Multidisciplinary Optimisation in Mission Analysis and Design Process

Executive summary

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1. INTRODUCTION

Aim of the Multidisciplinary Optimisation In Mission Analysis And Design Process study is to identify an efficient approach to tackle conflicts at different sub-systems levels, arising in space engineering during the whole design activity. This study focuses on a typical scenario that the system engineering has to deal with and is oriented to introduce an advanced Multidisciplinary Optimisation (MDO) methodology. Main scope of the study is to illustrate the conceptual aspects of the methodology and point out the applicability of the approach to a wide class of cases arising in space engineering.

The WATS (WAter vapour and temperature in Troposphere and Stratosphere) mission has been chosen as basic reference. This case study (see chapter 2) is described in a simplified form, in order to point out the conceptual aspects of the approach proposed. Technical engineering details that are not essential to understand the methodology have been deliberately neglected. The mission analysis, the power and the propulsion sub-systems have been selected as reference disciplines to simulate a realistic (even if simplified) space engineering environment.

A dedicated Multidisciplinary Optimisation approach is proposed (see chapter 3). It is based on a joint use of three methodologies: Neighbourhood Search, Game Theory and Multicriteria Decision Analysis. The Neighbourhood approach aims at finding (by means of a dedicated heuristics) a set of 'paretian' (non dominated) solutions at system level. The total number of such solutions could be extremely high. Then it becomes necessary to have efficient methods to reduce such number to a small subset of solutions to be considered “optimal” from the point of view of conflict reduction. The methods utilised are the Game Theory and the Multicriteria Decision Analysis. It is interesting to realise that such methods can work also without the set of paretian solutions given by the Neighbourhood approach. The input they require is simply a set of solutions, not necessarily paretian, which are considered feasible by the system engineer. This is the case that happens very often in practice. For this reason, the Game Theory and the Multicriteria Analysis methods have been applied to a possible feasible set of solutions of the WATS case study, bypassing the Neighbourhood approach.

A software prototype, considering all the three methodologies, has been developed to demonstrate the efficiency of the proposed method and the possibility to develop a general framework to solve a wide class of practical cases. The software prototype has been tested on a further illustrative case study, dealing with a simplified Mars mission (no three-dimensional orbital evolution is considered). The system engineering point of view is considered first and the utilisation of the software prototype is illustrated. Even if the case study considered is very simple, it shows that the proposed approach can be efficiently extended to a wide class of real cases and that the application of the methodology can be 'automated', by the development of such a framework.

2. WATS MISSION CASE STUDY

In this paragraphs the WATS mission case study is presented and it is shortly introduced in 2.1, while in 2.1.1 the reduced/tailored study logic, problem activity flow, trade-offs and conflicts of the WATS mission up to the level needed for the case study are shown.

2.1 PRELIMINARIES

The WATS mission has the aim of monitoring variations and changes in the global atmospheric water vapour distribution and winds in lower stratosphere and upper troposphere. It consists of a constellation of LEO satellites at 650 km and 850km altitude.

The following observations are performed:

- Refractivity profiles from radio occultation events exploiting the L-Band signals of the global navigation satellite system satellites.
- Refractivity and absorption profiles from LEO to LEO (Low Earth Orbit) cross-link occultation events using K-band signals emitted by each LEO for the derivation of water vapour absorption profiles

Radio occultation measurements allow the determination of transmitter to receiver ray path refraction in the atmospheric layers. Radio path refraction mainly depends on atmospheric physical properties. Due to the employment of radio frequency signals, bending angles are derived by Doppler shift in signal frequency with respect to the carrier. Refractivity of atmospheric layers can then be retrieved from the bending angle profiles. From this information, it is possible to derive pressure, temperature and humidity that are necessary for the study of water vapour distribution and winds. The measurements of radio occultation between the LEO satellites and GNSS (Global Navigation Satellite System) produce accurate information about the properties of stratosphere and external atmosphere layers. However, due to the absorption properties of lower troposphere layers, the achievable measurement results are inaccurate at the L-Band frequencies. The main problem of this zone is the dominance of oxygen absorption effect at frequencies lower than 10GHz. At the K-Band frequencies (LEO - LEO satellites occultation), the interaction between the electromagnetic field and the water vapour will be dominant, so more accurate data about lower troposphere structure and properties can be achieved.

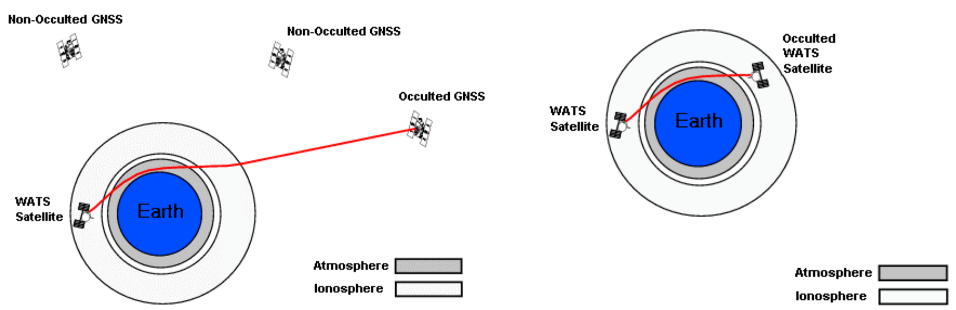


Figure 2.1-1: GNSS to LEO and LEO to LEO occultation concepts

The ESA (European Space Agency) stability and accuracy requirements in the experiment are reported in **Table 2.1-1**, while the ESA mission analysis requirements are reported in **Table 2.1-2**. Further information about WATS mission can be found in RD 2, RD 3, RD 4, RD 5 and RD 6.

Data type	Value
LEO-LEO minimal vertical atmospheric domain coverage	1km÷20km
GNSS-LEO minimal vertical atmospheric domain coverage	1km÷90km
GNSS to LEO cross-link bending angles measurement accuracy (single occultation)	10^{-6}rad
LEO to LEO cross-link bending angles measurement accuracy (single occultation)	10^{-6}rad
LEO to LEO cross-link amplitude attenuation measurement stability over 60 s (single occultation)	0.025dB
Baseline frequencies	10.3, 17.2 and 22.6GHz
Additional frequencies to be assessed	27.4 and 32.9GHz

Table 2.1-1: Measurement requirements

Data Type	Value
Number of occultation	LEO - LEO cross-links: ≥ 1600 events per day GNSS - LEO: > 6500 events per day (day = 24 hours period)
Spatial distribution	As homogeneous as possible within 24 hours period (i.e. aiming at an uniform density of events per unit area over the globe)
Temporal distribution	As homogeneously as possible within 30 days period in order not to create a diurnal bias (i.e. aiming at uniform density of events per unit local time)
Timeliness	At least 30% of the data should be available in near real time (2 - 3 hours)
Maximal Horizontal Atmospheric domain to be crossed during occultation	500 km
Baseline mission life time	7 years

Table 2.1-2: Mission analysis requirements

2.1.1 WATS Mission Case Study Logic

The WATS mission case study Logic is shown in
Figure 2.1-2. Where it is shown that, as requested by ESA, Mission Analysis and two subsystems (Power and Propulsion) had been chosen for the this case study. The relations among the subsystems and the Mission Analysis, through the spacecraft (S/C) configuration and with the feedback from Launch Strategy back to Mission Analysis are shown, as well. In
Figure 2.1-2: P/L means Payload, S/S means sub-system and ΔV is the Variation of Velocity of the Satellite.

