improve no criterion without causing a simultaneous worsening of at least one of the others. The classic flow to move within the search space is here applied paying particular attention to some of the relevant issues these algorithms revealed to have; more specifically: how to maintain a diverse population to prevent premature convergence and achieve a well distributed trade-off front; how to accomplish fitness assignment and selection, respectively, to guide the search towards the Pareto-optimal set, taking while being consistent with the constraints net[13]. These two topics are managed by different parts of the implemented algorithm:

- The genetic drift avoidance is accomplished by a lateral interference operator (IL) coupled with the activation of an individual basin, the so called tabu-list (TL), to preserve good detected solution while keeping searching
- The fitness assignment and the individuals selection is faced by means of an innovative method specifically thought for this study[14].

The main purpose of the TL is to guarantee a certain level of equilibrium between the information flow to the next generation, by rescuing the dominant individuals from the disruptive action of the genetic operators, and the possible forcing trends, that could stop the search path in a limited region leading to a premature convergence into local minima. The TL uploading process consists of a modification of the Tan's et al. version[14]: no need to carry out a further selection based on the distance among the different individuals in the objective space, carried out to take into account information that could enrich genetic patrimony of the whole population. The selection of individuals to come from the TL, as well as the restriction imposed on the current population, to keep its size constant according to the generation number are dealt by the IL operator [14]. Its purpose, in fact, is to uniformly sample the TL and to preserve the diversity among the individuals that will constitute the parents for the next generations. For further details on the search mechanism refere to Tan's paper [14].

The creation of the new generation embodies an innovative step in the algorithm. The method developed comes from the necessity to perform a wide and adequate search through the variable domains, taking into account the quite complex nature of the feasibility zones. The suggested mechanism is close the Game Theory techniques as two populations, that is two players, are in charge of different search space sub-zones; the generating pool is split in two sub-populations composed by homogeneous genes. More specifically the $\underline{x}_t$ and the $\underline{x}_{conf}$ space are visited separately by two dedicated similar search mechanisms. The genetic operators act separately on the two subparts paving the way to the reconstruction of two new different and complete populations, which have then to be evaluated according to consistency and ranking. The new best fitting individuals become the current population from which the latest dominants to upload the TL are selected.

A test campaign occurred to critically evaluate the implemented algorithm on the scenarios proposed by the related literature[13]. The proposed algorithmic architecture revealed to be effective in spite of the different levels of complexity of the treated problems.

THE SIMULATION RESULTS

The requirement of a tool to be generally applicable as far as possible, no matter of the long term goal of the program and the visited time span, has been preserved. To test that feature the results obtained for two real space programs embodying heterogeneous situations are presented. The first simulation run on the Apollo program scenario and it has been expoited to carry out a critical analysis on the tool to better tune it. The second test concerns the ESA Aurora Programme and it presents the typical features of planning of future events[1].

