A Traffic Model for the International Space Station: An MIP Approach[1]

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Abstract

The International Space Station poses very challenging issues from the logistic point of view. Its on-orbit stay is to be significantly extended in the near future and ever increasing experimental activity in microgravity is expected, giving rise to a renewed interest in the related optimization aspects. A permanent logistic support is necessary to guarantee its operational working, as well as the performing of the scientific activity on board. A traffic model, based on a Mixed Integer Linear Programming (MIP) approach, has been adopted to carry out the requested logistic planes. It is discussed in this chapter providing some insights concerning the topical applicative context.

Keywords: International Space Station (ISS) logistic support/plan, European Automated Transfer Vehicle (ATV), traffic model, on-board resource re-supply, Mixed Integer Linear Programming (MIP) approach.

1. Introduction

A major space venture the entire world has been witnessing in the last three decades is undoubtedly represented by the International Space Station (ISS, http://www.nasa.gov) program, conducted by the space agencies of USA (NASA), Russia (RKA), Europe (ESA), Japan (JAXA) Canada (CSA) and Italy (ASI): http://www.nasa.gov, http://www.roscosmos.ru, http://www.esa.int, http://www.jaxa.jp, http://www.asc-csa.gc.ca, , http://www.asi.it/en).

The worldwide space environment, involving both national agencies and the whole topical industry, is currently showing a renewed interest in the ISS as its dismantling is nowadays expected

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to be put off quite significantly into the near future. Regardless of a secure prediction about the precise time the event will actually occur, the growing momentum is ever more evident, aimed at taking advantage of this new opportunity as much as possible, with its expanding horizons for Science and Technology.

This prospective scenario determines a direct influence on two different fronts, i.e. the one of the research and that of the technological support. The first is expected to look into new and promising perspectives in the microgravity experimental field, while the second will be asked to provide a significantly improved capability to carry out the requested on-board activity suitably, certainly expected to give rise to challenging issues of cost-effectiveness and benefit maximization at the same time. The logistic support optimization becomes, as an obvious consequence, a major goal determining the necessity to adopt the cutting-edge methodologies available on-the-shelf day after day.

Benefiting from its optimization expertise in support to space logistics and flight operations, in the recent past, Thales Alenia Space has achieved, on ESA funding , an ad hoc traffic model (Fasano 1996, Fasano and Provera 1997), to look into the contribution effect, on the overall ISS scenario, of the European Automated Transfer Vehicle (ATV, http://www.esa.int), within the frame of the already existing international fleet of vehicles.

The traffic model has been achieved by adopting a Mathematical Programming approach. A Mixed Integer Programming (MIP) formulation has been followed, representing the problem in terms of a *Lot Sizing* type (see for example W. van den Heuvel, 2010), in the presence of additional constraints. Different versions of the same basic mathematical model have been taken into account, depending on the specific optimization criterion relevant to the current analysis to implement, as well as on the time scale under consideration.

In this chapter, Section 2 describes the ISS logistic plan problem that appeared when the ATV introduction was under study, pointing out the operational constraints, posed both by the ISS configuration, its orbit-keeping requirements and launcher/vehicle characteristics. Section 3 is dedicated to the relative mathematical formulation, while Section 4 gives some insight on the applicative context.

A possible extension of the present traffic model asset is going to be investigated thoroughly, to provide an upgraded analysis environment up to looking into the ever more challenging logistic problems the ISS is foreseen to give rise to in the near future. We are, moreover, quite confident that the approach we are currently putting forward to support the prospective ISS logistic plans will offer a valuable methodological starting point to win the paramount challenge the future manned and unmanned interplanetary missions are to give rise to.

2. The ISS logistic support and the traffic problem

The ISS is a large infrastructure, basically consisting of pressurized elements, such as crew quarters, laboratories, nodes and service modules; a truss accommodating external locations for experiments, solar panels and radiators. It also provides facilities to allow externally-mounted equipment to perform observation (stars, Sun and Earth) and environmental monitoring operations. It is permanently human tended (6-7 crew-members) ensuring shirtsleeve environment to perform scientific and technological experiments in microgravity conditions. The relative operational orbit must always be included between 410 and 450 km altitude.