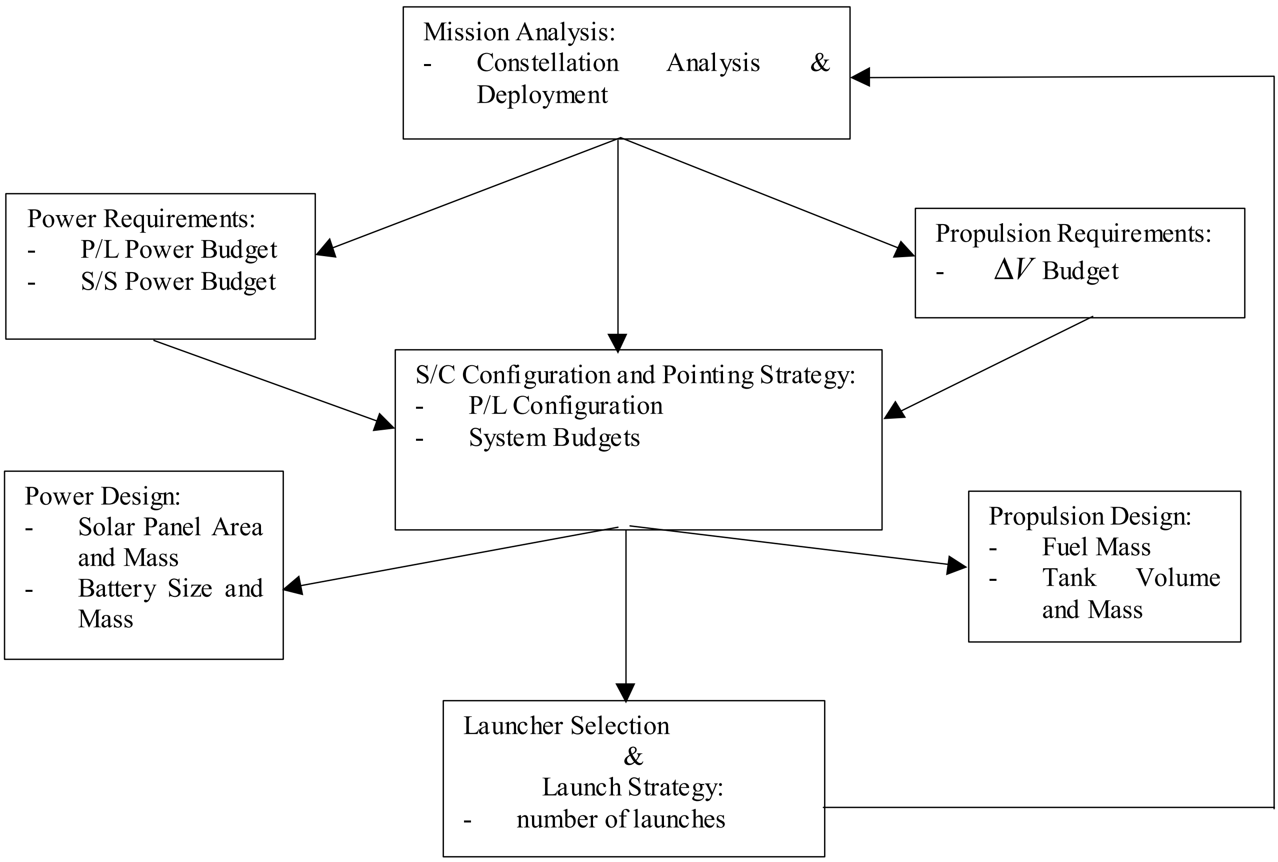


Figure 2.1-2 WATS Mission Case Study Logic

The WATS mission case study logic is a parallel representation of the WATS mission case study. In order to fully understand the activity flow related to
Figure 2.1-2, the WATS Mission Case Study Activity Flow and Trade-offs are shown, in a sequential way, in Table 2.1-3. It must be underlined that in this case study: the Event is the LEO to LEO occultation (see Figure 2.1-1). In Table 2.1-3: $\Delta\Omega$ is the Ascending Node Separation between the planes of the satellite orbits in the constellation and $\Delta\vartheta$ is the True Anomaly Separation among the satellite position on the orbits in the constellation. In
Figure 2.1-2 and in Table 2.1-3 are summarised all the Activities, Trade-offs, Constellation and Satellite Parameters, involved in the Trade-offs; as well as, Feedback check and flow that are exploited and described in 2.2.

- Mission Analysis
  - Constellation Analysis and Trade-offs:
    - number of Events:
      - number of Satellite
      - $\Delta\Omega$ Distribution
      - $\Delta\theta$ Distribution
  - Constellation Deployment and Trade-offs:
    - ΔV Budget:
      - Parking Orbit Analysis
      - Transfer Orbit Analysis
- S/C Configuration, Pointing Strategy and Trade-offs
  - Earth Pointing versus Sun Pointing:
    - P/L Configuration:
      - number of Antennas and of Receivers:
        - P/L Mass and Power
    - System Budgets:
      - Overall satellite Mass and Power budget:
        - Fuel Mass
        - Tank Volume and Mass
        - Solar Array Area and Mass
        - Battery Size and Mass
- Launcher Selection, Launch Strategy and Trade-offs:
    - Launcher Selection:
      - number of Launches

Table 2.1-3 WATS Mission Case Study Activity Flow and Trade-offs

It must be stressed that the main task of Mission Analysis and System Engineering activity is to find conflicts among the parts involved in this Case Study. That is why, the overall Case Study Logic and Activity Flow and Trade-offs, given in
Figure 2.1-2 and in Table 2.1-3, are summarised with the following two main conflicts:

1. Between number of Satellite and number of Launches: in order to lower as much as possible the number of launches and to rise as much as possible the number of satellite
2. Among Payload, Power Subsystem and Propulsion Subsystem: in order to have the Payload as simpler and lighter as possible, to have the power subsystem as simpler and lighter as possible and to have to propulsion subsystem as simpler and lighter as possible.

The 1st conflict leads to minimise as much as possible the mass budget of the satellite and drives the 2nd conflict with the request to find the minimum of the sum of the Payload, Propulsion and Power masses.

The 2nd conflict is through the S/C Configuration (Antennae Layout, Solar Array and Propulsion options) and Pointing Strategy (Earth Pointing vs Sun Pointing) as explained in following table.

Best	Worst
Power: Less Mass, Battery Volume and Solar Panel Area (Sun Pointing)	P/L: More Antennas and Receivers
Propulsion: Less Fuel Mass and Tank Volume and Mass (Earth Pointing without Attitude Manoeuvres)	Power: More Mass, Battery Volume and Solar Panel Area
P/L: Less Antennas and Receivers (Earth Pointing with Attitude Manoeuvres)	Propulsion: More Fuel Mass and Tank Volume and Mass

Table 2.1-4 2nd Conflict Explanation

2.2 PROCESS MODEL

The Process Model is the full set of equations, fixed parameters and input/output parameters that are needed to perform the analysis and trade off in order to manage the conflicts (see page 8) of WATS Mission Case Study and to find an optimised solution of them.

2.2.1 Mission Analysis

The scope of the mission analysis is to find the best distribution of satellite orbit parameters in order to "maximise" the number of events. A brief introduction to Occultation Theory and Characteristic is given in 2.2.1.1. Full explanation of the theory can be found in RD 7. In 2.2.1.1, all it is needed to fully understand following analysis and trade-offs it is summarised for reader's convenience.

2.2.1.1 Occultation Theory and Characteristics

The occultation event is computed for two satellites with position vectors $\vec{r}_i = r_i \vec{u}_i$ and $\vec{r}_j = r_j \vec{u}_j$. The distance d_{ij} (see Figure 2.2-1) from the origin O of the reference frame (Geocentric Equatorial Frame) and the straight line joining the apex of the vector $\vec{r}_i$ and apex of the vector $\vec{r}_j$ is given by:

(1)
$$d_{ij} = \frac{r_i r_j \sqrt{1 - \cos^2 \Delta_{ij}}}{\sqrt{r_i^2 + r_j^2 - 2 r_i r_j \cos \Delta_{ij}}}$$

while the co-ordinates of the point P_{ij} (see Figure 2.2-1) are the components of the vector $\vec{p}_{ij} = d_{ij} \vec{u}_{ij}$ (see Figure 2.2-1) from the centre of the Earth that is given by:

(2)
$$\vec{p}_{ij} = \frac{X_{ij} \vec{u}_i + \vec{u}_j}{\sqrt{1 + 2 X_{ij} \cos \Delta_{ij} + X^2_{ij}}} = d_{ij} \vec{u}_{ij}$$

where $X_{ij} = \frac{r_i \cos \Delta_{ij} - r_j}{r_j \cos \Delta_{ij} - r_i}$ and $\cos \Delta_{ij} = \frac{\vec{r}_i \cdot \vec{r}_j}{r_i r_j}$. There is an occultation event when $R_E < d_{ij} < R_E + h$, where R_E is the Earth Radius and h is given by instrument requirements.