The Apollo Program: validation process

Neil A. Armstrong's walk upon the lunar soil, happened on the 21 of July 1969, is one of the most famous historical events of the past century, certainly the most famous of the whole space exploration history, and the name "Apollo" reminds everyone that space-walk, as well as the great effort undertaken by the US during the second half of the Sixties ofto "[…]land a man on the moon and return him safely to the Earth, before this decade is out […]" (J. F. Kennedy, 25 May 1961)[3]. According to this, the Apollo program accomplishes the concept of space program as defined in this study, i.e. a sequence of space missions and tests, carrying out the same and well fixed final objective, to be achieved into a well defined time horizon. That is why this American project fits well the validation necessities. The simulation shown in Fig.1 was accomplished with a population of 100 individuals and termination test satisfied either through the achievement of the maximum number of generation (250) or through the identification of at least 200 Pareto dominant plans. Here the simulation stopped at generation 41 and the time unit is the Julian date starting from January 1950. As the objective space is 4-dimensional, the obtained solutions are projected upon all the planes that identify the whole possible combinations of 2 criteria per time, and consequently they cannot show their exact position in the real hyperspace. This particular choice implies that, among the solutions of the problem subjected to four criteria, a further selection is carried out giving preference to those individuals that result also dominant respect two determinate criteria, independently by the values of the projected remaining objective functions. By observing the fronts constituted by the global solution that are dominant in the subsequently reduced contexts, it can be seen how they express reasonable connections between the different criteria. In fact, decreasing the time spent to realize a plan, the economical resources as well as the uncertainty involved in the correspondent planning increase even if a modest technological development is achieved. In the mean time it clearly appears that innovative plans, according to the technological draw-back, are always marked by rising levels of uncertainty and by a considerable economical effort. The results of Fig.1 for the Apollo program submitted to the four objective criteria selected show that the historically realized planning (marked by the star) is not optimized with respect to the "minimum time" and "technology development" criteria. Although this might contrast the common idea that the Apollo program achieved in a brief period of time such an ambitious goal due to a high level of technology innovation, both these disagreements can be explained through a correct historical settlement of the program itself. Firstly, it must be noted that Apollo's final goal was not achieved in a minimum time but at the end of the available time horizon. That is why it is reasonable that the historical solution does not belong to the optimal front corresponding to the "minimum time" criterion. Concerning the TDI objective instead, references show that the main part of technology innovation improvement, necessary for landing the man on the Moon, was not committed to Apollo but to a dedicated program named Gemini [2,3]. This project arose in the 1962 carrying out the specific intent to "fill the technological gap between the Mercury program (first American human space flights) and the Apollo one", and so achieving that peculiar technological improvement that does not correspond with the human landing itself [3]. Due to an opportune initialization of the code, a further simulation considering the missions and the technological context of the Gemini program has been accomplished. This provided results that confirm what found in the historical documents.

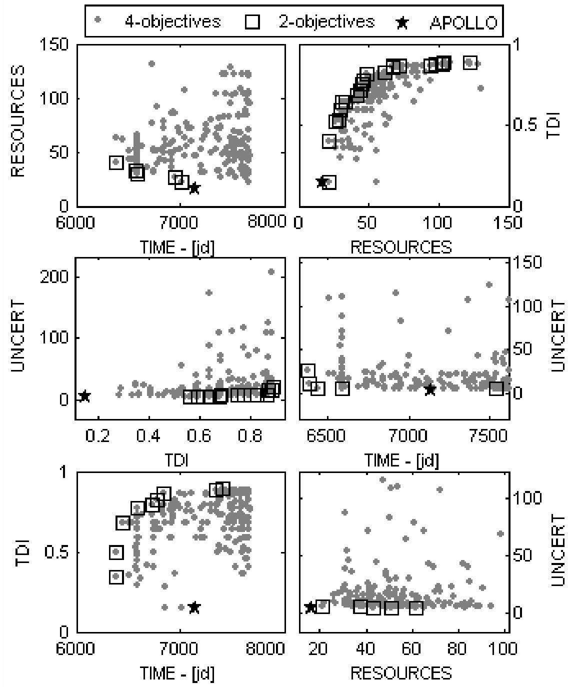


Fig. 1: Projected Pareto fronts obtained for the Apollo simulation subjected to 4 criteria.