The permanent human presence aboard the ISS, maintaining its standard operational conditions, the willingness to exploit the microgravity conditions, as much as possible, to perform scientific experiments, the requirement of keeping the allowed orbital altitude and the very limited resource availability have led to the necessity of a continuous flow of materials, hardware and fluids from Earth to space and vice-versa.

The overall operational scenario generated by the ISS maintenance and utilization demand thus determines the necessity of optimizing, time after time, the logistic plans, based on different time scales, with the further capability to afford last minute updating and quick re-arrangements.

A first very demanding issue concerns the on-orbit resource re-supply, in order to permanently guarantee the crew a habitable environment and provisions, to execute the requested payload (i.e. experimental facility) operations, as well as to perform the ISS overall maintenance. In addition to this, a periodical on-orbit intervention is requested to achieve recurrent re-boosting operations to maintain the ISS orbit altitude within its admissible range, since, owing to the atmospheric drag, it tends continuously to decrease. All this implies an accurate upload/re-boosting plan, while a download one is, on the other side, expected to retrieve the experimental material to post-process on the ground and to collect the trash produced on board that has either to be returned to Earth or destructively de-orbited in the atmosphere.

The re-supply material uploaded to the ISS is generally indicated either as *pressurized*, when transported in a vehicle that ensures a pressurized environment for the load, or *unpressurized*, when it does not provide any pressurization, while the third category of upload cargo is represented by the fuel. The download cargo consists both of experimental material and trash.

A fleet of launchers and vehicles is available to provide the ISS with the requested logistic support, including the re-boosting capability. Different launchers are associated to the vehicles and the resulting transportation systems differ from each other with respect to their specific characteristics. Several aspects have to be taken into account such as the necessary equipment allowing the crew transportation, the maximum reachable altitude, the possibility to return cargos to Earth, the maximum upload and download capacity, the minimum elapsed time between two subsequent launches, the maximum admissible number of flights per year, as well as the maximum on-orbit stay time.

Strong impacts on the overall planning task come further up, as the payload operations under microgravity conditions must be nominally guaranteed for at least a minimum number of periods per year and this puts constraints on the minimum elapsed time between one launch and the following one. And, in addition to all this, tight safety requirements have to be posed. In case of skipped vehicle arrival, for whatever reason, such as a missed rendezvous, the ISS has, as a matter of fact, to survive up to the next possible launch. This determines at least the provision of the necessary crew re-supply and the fuel amount to guarantee the contingency re-boosting intervention (by activating the on-board motors).

The ISS itself introduces mandatory constraints deriving from its configuration: the quite limited on-board re-supply capacity for each kind of resource and the capability to allow the simultaneous presence of different cargo carriers, strictly depending on the current docking location available on board.

It is even too obvious that the problem to tackle, owing to its extremely high complexity, in terms of variables and constraints to satisfy at the same time, as well as the necessity to perform the requested analysis swiftly and efficiently, cannot be faced with a paper-and-pencil approach.

The traffic model is up to accomplishing this task successfully by determining, for each given analysis period, a logistic plan, optimized with respect to a selected criterion, relevant to the current scenario to look into.

Its specific scope is that of defining:

- The earth-to-orbit vehicle launch and departure times;
- The cargo each earth-to-orbit vehicle has to deliver and return, for each load typology (including the trash);
- The activation time and duration of the re-boosting phases, the vehicle to utilize and the relative orbit altitude retrieval;
- The on-board resource availability time profile (in particular the final state), for each resource typology;
- The on-board trash accumulation time profile (in particular the final state);
- the ISS altitude time profile (in particular the final state).

The target of the analysis, time after time under study, may focus on different aspects. One in particular could address the definition of feasible operational scenarios at a minimum cost, but several others can be adopted as well, in order to better fit the perspective to look into, allowing, moreover, the comparison of different solutions.

The ISS operational scenario depicted hereinafter refers to the overall situation occurring when the issue concerning the ATV vehicle introduction, as additional transportation means for the already existing fleet, was under consideration. The relative framework is still mainly representative of the situation nowadays, but significant changes and enhancements have to be foreseen from now on, in a perspective of an ever more effective exploitation of the ISS activity.

As mentioned beforehand, the traffic model we are to discuss in this chapter has been purposely developed to provide ESA with the capability of investigating the operational scenarios deriving from the introduction of the ATV vehicles among the preexisting fleet. Such a relative late insertion encompassed, as a matter of fact, several issues.