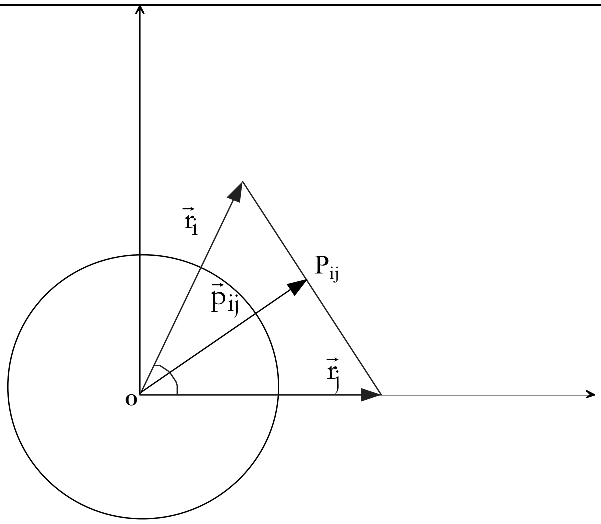


Figure 2.2-1 Geometry of the Occultation Event

Once the co-ordinate x, y and z of the point P_{ij} are known the latitude and longitude of the point event are given by:

$$\mathrm{Lat}_{ij} = a\sin(P_{ijz})$$

(3)

$$\mathrm{Long}_{ij} = a\tan\left(\frac{P_{ijy}}{P_{ijx}}\right) + \varpi_E (t - t_0)$$

Where ϖ_E is the Earth angular rate.

From the vector $\vec{p}_{ij}$ it is possible to calculate $\vec{p}\,'_{ij}$, that is the position of the point P_{ij} with respect to satellite i in the local reference frame PQW (see RD 9) centred in satellite i. Once the co-ordinate of the vector $\vec{p}\,'_{ij}$ are know the azimuth and elevation of satellite j with respect to satellite i are given by:

$$\delta_{ij} = a\sin(p'_{ijp})$$

(4)

$$\alpha_{ij} = a\tan\left(\frac{p'_{ijq}}{p'_{ijw}}\right)$$

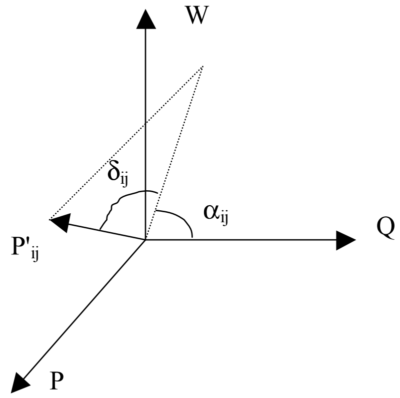


Figure 2.2-2 Azimuth and Elevation of satellite j with respect to satellite i

Equation 4 is needed in order to understand which is the statistic of the positions of the events within the satellite reference frame, this is needed to understand which is the better antennae layout of the satellite.

2.2.2 Power Subsystem

The scope of the Power Sub-system design is to size the solar array area and mass and to size the battery volume and mass.

2.2.2.1 Power theory and characteristics

The Power subsystem is defined by means of the following computations:

- From the power budget the Power Need (*PN*) from P/L and S/S is determined: *PN* [W]
- From the Eclipse Period (*EP*) and *PN* the Battery Energy Need (*BEN*) is determined:

$$BEN = PN \cdot EP \ \mathbf{[W \cdot h]} \quad (5)$$

- From Day Light Period (*DLP*) and *BEN* the Power Need for Battery Charging is determined (*PNBC*):

$$PNBC = \frac{BEN}{DLP} \ \mathbf{[W]} \quad (6)$$

- From *PN*, *PNBC* and Solar aspect ANgle (*SAN*) the Total Power Need (*TPN*) is determined:

$$TPN = \frac{PN + PNBC}{\cos\left(SAN \cdot \frac{\pi}{180}\right)} \ \mathbf{[W]} \quad (7)$$

- Once *TPN* and *BEN* are known, using the Specific Power and Energy parameters, the Solar Array area and mass and the Battery Volume and Energy are determined.

2.2.3 Propulsion Subsystem

The scope of the propulsion subsystem design is to size propellant mass and the propellant tank's mass and diameter.

2.2.3.1 Propulsion Theory and Characteristics

The Propulsion Subsystem is defined starting with the determination of the total variation of velocity ΔV [$m\cdot s^{-1}$]. The propellant mass m_p [kg] is computed from:

$$m_p = m_f \cdot \left[e^{\left(\frac{\Delta V}{I_{sp} \cdot g}\right)} - 1 \right] = m_o \cdot \left[1 - e^{-\left(\frac{\Delta V}{I_{sp} \cdot g}\right)} \right] \qquad (8)$$

where m_f [kg] is the final mass and m_o [kg] is the initial mass (w.r.t. the variation of velocity, i.e. the manoeuvre), I_{sp} [s] is the specific impulse of the propellant and g=9.80665 ms^{-2}.

Once the propellant mass has been computed the volume V_T [litres] and diameter D_T [m] of the tank can be obtained from:

- Monopropellant

$$V_T = \frac{m_p}{\rho_p} \text{ and } D_T = 2 \cdot \sqrt[3]{\frac{3}{4 \cdot \pi} \cdot V_T \cdot 10^{-3}} \qquad (9)$$

where ρ_p [$g\cdot cm^{-3}$]=[$kg\cdot liter^{-1}$] is the density of the propellant.

- Bipropellant

$$V_T = \frac{m_p}{\rho_1 + \rho_2} \text{ and } D_T = 2 \cdot \sqrt[3]{\frac{3}{4 \cdot \pi} \cdot \frac{V_T}{nT} \cdot 10^{-3}} \qquad (10)$$

where ρ_1 and ρ_2 are the density of the fuel and of the oxidiser and nT is the number of tanks (≥ 2). Previous equations are valid under the realistic assumption that the volume of the tanks is the same for both of them. In fact from $\rho_1 \cdot V_1 + \rho_2 \cdot V_2 = m_p$ with $V_1 = V_2 = V_T$ it follows **10** and that $m_1 = \rho_1 \cdot V_T$ and $m_2 = \rho_2 \cdot V_T$.

The tank mass m_T [kg] can be obtained from:

$$m_T = 0.1 \cdot m_P \qquad (11)$$

For a complete design of the propulsion subsystem, the propellant mass m_{attman} [kg] needed for attitude manoeuvres must be computed. That is:

$$\textbf{(12)} \quad m_{attman} = \frac{4 \cdot I_C \cdot \Theta_m}{T \cdot L_t \cdot g \cdot I_{sp}}$$

where Θ_m is the angle [radians] swept in time T [sec], I_C [kg·m²] is the Spacecraft moment of inertia about the control axis and L_t [m] the thruster lever arm about this axis.

2.2.4 Spacecraft Configuration and Pointing Strategy

The scope of the Spacecraft configuration and pointing strategy is to find the best layout of Satellite Sub-system and the best pointing strategy with respect to the total system resources.

The following topics are related to the S/C Configuration:

- Interplay between number of antennae and solar panel area and mass
- Interplay between number of antennae and fuel mass
- Interplay between fuel mass and solar panel area and mass
- System Budgets: Mass, Power and Volume

2.2.5 Launcher Selection and Launch Strategy

The scope of Launcher Selection and Launch Strategy is to find a suitable launcher in order to optimise the number of launches for the selected constellation deployment.

The following topics are related to the Launcher and Launch Strategy:

- minimum number of launches w.r.t. propellant need for constellation deployment

In order to minimise the number of launches the technique of using differential precession between orbits with different altitudes must be used for constellation deployment. This technique is used in order to phase the satellite in ascending node separation. The technique consists in launching clusters of satellite on a parking orbit. From that orbit, first of all, a satellite goes, with its own propulsion, to the nominal orbit; while, the other satellite of the cluster wait on parking orbit till the right ascending node separation had been reached. This, of course, costs because of the drag compensation needed on parking orbit. After the right ascending node separation had been reached each satellite by each goes to the nominal orbit with its own propulsion.