By making a comparison in the variable space between the obtained solutions closest to the Apollo project and the American program itself, it clearly appears that they do not completely agree, although many features like the logical order of the fundamental steps as well as the poor tendency to use highly innovative technology in key-phases of the plan, are preserved. Despite this, those solutions suggest the achievement of the final target much before July 1969, or to use technologies, like RTGs and magnetic and laser sensors, not anticipated for the Apollo program. Both the advanced achievement of the final goal and the greater technological development, strongly influence the fitness gained in terms of uncertainty and, above all, in terms of management of the economic resources. Though, for the first of these criteria, it is possible to find, at least in a restricted number of solutions, a plan that minimizes the different technological developments undertaken compared with Apollo's. For the economical aspect this cannot be accomplished at all. These considerations lead to the idea that, in reality, the Apollo project was not meant to be optimized with respect to all of the criteria introduced in this study. This is connected to the arbitrary definition of the "optimum condition" in a MO problem. Moreover, some of the aspects relevant for the space planning activity, such as political and legal features, are not taken into account in this analysis. Although, considering the time placement of the American program, they are without any doubt crucial. As a consequence, in order to identify the possible design-drivers of the historically realized project more simulations have been accomplished with respect to other plausible contexts. The first objective excluded is the "minimum time" criterion, in order to explore the consequences due to some structural lacks of the formalization, such as the absence of time constraints on launcher availability and launch windows, or the rough estimation of the missions' preparation phase duration. However, even ignoring the time criterion, although the target milestone is scheduled much later than in the problem subjected to four criteria, the global optimum reflects the compromise of achieving a wide technological enrichment compatible with acceptable levels of uncertainty and costs, as there are no incentives for a strong exploitation of the first part of the time horizon. Both the historical documents about the Apollo project and the results obtained so far suggest a design philosophy clearly in contrast with this approach. They advise that the American program intended to specialize in a restricted number of technological solutions in order to guarantee the highest safety level as possible for its success. Given this discrepancy, the next steps are the research of the design-driver of the Apollo planning. For this reason the further criterion to be excluded is the technological relapse (TDI) and hence the optimization reduces to a simple minimization of uncertainty and economical efforts. According to the results obtained by this last simulation, the historical Apollo resides on the optimal front. By carrying out a research of the closest solutions to Apollo in the variable space, plans highly coincident with Apollo are found. The only differences concern the choice to allocate one "arrow" less (causing a small increase of uncertainty), investing the remaining resources to activate some new technologies (radio and magnetic sensors) that had not previously been employed, causing a modest improvement in terms of TDI. As a consequence of the initial settings of this simulation, no information can be derived regarding the time placement of the target milestone.

The Aurora Programme

After having validated the proposed code through the Apollo program, a real simulation can be performed. It concerns the research of optimal mission sequences for the Aurora program, "an European space exploration program, based on a planning culminating in a journey of European astronauts towards Mars around 2030" [1]; which fixes a well determined final target and a time limit to achieve it, embodying the concept of a space program defined in this study, as previously done by Apollo. Unlike what happened for the American program, a historical analysis cannot be performed in order to identify the missions to be part of the plan.

NAME	a / M
SOFT LANDING	a
ELLIPTIC DOCKING	a
LIFE CLOSE CYCLE	a
EXOMARS	M
MARSNET	M
MARS SAMPLE RETURN	M
ISRU	M
HUMAN MARS MISSION	M

Table 1: Missions selected for the Aurora simulation

By making a comparison of different ESA documents on the subject, the mission candidates to constitute the program have been selected according to table 1. The time horizon is set to be the period from 2005 to 2035 and, taking into account its scope, a broad time scale has been set[1]. The time constraints due to the order of the milestones are defined by the logical tree of table 2.

EXO → MSR
→ ISRU →HUMAN MISSION
MARSNET

Table 2: Pre/post requisites for the milestones

The subsystems and abilities that constitute the control variable vector, as well as their domain and configuration constraints are the ones usually considered when dealing with the system design. Analysing the results of the simulation submitted to all the four criteria selected, it can be seen that the values reached by the TDI and the uncertainty objective functions are, on average, much higher than the one obtained during the Apollo simulations. This phenomenon is a consequence of the broad availability of technology solutions, greater in number and more various in types and exploitable over a wider time horizon. Systematically higher values of the uncertainty index testify the attempt to test new opportunities, which, even if not particularly advantageous in the near future, could cause positive relapses for forthcoming developments.

In order to expound the shape of the global optimum hyper-surface and, in the same time, to assess the effectiveness of the spurs produced by the different criteria, an analysis regarding the position of the obtained solutions, respect an utopia point has been accomplished. This particular point could be ideally reached by a theoretical planning characterized by a target milestone launch date slightly after the minimum time specified by the pre/post constraints, by a null economical resources effort, by a maximum technological development and, finally, by a null uncertainty level. The counterpart condition can therefore be defined, which is the point that symbolizes, in the objective space, the worst plan obtainable. Hence the dominants can be ranked according to their distance from the utopia point, normalized with respect to the maximum obtainable distance, which is the one between the above mentioned point and its counterpart.

Fig.2 shows all the plans, solutions of the 4-objectives problem, with their normalized distances from that utopia point. The plans marked by stars belong to the nearest region to the utopia point, whereas, considering every sub-picture, the ten best individuals, among the same pool of dominants, according to a criterion at once, are also marked. It is then possible to identify some particularly meaningful regions upon the global optimal surface: the “knee” (the surface region occupied by the elements nearest to the utopical point) and those parts representing the single criteria’s optimums.