A traffic model had indeed already been sketched by NASA (Boeing 1996), with flight predictions both for NASA and RKA vehicles. The introduction of the ATV within quite a consolidated scenario had to prove not to represent a jeopardizing factor, but an actual improvement of the previous state.

Different prospective ATV missions had to be considered, in order to tailor properly the vehicle features with respect to the expected ISS needs. The candidate missions should contemplate different cargo capabilities typologies, such as: the delivery of *unpressurized* cargo only; the delivery of *pressurized* cargo only; the delivery of re-boosting fuel only; the delivery of a mix of *pressurized*/*unpressurized* cargo and re-boosting fuel.

The ATV design should have been goal oriented, depending on the expected vehicle contribution to the ISS, both in terms of mission typology and quantitative support, so that the possible partition between the *pressurized/unpressurized* cargo and fuel had to be defined suitably.

As the ISS program was already in a phase where changes in earth-to-orbit vehicle performances and parameters, as well as in logistic requirements happened quite often, the need to reiterate the analysis process at a very high rate was understood.

3. The Mathematical Model

The traffic problem described in the previous session can be considered in terms of optimal control. From this point of view, the state variables represent the resource and trash accumulated on board at any time, as well as the ISS altitude, while the upload/download mass and the re-boosting activity correspond to the control variables. All of them are subject to the transportation and operational constraints implied by the vehicle characteristics, the ISS storage capacity and maintenance requirements.

The topical formulation can then be carried out by introducing a set of mathematical sub-models governed by a state (vectorial) equation as the following:

$$\frac{ds}{dt} = f[s(t),t],$$

defined on each sub-interval $[t_j, t_{j+1}]$ ($j \in \{0, \dots, n-1\} = J$) the overall analysis period $[0,T]$ is partitioned into; the terms t_j are (control) variables, representing the times (instants) when the control actions (i.e. upload, download and re-boosting) $u_0, \dots, u_{n-1}$ are taken; $t_0=0$ and $t_n=T$). The vector s(t) represents the state variables (functions of the time t) while, for each sub-interval $[t_j, t_{j+1}]$, the initial conditions below are stated:

$$s(t_j) = s_j + u_j,$$

meaning that the state s_j, of $s(t)$ at the end of the previous sub-interval $[t_{j-1}, t_j]$, is (instantaneously) modified by the control action associated to the vector (control) variable u_j. For each $t \in [0,T]$ and $j \in J$, lower and upper bounds are further imposed on the state variables:

$$\underline{S} \leq s(t) \leq \overline{S},$$

while further conditions encompassing launch windows, vehicle availability, cargo capacity act as additional constraints for the control variables.

An objective function with the following general form is then defined:

$$min_{t_1,\dots t_{n-1};u_0,\dots u_{n-1}}\{\sum_{j=0}^{n-1}\int_{t_j}^{t_{j+1}} p[\,s(t),u_j,t\,]\,dt+q(t_1,\dots,t_{n-1},u_0,\dots,u_{n-1},s_n)\},$$

where the functions p and q have to be specified, depending on the optimization criterion selected (e.g. integral averages), and the (vector) variable s_n represents the system final state at time T.

The approach described (in a simplified form) hereinafter is nonetheless based on a discretization of the variables, constraints and objective function, based on the total time period partition into n sub-intervals (still denoted as $[t_j,\ t_{j+1}]$) of prefixed duration (e.g. Tabak and Kuo 1970). This approach is quite suitable to deal with both decisional and integer variables, implicitly included in the problem. In such a way the original problem assumes the typology of a *Lot Sizing* one, in the presence of additional constraints. As a matter of fact, from the logistic point of view, the ISS can be essentially interpreted as a warehouse, with given storage capacity for each type of goods to consider; the resource consumption and the orbit altitude, as the customer demand for each sub-period, the earth-to orbit vehicles as the transportation means employed, with given load capability for each type of product. In the following all the variables involved are assumed as non-negative.

The state equations concerning the on-board resources (excluding the fuel) are described here below:

$$\forall\alpha\in A,\forall j\in J\qquad r_{\alpha(j+1)}=r_{\alpha j}-D_\alpha+\sum_{i\in I}r^*_{\alpha ij}\,,\tag{1}$$

where the variables $r_{\alpha j}$ represent, for each $\alpha\in A$ (set of resource typologies), the amount of the relative resource at time j; D_α the resource α demand per time interval, assumed as positive constant and $r^*_{\alpha ij}$ the resource α quantity transported on board by the vehicle $i\in I$ (set of vehicles) at time j.