That is why, in order to optimise the number of launches, the time ΔT [day] needed to reach the desired Ascending Node Separation $\Delta\Omega$ [°] (see RD 9) among satellite's orbit planes has to be computed. For circular orbit (e = 0, see RD 9) it is obtained from:

(13) $$\Delta T \cong \frac{\Delta\Omega}{-2.06474\times10^{14}\cdot\left[a_P^{-\frac{7}{2}}-a_N^{-\frac{7}{2}}\right]\cdot\cos\left(I\cdot\frac{\pi}{180}\right)}$$

where a_P [km] is the positive axis of the Parking orbit, a_N [km] is the positive axis of the Nominal orbit, I [°] is the inclination of the orbit planes and $\Delta\Omega = \Omega_P - \Omega_N$ is the desired difference between the ascending node of the parking orbit and the ascending node of the nominal orbit (see RD 9). In order to compute the propellant need for constellation deployment the variation of velocity ΔV_D [km·s^{-1}] per orbit to compensate the orbit decay due to Drag force on parking orbit and the variation of velocity ΔV_T [km·s^{-1}] to reach the operational orbit had to be evaluated. They are obtained from:

(14) $$\Delta V_D = \pi\cdot\left(C_D\cdot\frac{A}{m}\right)\cdot\rho\cdot a\cdot V$$

where A [m²] is the satellite cross-sectional area, m [kg] is the satellite mass, ρ [g·m^{-3}] is the atmospheric density, a [km] is the positive axis and $V = 631.34812\cdot a^{-\frac{1}{2}}$ [km·s^{-1}] is the satellite circular velocity and

(15) $$\Delta V_T = \sqrt{\frac{\mu}{r_P}}\cdot\left[\sqrt{\frac{2\cdot\frac{r_N}{r_P}}{1+\frac{r_N}{r_P}}}\cdot\left(1-\frac{r_P}{r_N}\right)+\sqrt{\frac{r_P}{r_N}}-1\right]$$

where r_P [km] and r_N [km] are the radius of the parking and nominal circular orbit and $\mu = 3.986005\times10^5$ [km^3·s^{-2}] is the Earth Gravitational Parameter.

2.2.6 Constellation Analysis and Trade-offs

In order to find an optimised constellation a set of constellations had been studied with number of satellite starting from 4 and reaching 16, with a step of 4. For each constellation an uniform distribution of Ω and ϑ had been studied within the following interval $\Omega \in [0°, 360°]$ and $\theta \in [0°, 360°]$. The other parameters of the constellation had been fixed for the sake of simplicity without loosing reality of the found conflicts.

The optimised constellation is the one that satisfies the number of occultation events as much as possible with the minimum number of satellites and a suitable distribution of satellite orbits ascending Node (Ω) and satellite on orbits true anomaly (ϑ) (see RD 9).

- The following options can be considered for the Constellations Trade-off:
  - Satellite number
  - Satellite Ascending Node (Ω) separation and distribution
  - Satellite True Anomaly (θ) separation and distribution

For the sake of clarity it must be stressed that some requirements during the WATS phase A study (see RD 4) had ben traslated into index that had to be made as high as possible. One of them is the number of occultations. It can be seen at page 64 figure 6.3 of RD 4 that the number of LEO-LEO occultation events is far less than 1600. So we can say that the requirement on number of occultations is not a "Must" to be reached at any cost.

In Table 2.2-1, it is summarised the number of events as a function of the number of satellite.

Number of events	Number of satellite
93	4
410	8
1142	12
2029	16

Table 2.2-1 Number of Events w.r.t. Number of Satellite for the set of constellation

From Table 2.2-1, it is possible to see that the requirement of number of events ($\geq$ 1600) is met for a number of satellite between 12 and 16. As we already know that it will be difficult to deploy a constellation of more than 12 satellite both by the point of view of constellation deployment and overall mission complexity; an attempt to rise the number of events, for the constellation of 12 satellite, tuning (optimising) the Ω and ϑ distribution had been done. The complete results of this optimisation are given in the Final Report (RD 1). For what regarding the number of events, it had been found that with an optimised distribution of Ω and ϑ the 12 satellite constellation rises it from 1142 up to 1281. As the requirement of number of events $\geq$ 1600 is not a "Must" to be reached at any cost, the optimised constellation of 12 satellites can be considered the baseline for the remaining trade-offs to be solved at spacecraft and launcher level. What is important to be noticed, in the optimised constellation of 12 satellites, it is that $\Delta\Omega_{ij}$, between the satellite "i" and the satellite "j" with same altitude, is 30° (see RD 1)).

2.2.7 Spacecraft Configuration, Pointing Strategy and Trade-offs

Mission analysis output is that a constellation deployment with four launches of three satellite is quite feasible (see RD 1). This, in turn, leads to the attempt to limit the overall satellite mass either within 250 kg if a Rockot class launcher will be used or within 450 kg if a Tzyklon class launcher will be used (see RD 1). As first shot the Rockot launcher will be taken into account for the sake of lower cost. In the following trade-offs, it will exploited the attempt to have P/L, Power Subsystem and Propulsion Subsystem as simpler and as lighter as possible.

The following tasks will be considered:

- P/L:
  - (best) 1 receiver and not more than 6 antennae
  - (good) 1 receiver and 12 antennae (in order to have a 360° of azimuth coverage)
  - (worst) 3 receivers and 36 antennae (in order to have 360° of azimuth and ±90° of elevation coverage).
- Power subsystem:
  - (best) to have a Sun pointing configuration
  - (good) to have an Earth pointing configuration
  - (worst) to have an Earth pointing configuration with attitude manoeuvres.
- Propulsion Subsystem:
  - (best) to have an Earth Pointing configuration
  - (good) to have a Sun pointing configuration
  - (worst) to have an Earth pointing configuration with attitude manoeuvres.

2.2.7.1 Earth Pointing versus Sun Pointing

It must be noticed that with:

- Sun pointing configuration:
  - P/L must have 3 receivers and 36 antennae
  - Power Subsystem must cope with a higher power peak from P/L that will be charged on the battery
  - Propulsion subsystem must hold the propellant for orbital manoeuvres.
- Earth pointing configuration:
  - P/L must have 1 receiver and 12 antennae
  - Power Subsystem (Solar Array) must cope with a larger Solar aspect ANgle (SAN = 45°)
  - Propulsion subsystem must hold the propellant for orbital manoeuvres.
- Earth pointing configuration with attitude manoeuvres:
  - P/L can have just 1 receiver and 6 antennae
  - Power Subsystem must cope with a power peak from P/L and sub-systems, during the attitude manoeuvre, that will be charged on the battery
  - Propulsion Subsystem must hold the propellant for orbital and attitude manoeuvres.

2.2.7.2 System Budget

The system budgets for all the Satellite Configuration and Pointing strategy (see 2.2.4 and 2.2.7.1) taken into account are shown here below.