The knee expresses the situation of maximum compromise among the satisfaction of each criterion. However it can be seen that the minimum time objective function authoritatively leads the optimizing direction, as only its absolutely best fitting elements also results in the most promising (or nearly) for the global point of view. As an example, a possible planning is shown in Fig.3 which presents one of the sequences at minimum uncertainty. As found when dealing with the Apollo program, it seems to be the most reasonable planning approach, according to its practicability. Uncertainty, therefore, is a fundamental design-driver, to achieve which solutions optimizing the remaining criteria might be rejected.

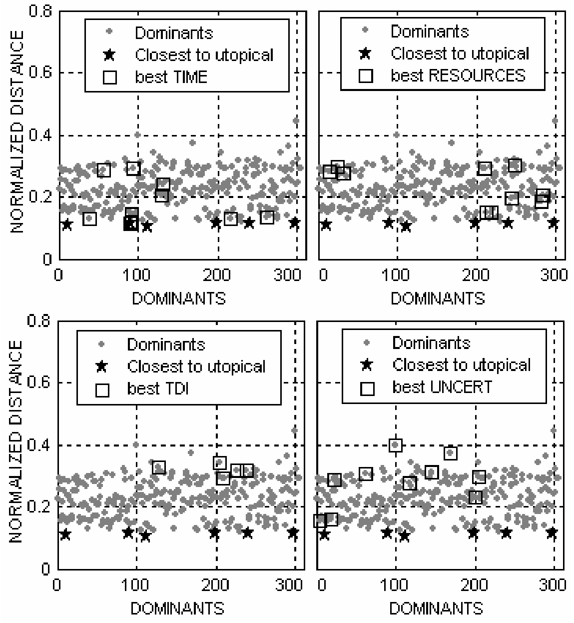
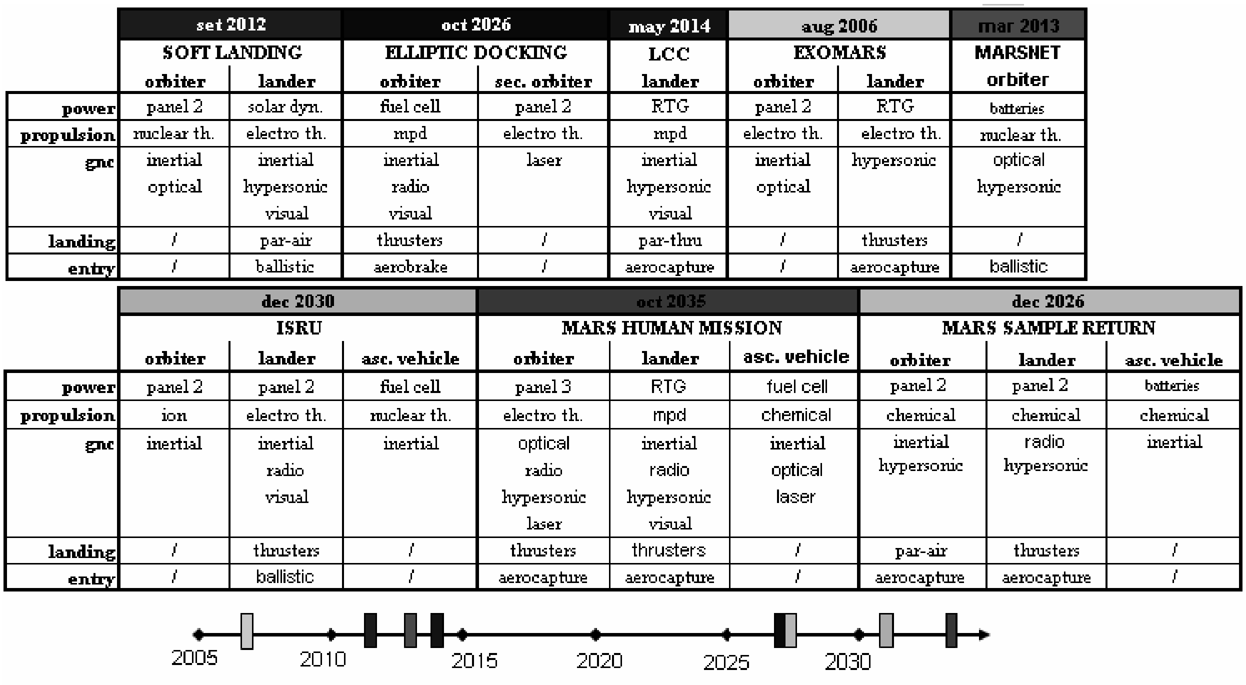