Similar equations hold for the amount of trash (waste) present on-board:

$$\forall j\in J\qquad w_{j+1}=w_j+\sum_{\alpha\in A}Q_\alpha-\sum_{i\in I}w^*_{ij}\,,\tag{2}$$

where Q_α , assumed as a positive constant, stands for the trash accumulation per time interval deriving from each resource α, and $w^*_{\alpha ij}$ the trash quantity downloaded by vehicle *i*, at time *j*.

As far as the re-boosting activity is concerned, the question is quite tricky, as two different kinds of fuel have to be taken into account. The first can be utilized by the vehicles to perform a re-boosting action, but has also to be stored on board, always guaranteeing a minimum level, in order to provide the ISS with the necessary attitude control and be available, as possible reserve, to operate re-boosting intervention (by the ISS motors), in case of contingency. In the following, it shall be called *extended-use* fuel and denoted as $\hat{f}$. The second one, on the contrary, can only be utilized by a vehicle in a (nominal) re-boosting phase. It is denoted as re-boosting fuel and referred to as *f*. The following equations are then stated for both fuels respectively:

$$\forall j \in J \qquad \hat{f}_{j+1} = \hat{f}_j - C_j + \sum_{i \in I} \hat{f}^*_{ij} - \sum_{i \in I} \hat{u}_{ij}, \tag{3}$$

$$\forall i \in I, \forall j \in J \qquad f_{i,j+1} = f_{ij} + f^*_{ij} - u_{ij}. \tag{4}$$

In equations (3), referring to the *extended-use* fuel, for each time j, C_j is the consumption per time interval due to the (nominal) attitude control; $\hat{f}^*_{ij}$ is the amount uploaded by vehicle *i* and $\hat{u}_{ij}$ is the quantity utilized by vehicle *i* for re-boosting purposes.

In equations (4), referring to the re-boosting fuel, for each time *j*, f^*_{ij} is the amount uploaded by vehicle *i* and u_{ij} is the quantity utilized by vehicle *i*, at time *j*, for re-boosting purposes. These equations are stated to take account of the quantity of fuel stored on board the vehicles temporarily docked at the ISS and their relative utilization for re-boosting activity during all periods (time intervals) of permanence as attached modules.

The equations here below address the ISS altitude trend […]

As mentioned in the previous session, moreover, the ISS orbit altitude must be included, at any time, within a given range, as this is implied by the lower and upper bounds below:

$$\forall j \in J \quad \underline{H} \le h_j \le \overline{H}. \tag{8}$$

The above conditions, indirectly, in addition to the ISS attitude control requirements, give rise to the following constraints relative to the *extended-use* fuel available on board that must hold at any time:

$$\forall j \in J \quad \hat{f}_j \ge \underline{\hat{F}}. \tag{9}$$

Upper limits on the ISS on-board storage capacity are given, taking into account the possible presence of attached vehicles during the whole time sub-interval $[t_j, t_{j+1}]$. The 0-1 (indicator) variable σ_{ij} is then introduced, with the following meaning:

$\sigma_{ij}=1$ if vehicle i is attached during the sub-interval $[t_j, t_{j+1}]$
(at least at t_j),
$\sigma_{ij}=0$ otherwise.

The following upper bounds are then stated to take into account, at any time, the on-board storage capacity for each resource typology:

$$\forall \alpha \in A, \forall j \in J \quad r_{\alpha j} \le \overline{R}_\alpha + \sum_{i \in I} R^*_{\alpha i} \sigma_{ij}, \tag{10}$$

where $R^*_{\alpha i}$ is the maximum quantity of mass relative to each resource type α that can be loaded (i.e. stored on orbit) by vehicle *i*. Similarly, the following conditions hold, with an obvious meaning of the symbols introduced:

$$\forall j \in J \quad w_j \le \overline{W}_\alpha + \sum_{i \in I} W^*_{\alpha i} \sigma_{ij}. \tag{11}$$

And analogously, the constraints below are posed concerning the *extended-use* fuel stored on board:

$$\forall j \in J \qquad \hat{f}_j \leq \overline{\hat{F}} + \sum_{i \in I} \hat{F}_i^* \sigma_{ij} , \tag{12}$$

where $\overline{\hat{F}}$ is the maximum fuel loadable by the ISS and $\hat{F}_i^*$ is the maximum loading capacity relative to vehicle *i*.