Pointing Strategy	Satellite Mass [kg]	Satellite Configuration	Satellite Mass [kg]	Satellite Configuration
Sun Pointing	278	S_j, N_iH_2, Biprop	267	M_j, L_i-Ion, Biprop
Earth Pointing	237	S_j, N_iH_2, N_2H_4	227	M_j, L_i-Ion, N_2H_4
Earth Pointing with Attitude Manoeuvre	300	S_j, N_iH_2, N_2H_4	287	M_j, L_i-Ion, N_2H_4

Table 2.2-2 Satellite Mass Budget

Pointing Strategy	P/L Mass [kg]	Satellite Configuration	P/L Mass [kg]	Satellite Configuration
Sun Pointing	109	S_j, N_iH_2, Biprop	109	M_j, L_i-Ion, Biprop
Earth Pointing	42	S_j, N_iH_2, N_2H_4	42	M_j, L_i-Ion, N_2H_4
Earth Pointing with Attitude Manoeuvre	40	S_j, N_iH_2, N_2H_4	40	M_j, L_i-Ion, N_2H_4

Table 2.2-3 P/L Mass Budget

Pointing Strategy	Propulsion Mass [kg]	Satellite Configuration	Propulsion Mass [kg]	Satellite Configuration
Sun Pointing	38	S_j, N_iH_2, Biprop	38	M_j, L_i-Ion, Biprop
Earth Pointing	74	S_j, N_iH_2, N_2H_4	74	M_j, L_i-Ion, N2H4
Earth Pointing with Attitude Manoeuvre	119	S_j, N_iH_2, N_2H_4	119	M_j, L_i-Ion, N2H4

Table 2.2-4 Propulsion Subsystem Mass Budget

Pointing Strategy	Power Mass [kg]	Satellite Configuration	Power Mass [kg]	Satellite Configuration
Sun Pointing	29	S_j, N_iH_2, Biprop	19	M_j, L_i-Ion, Biprop
Earth Pointing	28	S_j, N_iH_2, N_2H_4	18	M_j, L_i-Ion, N_2H_4
Earth Pointing with Attitude Manoeuvre	35	S_j, N_iH_2, N_2H_4	21	M_j, Li-Ion, N_2H_4

Table 2.2-5 Power Subsystem Mass Budget

Having a look at
Table 2.2-2, the Earth Pointing strategy, with the S_j, N_iH_2, N_2H_4 Configuration, is the optimised solution among all that had been studied.

In fact, in this configuration the P/L is (good) (see
Table 2.2-3), Propulsion Subsystem is (best) (see
Table 2.2-4) (More mass that Sun Pointing but simpler as it is Monopropellant); while, Power Subsystem (see
Table 2.2-5) needs a bit more explanation, in fact, looking at the power subsystem budget Earth Pointing seems to be (best) for it instead of (Sun Pointing); this is not completely true.

In order to understand the situation, a look at Table 2.2-6 and

Table 2.2-7 is useful; in fact, Sun Pointing is (best) for Solar Array area and mass while, Earth Pointing is (best) for Battery volume and mass.

This means that is not possible to find a pointing strategy that is (best) for both Solar Array and Battery. In any case, as the overall policy is to find the optimised solution within the limit of overall satellite mass of 250 kg (see page 16), it is possible to assess that the Earth Pointing strategy, with the S_j, N_iH_2, N_2H_4 Configuration "does" is the optimised solution.

Pointing Strategy	SA Mass [kg]	Satellite Configuration	SA Mass [kg]	Satellite Configuration
Sun Pointing	10	S_j, N_iH_2, Biprop	5.5	M_j, L_i-Ion, Biprop
Earth Pointing	11	S_j, N_iH_2, N_2H_4	6.0	M_j, L_i-Ion, N_2H_4
Earth Pointing with Attitude Manoeuvre	14	S_j, N_iH_2, N_2H_4	8.0	M_j, L_i-Ion, N_2H_4
Pointing Strategy	SA Area [m²]	Satellite Configuration	SA Area [m²]	Satellite Configuration
Sun Pointing	2.1	S_j, N_iH_2, Biprop	1.5	M_j, L_i-Ion, Biprop
Earth Pointing	2.4	S_j, N_iH_2, N_2H_4	1.7	M_j, L_i-Ion, N_2H_4
Earth Pointing with Attitude Manoeuvre	3.0	S_j, N_iH_2, N_2H4	2.2	M_j, L_i-Ion, N_2H_4

Table 2.2-6 Solar Array Mass and Area Budget

Pointing Strategy	Battery Mass [kg]	Satellite Configuration	Battery Mass [kg]	Satellite Configuration
Sun Pointing	7.8	S_j, N_iH_2, Biprop	2.9	M_j, L_i-Ion, Biprop
Earth Pointing	5.7	S_j, N_iH_2, N_2H_4	2.1	M_j, L_i-Ion, N_2H_4
Earth Pointing with Attitude Manoeuvre	8.6	S_j, N_iH_2, N_2H4	3.2	M_j, L_i-Ion, N_2H_4
Pointing Strategy	Battery Volume [l]	Satellite Configuration	Battery Volume [l]	Satellite Configuration
Sun Pointing	7.1	S_j, N_iH_2, Biprop	1.1	M_j, L_i-Ion, Biprop
Earth Pointing	5.2	S_j, N_iH_2, N_2H_4	0.8	M_j, L_i-Ion, N_2H_4
Earth Pointing with Attitude Manoeuvre	7.9	S_j, N_iH_2, N_2H_4	1.2	M_j, L_i-Ion, N_2H_4

Table 2.2-7 Battery Mass and Volume Budget

3. THE PROPOSED MULTIDISCIPLINARY OPTIMISATION METHODOLOGY

3.1 BASIC CONCEPTS

This work proposes a new methodology for tackling multidisciplinary optimisation problems in space design characterised by non-collaborative entities. One of the main reasons to search for new methods and approaches to solve MDO problems is the increasing complexity of the engineering systems. Since solutions time for most analysis and optimisation algorithms increase at a super linear rate, the computational cost of MDO is usually much higher than the sum of the costs of the single disciplines represented in the MDO itself.

Several papers are available in literature dealing with MDO problems, but they are typically based on the application of particular uses of classic approaches for mono-objective problems.

Collaborative Optimisation (COLOP – see [RD 10]) is a new design architecture specifically created for large-scale distributed analysis applications, and is based on the decomposition of problems along the lines of the constituent disciplines. This method tries to solve each subsystem maintaining its independence from the others, leaving to a top level system the task of managing the interactions between the set of subsystems. It means that from the system level is deduced a simplified model for each subsystem, which involves only its variables, constraints and objectives, so COLOP seeks to solve MDO problems in a way that preserves the autonomy of the disciplinary calculation by eliminating from the system-level problem all those design variables local to individual disciplinary subsystems. Main drawback of COLOP is that it typically runs into computational difficulties when conventional non-linear programming algorithms are applied to the solution of the resulting system level.

Bi-level Integrated System Synthesis (BLISS – see [RD 11]) and its evolutions BLISS/RS and BLISS/S are recently introduced methods that use a gradient-guided path to reach the improved system design. This family is studied for maintaining multidisciplinary feasibility at the beginning of each path cycle. Starting from a best guess initial design, this method improves that design in iterative cycles, each cycle comprised of two steps. In step one, the system level variables are frozen and the improvement is achieved by separate, concurrent and autonomous optimisations in the local variable sub domains. If the starting point is feasible, then BLISS will maintain feasibility while improving the system objective. Otherwise, if the starting point is unfeasible, the constraint violations are reduced while minimizing the increase in system objective. Typical drawback of BLISS and its variants is that as they strongly exploit the use of derivatives, typically run into computational errors propagation.

To overcome the above drawbacks, in this project we propose a new method based on the joint use of three different disciplines: Combinatorial Optimisation, Game Theory and Multicriteria Decision Analysis. These disciplines are quite different and complementary to each other. Each discipline presents some advantages that make it appropriate for this study, but also some disadvantages that suggest an integration with the other ones. Here, we propose a general integrated framework in order to fill mutual deficiencies, originating a new methodology able to solve general MDO problems.

In a Combinatorial Optimisation context related to problems characterised by mathematical formulations presenting many non-linearities and then extremely complex or even impossible to be solved by means of exact approaches, heuristic approaches based on neighbourhood search techniques represent the most appropriate tool to generate good solutions. The neighbourhood search approach explores and evaluates the solutions space: actually, only a reduced subset of the solutions space is explored in order to reduce computational time, but the proposed approach typically has the ability of moving toward good solutions even evaluating few solutions, thing which is pretty important, especially in real problems like this, where the computational time required to evaluate a single solution may be significant. In spite of this, it is hard to directly and successfully apply Combinatorial Optimisation techniques to the whole problem as they are not totally suitable for multi-objective multi-disciplinary problems.

In order to overcome this issue, we make use of Game Theory and Multicriteria Decision Analysis, which constitute the most suitable approaches when dealing with problems characterised by conflictual objectives. On the other side, they base their activity on the evaluation of a set of Paretian solutions, but they are not able to generate

it, so they need a previous extern analysis. The preliminary role of Combinatorial Optimisation, which is particularly suitable for exploring the solutions space while searching for a set of Paretian solutions is clearly depicted in
Figure 3.1-1. Then, in parallel, Game Theory and Multicriteria Decision Analysis evaluate these solutions providing in output a (typically) strongly limited subset of solutions representing the best compromise for these conflicting multidisciplinary problems.