Fig. 2: Distribution of the dominant solutions with respect to their distance from the utopia point

This design philosophy requires the exploitation of the whole scheduling horizon, waiting for the technologies availability and for the space tests to be completed, in order to carry out the planning in the safest possible way. Moreover this approach does not reject some technological innovation, gaining a rather high TDI coefficient. As it was stated during the validation phase, while dealing with the Apollo program, there are strong limitations connected to the reliability of the minimum time criterion when assumed as the design-driver of feasible plans. Taking advantage of these results, as well as becoming aware of the excessive power of that criterion upon the multi criteria optimization, the designer should prefer those regions that privilege the remaining three criteria, and consequently should avoid all the solutions coinciding with the minimum realization-time as well as the “knee” itself.An alternative planning philosophy is the one focused on the achievement of the richest technological draw-back. In that case the program tends to distribute its missions on a wide period of time, exploiting the scheduling horizon until its latest available launch dates; as it repetitively adopts highly innovative technologies which require an appropriate period to be first studied than activated through their former employment. Moreover it undergoes a clearly logical key-steps development to balance the uncertainty effect connected to the innovations introduced: the available arrows are always scheduled ahead of those milestones that most benefit from them. By checking the position in the objective space of this planning, it results that the uncertainty level is remarkable despite the large waste of economic resources.



	set 2012		oct 2026		may 2014	aug 2006		mar 2013
	SOFT LANDING		ELLIPTIC DOCKING		LCC	EXOMARS		MARSNET
	orbiter	lander	orbiter	sec. orbiter	lander	orbiter	lander	orbiter
power	panel 2	solar dyn.	fuel cell	panel 2	RTG	panel 2	RTG	batteries
propulsion	nuclear th.	electro th.	mpd	electro th.	mpd	electro th.	electro th.	nuclear th.
gnc	inertial optical	inertial hypersonic visual	inertial radio visual	laser	inertial hypersonic visual	inertial optical	hypersonic	optical hypersonic
landing	/	par-air	thrusters	/	par-thru	/	thrusters	/
entry	/	ballistic	aerobrake	/	aerocapture	/	aerocapture	ballistic

	dec 2030			oct 2035			dec 2026		
	ISRU			MARS HUMAN MISSION			MARS SAMPLE RETURN		
	orbiter	lander	asc. vehicle	orbiter	lander	asc. vehicle	orbiter	lander	asc. vehicle
power	panel 2	panel 2	fuel cell	panel 3	RTG	fuel cell	panel 2	panel 2	batteries
propulsion	ion	electro th.	nuclear th.	electro th.	mpd	chemical	chemical	chemical	chemical
gnc	inertial	inertial radio visual	inertial	optical radio hypersonic laser	inertial radio hypersonic visual	inertial optical laser	inertial hypersonic	radio hypersonic	inertial
landing	/	thrusters	/	thrusters	thrusters	/	par-air	thrusters	/
entry	/	ballistic	/	aerocapture	aerocapture	/	aerocapture	aerocapture	/

Fig. 3: Planning, solution of the problem subjected to 4 criteria: the minimum uncertainty solution

FINAL REMARKS

At the end of this study, it can be inferred that the long term space scheduling embodies a complex issue, whose solution requires the construction of a suitable logical scheme, the employment of various investigation techniques as well as the development of dedicated tools and models. Despite this, dealing with such a complex subject is, without doubt, essential for the development of the forthcoming space programs, and so it becomes necessary to assemble an adequate tool focused on this aim.

The main result obtained consists in having built a logical structure which is useful for relieving the designers’ task, in terms of reducing the enormous number of possibilities to a restricted group of plans representing alternative, equally optimal philosophies. The suggested architecture possesses general and modular features, in order to cover the whole of the possible scenarios and the heterogeneity of the information connected to the development of preliminary plans. To deal with this peculiar working scenario, it has been necessary to elaborate some dedicated models to evaluate the most relevant aspects. Once stated these objective features, the control variable vector has been formalized as a sequence of missions described by their launch date and by the high level configuration of their modules.