For similar reasons, the following conditions are added, with an obvious meaning of the symbols:

$$\forall i \in I, \forall j \in J \qquad f_{ij} \leq F_i^* \sigma_{ij} . \tag{13}$$

A threshold relative to the overall mass loaded, at any time, on the ISS, including the fuel of the vehicles temporary attached, obviously has to be considered and this is achieved by posing the following constraints (based on a rough approximation):

$$\forall j \in J \qquad \sum_{\alpha \in A} r_{\alpha j} + \hat{f}_j + \sum_{i \in I} f_{ij} + \sum_{\beta \in B} e_{\beta j} + w_j \leq M . \tag{14}$$

To control the launch and return activities, as well as their relative upload and download actions, the following 0-1 variables are further introduced, with their corresponding logical meanings:

$\lambda_{ij}=1$ if vehicle i is launched (and reaches the ISS) at time *j*,
$\lambda_{ij}=0$ otherwise;
$\rho_{ij}=1$ if vehicle i performs its re-entry from the ISS at time *j*,
$\rho_{ij}=0$ otherwise.

A number of constraints have then to be considered, in order to take into account the upload capability relative to the utilization of each vehicle. As a first step, it has to be pointed out that a maximum altitude limit $H_i \in [\,\underline{H}, \overline{H}\,]$ is associated to each vehicle *i*. The constraints below are then introduced to guarantee that, if, at a certain time *j*, the ISS altitude is higher than the limit associated to a vehicle, it cannot be launched within the corresponding sub-interval:

$$\forall i \in I, \forall j \in J \qquad \lambda_{ij} \leq 2 - \frac{h_j}{H_i}. \tag{15}$$

A further set of constraints, whose meaning is obvious, involves both the launch, re-entry and on-board stay decisional variables. It is reported here:

$$\forall i \in I \qquad \sum_{j \in J} \lambda_{ij} \leq 1, \tag{16}$$

$$\forall i \in I \qquad \sum_{j \in J} \rho_{ij} \leq 1, \tag{17}$$

$$\forall i \in I, \forall j \in J \qquad \sigma_{ij} \geq \lambda_{ij}, \tag{18}$$

$$\forall i \in I, \forall j \in J \qquad \sigma_{ij} \geq \rho_{ij}, \tag{19}$$

$$\forall i \in I, \forall j \in J / j \geq 1 \qquad \sigma_{ij} \leq \sum_{j' \leq j-1} \lambda_{ij'}, \tag{20}$$

$$\forall i \in I, \forall j \in J / j \geq 1 \qquad \sigma_{ij} \leq 1 - \sum_{j' \leq j-1} \rho_{ij'}, \tag{21}$$

$$\forall i \in I, \forall j \in J / j \geq 1 \qquad \sigma_{ij} \geq \sum_{j' \leq j} \lambda_{ij'} - \sum_{j' \leq j-1} \rho_{ij'} + \Lambda_i, \tag{22}$$

where Λ_i is a parameter equal to one, if at the initial time *(t=0)* vehicle *i* is attached to the ISS and zero otherwise.

The following constraints express the conditions that if, at time *j* the vehicle *i* is not launched, its cargo overall capacity is null:

$$\forall i \in I, \forall j \in J \qquad \sum_{\alpha \in A} r^*_{\alpha ij} + \hat{f}^*_{ij} + f^*_{ij} \leq M_i \lambda_{ij}, \tag{23}$$

where M_i is the maximum mass capacity associated to vehicle i, corresponding to the altitude $\underline{H}$ (i.e. the minimum admissible). When vehicle i is, however, supposed to reach a higher altitude, its maximum capacity decreases (as a rough approximation) linearly, with rate K_i (>0). The following constraints are then posed (they become redundant when the corresponding λ_{ij} is zero):

$$\forall i \in I, \forall j \in J \qquad \sum_{\alpha \in A} r^*_{\alpha ij} + \hat{f}^*_{ij} + f^*_{ij} \le M_i - (h_j - \underline{H})K_i \tag{24}$$