The advantage of the proposed approach, with respect to the existing conventional algorithms for MDO problems, is that it strongly reduces the probability of computational mistakes as the neighbourhood search approach is totally uncorrelated from the mathematical modelling of the problem and the only requirement is the capability of computing the values of the given solutions. Further the neighbourhood search approach allows the exploration of a quite reduced subset of the solutions space, decreasing the computational costs. This is significant since in real cases, when working on full complex problems, we typically encounter a solutions space whose size may be very large (millions of units for instance) and the time requested to compute a single solution may be not negligible. Finally, there are methods which are not able to provide solutions until the execution is ended, while in the proposed approach, several (typically good due to their Paretian peculiarity) solutions are generally available even if it is stopped in advance.

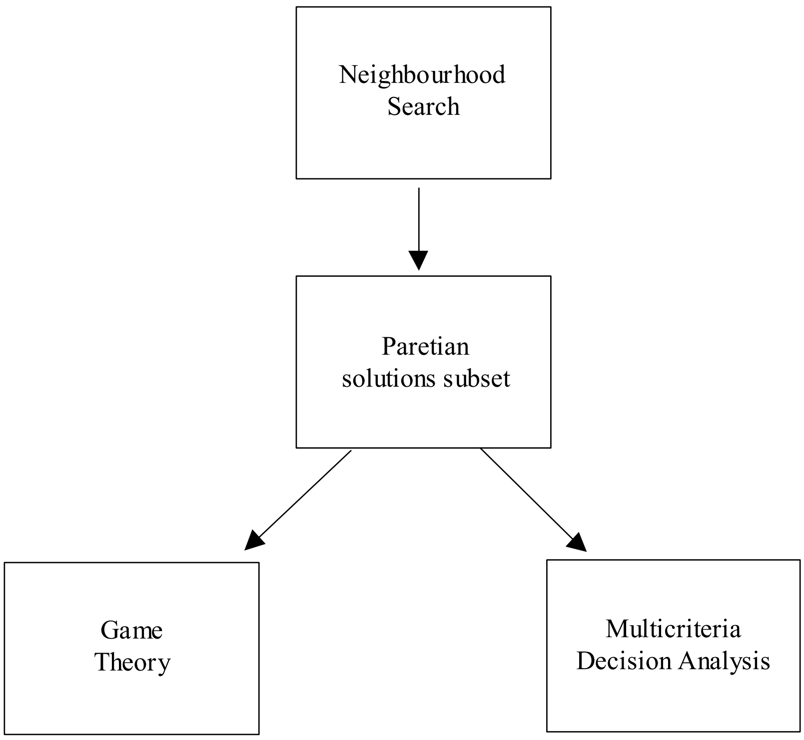


Figure 3.1-1: Disciplines interaction

3.2 APPLYING THE MULTIDISCIPLINARY OPTIMISATION METHODOLOGY TO THE WATS MISSION CASE STUDY

The WATS case study introduced in Chapter 2, was characterised by the presence of very complex optimisation problems, both at subsystem and at system level. Actually, all encountered optimisation issues were solved 'by hand', on the basis of the engineer expertise. In particular, no optimisation routine was available to optimise each single subsystem. The absence of such routines made inapplicable the neighbourhood search approach (for which each subsystem is a 'black box'). The implementation of these subsystem routines was however beyond the scope of this work.

For the game theoretic approach a suitable utility function was defined for the two players of the case study, depending on the number of events. The three approaches, Nash equilibrium, Nash solution and Kalai-Smorodinsky solution allow to have a first insight to their features: the Nash equilibrium and the Nash solution coincide and the corresponding point gives his maximal feasible utility to player “number of satellites”, but the other player “number of launches” cannot improve his utility without the help of the first player (Nash equilibrium) and this theoretical increase of utility is however not counterbalanced by the loss of utility of the first player (Nash solution). On the other hand the Kalai-Smorodinsky solution takes into account that it is not fair to give the maximal utility to one player, while the other is penalised with respect to his best opportunity, so reduces the utility for the player “number of satellites” and increases the utility for the player “number of launches”.

The Multicriteria Decision Analysis methods work with a set of solutions, not necessary efficient in terms of Paretian solutions but feasible or admissible, in relation to the system engineer’s point of view on the decision problem. For this reason, a Multicriteria approach has been applied to the WATS case study to structure the decision problem, elaborate the reduced set of all the feasible solutions and a consistent evaluation model. This model allows the application of a Multicriteria method (such as an ELECTRE method) to the solutions to rank them and identify the best solution.

4. MARS MISSION

The task of the Mars mission case study is to manage the conflict between the RF subsystem of the rover and the power subsystem of the rover and to find the orbit that help to lower as much as possible the conflict between the two subsystems of the rover and that lower as much as possible the conflict between the rover it self, on one side, and the orbiter, on the other side.

The conflict between the two subsystems is:

- The rover RF subsystem wants to have the data volume per orbit as high as possible, that in turn means it wants to have RF power peak as high as possible.
- The rover power subsystem wants to have the solar panel as small as possible, that in turn means it wants to give to RF subsystems as low power peak as possible.

The conflict between the rover and the orbiter is:

- The rover RF subsystem wants to have the data volume per orbit as high as possible, that in turn means it wants to have Orbiter/Rover contact period as long as possible.
- The Orbiter, for the sake of other experiments (e.g. remote sensing), wants to have operations as simpler as possible, that in turns means the Orbiter wants to stay on a circular orbit.

The example is a reduction of a real Mars missions. Where a rover needs to send data to Earth ground station via data relay orbiter.

4.1 MISSION ANALYSIS

In this simplified case the mission analysis gives the Orbiter/Rover contact period durations and Orbiter/Rover maximum range per contact period. The trade-off is between a circular orbit e.g. 500 x 500 km and several elliptic orbits, in order to find the best orbit that optimise the overall conflicts.

In this simplified case, instead of considering the data volume per Martian day (as usual in this type of mission), we consider the data volume per overhead passage. This is not a reductive hypothesis; in fact, maximising the data volume per overhead passage gives the maximum data volume per Martian day (This is only true for this "simplified case" where we just have overhead passage).

4.2 RF SUBSYSTEM

The RF subsystem is defined by means of the link budget equation, with all the technologic parameters taken from INTERMARSNET study (see RD 26), is:

$$P_T = \frac{d^2}{3.16 \cdot 10^{15}} \cdot R_b \qquad (16)$$

where P_T is the Transmitting Power [W], d is the Orbiter/Rover range [m] and R_b is the transmitting Bit Rate [bps]. The trade off is to find the Bit Rate that maximise the Data Volume [Mb] per Orbiter/Rover contact period.

4.3 POWER SUBSYSTEM

The Power subsystem is defined by means of the equations and parameters as in 2.2.2; but, taking into account that the power P from solar array at 1.5 AU (average Sun/Mars distance) is P=Po·r-α, where Po is the power from solar array at 1 AU (average Sun/Earth distance) and α=1.7 instead of α=2 because of the better performance of the solar cell for the major distance from the Sun.

4.4 RF SUBSYSTEM

The Data Volume and the Trasmitting Power (Pt) as a function of Bit Rate (Rb) and Contact Time are given in the Final Report (RD 1), where the range as a function of Contact Time and the Energy, required to cope with the RF transmitting power peak, as a function of Contact Time are shown as well. Pt had been computed as explained in 4.2.

4.5 POWER SUBSYSTEM

The Rover solar array sizing had been done in the Final Report (RD 1).

4.6 CONCLUSIONS

In order to find the optimal solution, that is the solution maximising the data volume while lowering the transmitting power (i.e. the solar array mass) and looking for an orbit as near as possible to a circular orbit (i.e. operations as simpler as possible), the definition of the I_{eff} efficiency index is very useful:

$$I_{eff} = \frac{DV}{P_T} \qquad (17)$$

where DV is Data Volume [Mb] and PT is the RF Transmitting Power Peak [W]. A look at the following Table 4.6-1 will let us find the optimal solution. The optimal solution is the one with I_{eff} as much as possible near to 1 value. The optimal solution has been found looking at the tables with the sizing parameters of the rover subsystems (see Final Report, RD 1). For a given Solar Array Area (SAA) a Tx Energy value is fixed and all the Data Volume with Tx Energy value near by the fixed one are considered. The I_{eff} says which is the optimal solution.