A dedicated algorithm has been encoded for handling the optimization process compatible with the complex formalization required to describe a preliminary study plan. The main difficulties involved in this process derive either from the inhomogeneous nature of the control variables or from the strong correlations among them. As a consequence, in order to accomplish an evolutionary process, a clearly innovative reproduction strategy is suggested to better explore the search space. During

the development of this study, really different plans, such as Gemini, Apollo and Aurora programs, have been treated, though supporting the generality of the suggested solving method. Although these two first applications mainly deal with historical reviews to assess the method's performances, the last one is intended to find possible solutions for a still opened issue, providing some optimal and alternative preliminary plans. The achievement of significant results for all the three scenarios explored, demonstrates that it is possible to study the long term space program problem through a global and automatic approach. Moreover this method is believed to be the right way to lead the designer to the real optimum problem solution. Concerning the aspects shown so far, the forthcoming development for the present research is the realization of the elements needed to close the logical scheme, in order to generate detailed solutions. It is advisable to further develop and refine the adopted models to increase the final accuracy and generality. Furthermore, an approach with number and type of missions unlocked could be considered. The mission objective would become the input so that milestones and arrows domains would also be built in an autonomous way. Hence every task set by the user, instead of being concentrated in only one mission, could be distributed over different missions. Finally, launch window management could be introduced improving the physical reality modelling which is currently poor.
Progress in these directions will achieve an high quality and versatile tool, extending its application possibilities beyond space planning *strictu sensu*.

REFERENCES

[1] AURORA PUBLIC DOCUMENTS, ftp://ftp.estec.esa.nl/pub/aurora/

[2] WILLIAM DAVID COMPTON, "Where No Man Has Gone Before: A History of Apollo Lunar Exploration Missions", The NASA History Series NASA SP-4214 - 1989

[3] BARTON C. HACKER, JAMIES M. GRIMWOOD, "On the Shoulders of Titans: A History of Project Gemini", The NASA History Series NASA SP-4203 - 1977

[4] BENOIT GODIN, "The Emergence of Science and Technology Indicators: Why Did Governments Supplement Statistic With indicators", Project on the History and Sociology of S&T Statistics – Paper No. 8 – 2001

[5] ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT, "The measurement of scientific and technological activities using patent data as science and technology indicators", Paris 1994

[6] JOHN C. MANKINS, "Technology readiness level – a white paper – April 6, 1995", Advanced Concept Office – Office of Space Access and Technology – NASA

[7] RALPH R. BASILIO, KIM S. PLOURDE, "A Systematic Risk Management Approach Employed on the CloudSat Project", JPL – Pasadena, California

[8] Dr. MICHAEL STAMATELATOS, "Probabilistic Risk Assessment: What Is And Why Is It Worth Performing It?", NASA Office of Safety and Mission Assurance

[9] "NASA Cost Estimating Handbook 2004", http://ceh.nasa.gov/webhelpfiles/Cost_Estimating_Handbook_NASA_2004.htm

[10] CHARLES D. HUNT, MICHEL O. VAN PELT, "Comparing NASA and ESA Cost Estimating Methods for Human Missions to Mars", Proceedings of ISPA 26th Annual Conference, May 2004

[11] MATTHIAS EHRGOTT, XAVIER GANDIBLEUX, "An Annotated Bibliography of Multiobjective Combinatorial Optimization", Report in Wirtschaftsmathematik Nr 62/2000, April 2000

[12] CARLOS COELLO, "An Updated Survey of GA-Based Multiobjective Optimization Techniques", ACM Computer Surveys 1998

[13] E. ZITZLER, K. DEB, L. THIELE, "Comparison of Multiobjective Evolutionary Algorithms: Empirical Results", Evolutionary Computation, Vol. 8, No. 2, 2000

[14] K.C. TAN, E.F. KHOR, T.H. LEE, Y.J. YANG, "A Tabu-Based Exploratory Evolutionary Algorithm for Multiobjective Optimization", Artificial Intelligence Review 19: 231-260, 2003