Considering the different loading capacity characteristics, with reference to each single cargo typology, the following constraints are then stated (with obvious meaning of the symbols):

$$\forall \alpha \in A, \forall i \in I, \forall j \in J \qquad r^*_{\alpha ij} \le R^*_{\alpha ij}\lambda_{ij} \tag{25}$$

$$\forall i \in I, \forall j \in J \qquad \hat{f}^*_{ij} \le \hat{F}^*_i \lambda_{ij}, \tag{26}$$

$$\forall i \in I, \forall j \in J \qquad f^*_{ij} \le F^*_i \lambda_{ij}. \tag{27}$$

Furthermore, since the vehicles have generally a limited *pressurized* cargo capacity, the following constraints hold:

$$\forall i \in I, \forall j \in J \qquad \sum_{\alpha \in A'} r^*_{\alpha ij} \le M'_i \lambda_{ij}, \tag{28}$$

where $A' \subset A$ is the sub-set of *pressurized* resource typologies and M'_i is the relative loading upper bound, corresponding to vehicle *i*.

[…]

As far as the **objective function** is concerned, and coming back to what already mentioned in the previous session, different choices can be made, depending on the specific analysis task under consideration. We report here one of the possible ones that showed to be quite useful at a preliminary level, when some of the characteristics both of the ISS and even the main ATV features, such as for instance the load capacity relative to the different cargo typologies, were not yet consolidated. To this purpose some of the model constraints were relaxed, by introducing (non-negative) slack variables representing the relative constraint violation. The corresponding version of constraints (23), for instance, assumes then the form:

$$\forall i \in I, \forall j \in J \qquad \sum_{\alpha \in A} r^{*}_{\alpha ij} + \hat{f}^{*}_{ij} + f^{*}_{ij} \le M_i \lambda_{ij} + \tilde{m}_{ij}, \tag{36-1}$$

$$\forall i \in I, \forall j \in J \qquad 0 \le \tilde{m}_{ij} \le \tilde{M}_i \lambda_{ij}, \tag{37-2}$$

where $\tilde{M}_i$ represents, for each vehicle i, the maximum relaxation admitted for the relative overall mass capacity. Since similar readjustments can obviously involve several other constraints of the model, the objective function, to be minimized, simply consists of the sum of the slack variables taken into account, time after time, on the basis of the current analysis task and properly weighted.

[…]

4. Applicative aspects

This session provides some information concerning the overall operational scenario, beginning from the state-of-the-art context to deal with when the traffic model was initially developed to investigate the ATV introduction within the preexisting vehicle fleet.

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The overall outcome of the analysis carried out to evaluate the possible contribution deriving from the ATV introduction within the previous fleet composition, can be summarized as follows.

The ATV mission that could better support the re-supply and return scenario was the one up to delivering to orbit the so called *mixed* cargo (*pressurised* cargo plus fuel).

The introduction of a properly designed ATV *mixed*-cargo vehicle resulted in being beneficial to the re-supply and return scenario, since such an ATV mission could replace two Progress-X missions or, alternatively, one single Progress-X, if higher resource re-supply capacity were required. This replacement would have alleviated the high Progress-X flight rate (from up to 7 missions per year to 5 missions per year) that was considered a potential criticality for the whole ISS program. Such a replacement was also beneficial with respect to the number of the extended microgravity periods.

An on-orbit stay of 4 months was considered the shortest period for a proper exploitation of the ATV utilization, while, on the contrary, a duration exceeding 6 months would have led to an overdesign of its pressurized module. The optimal share of cargo resulted in the following partition:

5000-6000 kg of *pressurized* cargo;
1000 kg of *extended-use* fuel;
3000-4000 kg of re-boosting fuel.

Several analysis scenarios were assessed thoroughly, focusing on different time scales, operational options and specific objective functions. Most of the cases proved to be quite challenging from the computational point of view. Instances dealing with an analysis period covering 1-3 years involved up to 100000 constraints, 150000 continuous variables and 3000 decisional variables (requesting, as order of magnitude, even more than 10 hours of computational time with a standard MIP-solver environment).

In the light of the prospective scenarios expected for the ISS exploitation, from now on, a new trend is rather oriented towards less precise, but quicker computational exercises, implying the development of a smart version of the previous traffic model. A dedicated research effort is hence currently ongoing, focusing both on the model formulation and MIP-strategy improvement. The reference frame for the experimental analysis under study consists essentially of the following environment, in terms of platform and

MIP solver: XP Professional Service Pack 2, Core 2 Duo P8600, 2.40 GHz, 1.93 GB RAM; IBM ILOG CPLEX Optimizer 12.3.