SAA	0.19	m²		
Tx Energy	0.05	Wh		
Rb [bps]	Energy [Wh]	Pt [W]	DV [Mb]	Ieff
2000	0.05	0.43	0.90	2.0930
4000	0.11	0.85	1.80	2.1176
6000	0.16	1.28	2.70	2.1093
8000	0.21	1.70	3.60	2.1176
10000	0.27	2.13	4.50	2.1127

SAA	0.20	m²		
Tx Energy	5.00	Wh		
Rb [bps]	Energy [Wh]	Pt [W]	DV [Mb]	Ieff
2000	6.34	11.03	4.14	0.3753
6000	4.01	10.69	8.10	0.7577
8000	5.35	14.26	10.80	0.7574
10000	6.68	17.82	13.50	0.7575

SAA	0.22	m²		
Tx Energy	31.00	Wh		
Rb [bps]	Energy [Wh]	Pt [W]	DV [Mb]	Ieff
8000	25.36	44.11	16.56	0.3754
10000	31.70	55.13	20.70	0.3755

Table 4.6-1 Optimal Solution

It is now possible to say that the optimal solution is:

Rb = 6000 Bps, SAA = 0.20 m², Battery mass = 0.09 kg and Operative Orbit = 500 x 2000 km

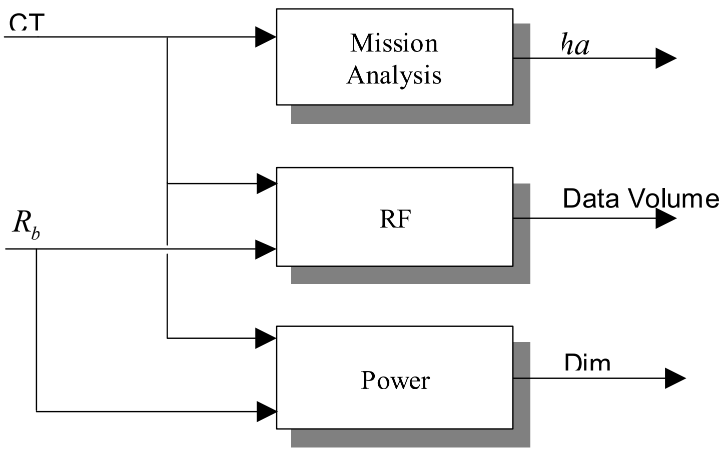
This means that the orbit is not very far from the circular one, the battery mass is compatible with an overall mass of the rover equal to 16 kg (see RD 27), the solar array area is quite small compared with a maximum allowable area of 0.25 m² (see RD 27) and the data volume is very close to the 10 Mb data volume per day of INTERMARSNET mission.

5. APPLYING THE MULTIDISCIPLINARY OPTIMISATION SOFTWARE PROTOTYPE TO THE MARS MISSION CASE STUDY

5.1 MARS MISSION STRUCTURE

In order to implement the local optimisers able to compute the solutions outputs, it is useful to analyse the MARS mission structure taking also into account the conflicts described in section 4. This mission presents three constituent subsystems, shown below.

- The Mission Analysis subsystem receives in input the Contact Time and returns the chosen orbit computed by means of the ha value.
- The RF subsystem, starting from the Contact Time and the Transmitting Bit Rate, returns the Data Volume sent to the Ground station.
- The Power subsystem, through Bit Rate and Contact Time input, computes the solar array dimension.



5.2 THE GAME THEORETIC APPROACH FOR THE MARS MISSION

We describe the algorithms for computing the Nash equilibrium in pure strategy for the non co-operative game and the Nash solution and Kalai-Smorodinsky solution for the associated bargaining problem (co-operative game without side payments).

<u>Nash equilibrium</u>
We suppose that the game is represented in strategic form $(N, (\Sigma_i)_{i \in N}, (\pi_i)_{i \in N})$, where $N = \{1,...,i,...,n\}$ is the set of the players, Σ_i is the set of strategies of player i, and π_i is the payoff function of player i, that assigns to each strategy profile $(\sigma_1,...,\sigma_n)$ his payoff $\pi_i(\sigma_1,...,\sigma_n)$.
For each player i, $i \in N$ consider each strategy profile of the players different from i, denoted by σ_{-i}; for each σ_{-i} determine the best reply of player i, i.e. the strategy $\sigma_i \in \Sigma_i$ with the highest payoff $\pi_i(\sigma_{-i},\sigma_i)$.
The strategy profiles containing only best replies are the Nash equilibriums of the game.

Nash solution

Taking into account the reduced size of the model (we have an approximation of the Pareto boundary made up by 96 points), which considers a small number of Pareto optimal solutions it is more efficient to use a special purpose algorithm instead of a general one.

Let $PO = \{(x^j_1,..., x^j_n)_{j = 1,..., p}\}$ be the set of Pareto optimal solutions, where in this case p assumes the value 96; for each $j = 1,..., p$ compute the Nash product $\prod_{i \in N} (x^j_i - d_i)$ and take as Nash solution the Pareto optimal point for which the value of the product is maximal. $(d_i)_{i \in N}$ is the disagreement point, that can be represented by the null solution (0, ..., 0) if nothing is done without an agreement or by the Nash solution if it is unique. Only individually rational points are considered, i.e. those points such that $x^j_i \geq d_i$ for each $i \in N$.

Kalai-Smorodinsky solution

Also in this case it is more efficient to use a special purpose algorithm instead of a general one.

Let $u_i = \max \{x^j_i, j = 1,..., p\}$ for each $i \in N$ and let $(u_1,..., u_n)$ the "utopia point". Consider the line through the disagreement point and the utopia point and compute the distance of each point in PO from this line; the Kalai-Smorodinsky solution is the nearest point.

The case study considers three players corresponding to the apogee altitude, data volume and solar array size. The data are those used in the other approaches, obtained having in input pairs of contact time and transmitting power.

In order to define the utility of each player two steps were performed:

- the utility for apogee altitude and solar array size are reversed in the sense that the lower is the value the higher is the utility;
- the utilities are normalised in the interval [0, 1000].

The computation of Nash equilibriums was omitted as starting from a set of Paretian solutions (quite) all of them result in Nash equilibriums.

5.3 THE MULTICRITERIA DECISION ANALYSIS APPLICATION TO THE MARS MISSION

The Neighbourhood generation of results for the ELECTRE application produced a matrix with alternative solutions, as rows, and evaluations of each solution on each criterion, as columns. The columns correspond to the criteria, which are a decisional expression of preference, as the relative importance of each criterion[1]. The matrix the Neighbourhood search generated presents ninety-six rows and four columns. The decisional indication is that the first three criteria have the same importance and the fourth can have the same importance of the others.

The criterion g_4 is the expression of an efficiency measurement (the ratio between the Data Volume and Transmission Power indices) that can be used as criterion with some prudence. The Data volume is another criterion (g_2) and therefore there is a correlation between these two elements of the model. Each correlation between factors has to be avoided in most Multicriteria methods. ELECTRE III, as all the other outranking methods, can accept some correlation elements because the aggregation between evaluations is not a sum of values (it can be described as a concordant synthesis of positions), but in any case this kind of criterion has to be analysed attentively.

In this case, the criterion is accepted as the expression of a risk (of choosing a not efficient solution), but its weight may be indicated as lower than the other criteria. At the same time a veto threshold is imposed to express the concept of risk more operationally in the algorithm (the veto is introduced in the outranking relation model when there is risk, in this case of choosing a very little efficient solution, comparatively with another which presents worse performances on the other criteria but a really better index of efficiency). There are two scenarios of weights, because two are the different indications of minimum weight for g_4, and a third scenario that accepts the decisional indication of four criteria all with the same weight.

[1] The importance coefficient is indicated as 'weight' in this section because this term is the more general in the Multicriteria decision analysis context

5.4 FINAL REMARKS ON MARS MISSION

As we have seen, the Combinatorial Optimisation local search procedure based on the path re-linking strategy was able to generate from the two initial solutions provided a set of 96 Paretian solutions (see [RD 1]). This set represented then the input for the Game Theory and Multicriteria analysis approaches that evaluated these solutions and generated the related outputs.

With respect to the output generated by the Game Theory approach, it is worth to remark that the characteristic of the Nash solution (solution A0049, see Table 6.2-2 of [RD 1]), as it takes into account "what is given" to the players results also in a good quality solution for the multicriteria approach. On the other hand the Kalai-Smorodinsky solution (solution A0071, see always Table 6.2-2 of [RD 1]), that consider not only "what is given" to the players but also "what they could be given" looks for a Paretian solution that leads all the players towards their maximal utility, instead to ask a small "sacrifice" to one player if the other two can greatly increase their utilities.

The Multicriteria Analysis does not propose a single solution, but a ranking of the evaluated solutions and it arrives at robust conclusions only after a robustness analysis on the model parameters. The presented result is only the first ranking and solution A0049 (Nash solution for the Game theory approach) is present in the head of the ranking, but it is not the best solution. The reason is that the multicriteria model includes four criteria and there is some discordance, for solution A0049, in relation to the last criterion Efficiency. Instead solution A0071 (the Kalai-Smorodinsky solution) is only in the mid ranking. Completing the Multicriteria Analysis application, until robust conclusions are obtained, could be interesting to analyse the final position of solution A0071 in the ranking.

6. CONCLUSIONS AND FUTURE DEVELOPMENTS

This study focuses on an advanced methodology aimed at supporting the space engineer to tackle conflicts arising in a project during its phases: subsystem targets are generally oriented differently, so that what could be optimal for a particular subsystem could be not optimal, or even unfeasible, for other subsystems.

An advanced Multidisciplinary Optimisation approach, innovative to the authors' knowledge, has been introduced, in order to provide the space engineer with a systematic methodology to face complex projects. It is based on a joint use of Combinatorial Optimisation, Game Theory and Multicriteria Analysis.

The Combinatorial Optimisation approach is oriented to look into the Paretian solutions for the whole system, on the basis of the specific target functions relative to each single subsystem. The Paretian solutions are all the non-dominated ones, i.e. the improvement of any subsystem solution implies the worsening of at least another subsystem solution. As a consequence, from the system point of view, all Paretian solutions are equivalent. Due to the complexity of the overall system, a heuristic approach based on local search techniques is applied to derive these solutions.

The Game theory and Multicriteria Analysis are introduced to compare the Paretian solutions. Game Theory search is oriented towards the 'fairness' of the solutions, Multicriteria Analysis towards a similar aim, the identification of the most robust compromise solution. In other words if a solution is very interesting according to many of the parameters (a 'sufficient' concordance of reasons) this will be considered very well according to multicriteria analysis, only if a very strong discordance (veto) is not present on at least one criterion. The same solution (very interesting according to many of the parameters) will results in an interesting game theoretical solution only if the other criteria (players) are not too much penalised. The proposed methodology, which elaborates and then compares Paretian solutions, is not aimed at finding the optimal solution in the absolute sense of the term, but at helping to select a solution that is beyond all criticism.

A basic scenario, relative to the WATS mission, has been selected as starting point for the whole study reported in this document. This case study is considered from the engineering point of view first. The Mission Analysis, the Power and Pointing subsystems have been selected as reference disciplines. The conceptual aspects of the project are described, pointing out conflicts and trade-offs. Technical details from the engineering point of view have been purposely neglected in order to emphasise the methodological aspects.

The proposed methodology is described in this document. The Multicriteria Analysis uses a multicriteria approach (the Strategic Choice Approach) to elaborate a complete set of admissible solutions and the criteria to evaluate the solution set.

A software prototype has been developed to illustrate the susceptibility of the proposed methodology to be extended and 'automated', giving rise to a general decisional support system applicable to a wide class of practical cases. A demonstrative case study, dealing with a simplified Mars mission, has been performed. This case study is analysed by means of the software prototype. A set of 96 Paretian solutions have been generated by the Combinatorial Optimisation local search procedure. This set has then been evaluated by means of the Game Theory and Multicriteria analysis approaches generating in output a strongly restricted subset of solutions to be proposed to the final decision maker, as viable compromise solutions.

On the basis of the analyses performed and the obtained results, the methodology proposed results in being quite promising to tackle quite complex conflicts arising in space engineering. A future activity could include further subsystems (e.g. Thermal or Structural) as well as the development of a comprehensive decision support system addressed to efficiently support the whole life cycle of complex space programs.

With respect to this latter issue, an enhancement in the integration of the considered approaches could be searched in the generation of the Paretian solutions. Indeed, the proposed local search approach, while generating non dominated solutions, moves from the initial solution to the final solution by iteratively updating the current solution where the new current solution belongs to the neighbourhood of the old one. This implies that in each iteration typically a subset of neighbour Paretian solutions (with respect to the current one) exists, but only one of these neighbours must be selected as new current solution. Indeed, this can be viewed as an evaluation process among the solutions of this subset that could be performed by means of the Game Theory / Multicriteria analysis approaches.

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8. ACRONYMS LIST

ACE+	Atmosphere and Climate Explorer Plus
AM	Attitude Manoeuvre
AMCS	Attitude Measurement Control System
ASCII	American Standard Code for Information Interchange
AU	Astronomical Unit
BEN	Battery Energy Need
BLISS	Bi-Level Integrated System Synthesis
bps	bit per second
CA	Comparison Area
COLOP	COLlaborative OPtimisation
CT	Contact Time
CDMU	Command Data Management Unit
CT	Contact Time
DA	Decision Area
Dim	solar array Dimension
DLP	Day Light Period
DV	Data Volume
ΔV	Variation of Velocity
ΔV_D	Variation of Velocity to compensate Drag decay
ΔV_T	Variation of Velocity to reach Nominal orbit from Parking orbit
$\Delta\theta$	Variation of satellite true anomaly
$\Delta\Omega$	Variation of orbit ascending node
e	Eccentricity of orbit
EP	Eclipse Period
ESA	European Space Agency
FIFO	First In First Out
g	gravity acceleration
GaAs	Gallium Arsenide
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GT	Game Theory
H	Altitude of orbit
ha	Apogee Altitude
H_N	Altitude of Nominal Orbit
I	Inclination of orbit
I_{Eff}	Efficiency Index
I_{sp}	Specific Impulse
LEO	Low Earth Orbit
L_i-Ion	Lithium-Ion
M$	Million of Dollars
Mb	Megabit
MCDA	MultiCriteria Decision Analysis
MD	MultiDisciplinary
MDO	Multi Disciplinary Optimisation
M_j	Multy junction
MMH	Mono Methil Hydrazine
MMU	Mass Memory Unit
N/A	Not Applicable
NS	Neighbourhood Search
NTU	Non Transferable Utility
N_iH_2	Nichel Hydrogen

N_2H_4	Hydrazine
N_2O_4	Nitrogen Tetroxide
OBDH	On Board Data Handling
P	Period
PCU	Power Control Unit
Rb	transmitting Bit Rate
RFDU	Radio Frequency Distribution Unit
P/L	PayLoad
PN	Power Need
PNBC	Power Need for Battery Charging
PPDU	Power Protection Distribution Unit
Pt	Transmitting Power
QSL	Quasi Static Load
RD	Reference Document
RF	Radio Frequency
RFDU	Radio Frequency Device Unit
Rx	Receiver
SA	Solar Array
SAA	Solar Array Area
SAN	Solar aspect ANgle
SAT-LAN	number of satellites per number of launches
S/C	SpaceCraft
S_j	Single junction
S/S	SubSystem
TBD	To Be Defined
TL	Tabu List
TPN	Total Power Need
TTC	Telemetry and Tracking Communication
Tx	Transmitter
vs	versus
Wh	Watt-hour
WATS	WAter vapour and temperature in Troposphere and Stratosphere
w.r.t.	with respect to

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