A case study, referring to the mathematical model currently under study, is shown hereinafter, to give essentially a qualitative representation of the result typologies.

The relative analysis covers a 3-year period, partitioned in 36 months (sub-intervals). Since most of the information concerning the near future scenarios is still quite uncertain, in particular with respect to the new fleet that is going to be set up, the previous one has been kept as basic reference, even if some of its transportation systems have already been dismissed (as the Shuttle, for example) or are quite close to their last mission (as the ATV).

The objective function consists of the sum of the two relaxation slack variables concerning the maximum ATV capacity associated to both kind of fuel. The relative model instance contains about 51000 rows, 17000 continuous and 1200 binary variables.

Some of the overall case study results (obtained in about 30 CPU minutes) are summarized by the tables reported here below. Table 4 illustrates the launch and re-entry plan for each vehicle considered (in several cases they remain on orbit for more than one month). Table 5 reports the ISS *pressurized* cargo (the light bars indicate *unprocessed* mass, while the dark ones the *processed* mass). Table 6 refers to the trash trend. Table 7 shows the fuel present on board the ISS (the light bars represent the external-use fuel, while dark ones indicate the re-boosting one). Table 8 illustrates the trend relative to the ISS altitude. Table 9 points out the upload/download provided by a single vehicle and Table 10 the gap between the initial and final ISS states, during the whole analysis period.

[…]

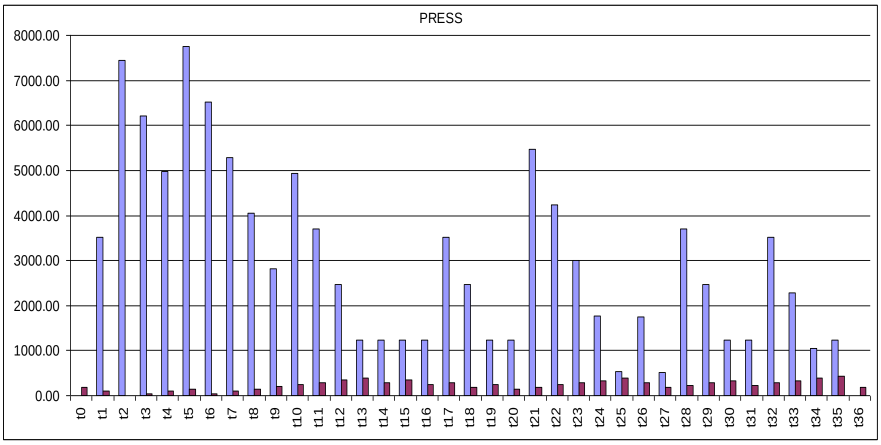

Table 5 - Case study ISS on-board pressurized cargo trend

Table 6 - Case study ISS on-board trash trend

Table 7 - Case study ISS on-board fuel trend

Table 8 - Case study ISS altitude trend

Table 9 - Case study upload/download provided by a single vehicle

Table 10 - Case study gap between initial and final ISS states

5. Conclusive remarks

This chapter has been devoted to the traffic problem that the International Space Station logistic issue has given rise to up to now and is expected to keep on yielding in the near future, with ever increasing complexity, as nowadays its dismantling plan has been put off significantly onward. In the recent past, the issue was looked into, in particular, by ESA when putting forward the introduction of the Automated Transfer Vehicle within the already existing international fleet of transportation systems, supposed to provide the International Space Station with the necessary logistic support. This very challenging problem has been successfully tackled by adopting a Mixed Integer Linear Programming model.

As the traffic problem embeds the flow of material to and from the ISS, as well as the sequence of missions of the various earth-to-orbit vehicles, including the re-boosting phases, the traffic model has been achieved in order to determine, for each given analysis period, an optimized logistic plan.

It has been discussed in this chapter, by giving a simplified version of its actual formulation and working out unnecessary details. It is to be properly updated/extended no sooner the ongoing operational scenario, including a new fleet, has been ultimately determined. Specific research is foreseen both from the modeling and computational strategy points of view. This chapter does not leave aside some applicative insights, useful to interpret the problem in its actual real-world framework.

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