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Constellation of Mini sounders for Meteorology deployment and renewal scenarios study with Petri nets

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The rapid expansion of satellite constellations, with a significant number expected to be operational within the next decade, presents both opportunities and challenges. These constellations are crucial for enhancing global communication, particularly in underserved areas, for advanced Earth observation capabilities, etc. However, the increasing number of satellites also exacerbates concerns regarding orbital debris and congestion in critical Low Earth Orbits and Geostationary Earth Orbits. Sustainable integration and efficient utilization of these constellations within the current space framework are essential. This paper explores the deployment and renewal strategies for satellite constellations, focusing on the weather constellation CMIM (Constellation of MIni sounders for Meteorology) as a case study. The study evaluates various scenarios, analyzing factors such as satellite type, quantity, reliability, redundancy within satellites or between the satellites of a plane, etc. A simulation-based approach, employing Petri nets combined with Monte Carlo simulations, is used to evaluate the impact of these factors on system performance, while also focusing on defining possible degraded revisit scenarios. During the project phase 0, the simulation models provide a comprehensive comparison of performance and cost metrics across multiple scenarios. Key considerations include the in-orbit stock management, renewal launch frequency, and redundancy strategies. The results contribute to optimizing service availability and ensuring the long-term efficiency and sustainability of satellite constellations in an increasingly populated space environment.

Keywords: Satellite constellation, Availability, Petri nets, Space, Deployment, Renewal, Redundancy, Monte Carlo, Phase 0.

1. Introduction

The Constellation of MIni sounders for Meteorology (CMIM) is a constellation project in heliosynchronous orbit at an altitude of 630 km, aimed at improving weather forecasting (see reference [4]). The purpose of this study is to define and analyze deployment scenarios for the CMIM constellation, in order to assess the impact of working assumptions (platform and payload reliability, satellite lifetime, frequency of renewal launches, etc.) on the expected availability performance of the system.

The simulator developed to model the deployment and renewal of the constellation is based on Petri nets, that are mathematical and graphical tools used to model and verify the dynamic behavior of discrete-event systems (i.e. with countable events). It has already been used previously to model AGILE at the French Space Agency (CNES), a project of IoT constellation (see reference [1]).

Petri nets consist of four elements: places (1), transitions (2), upstream arcs (3), and downstream arcs (4). The graphical representation of the network structure is presented in Figure 1.

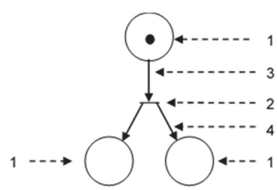

Fig. 1. Petri net graphical representation

A marking corresponds to an assignment of tokens to certain places in the Petri nets; these tokens represent the dynamic part of the model, as shown on Figure 2.

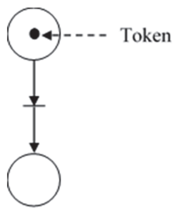

Fig. 2. Token in a Petri net

The execution of the Petri net is controlled by the number and distribution of tokens in the network. Tokens reside in places and control the firing of transitions in the network. Firing a transition allows moving tokens from an upstream place and creating new tokens distributed in downstream places.

A transition can be fired if it is valid, meaning that each upstream place has at least the number of tokens indicated on the arcs connecting it to the transition.

Petri nets have predicates, which can be guards or assignments:

- A guard is a condition to be met on one or more variables/parameters for a transition to be fired.
- An assignment is a modification of the value of one or more variables/parameters following the firing of a transition.

The constellation is modelled using GRIF, a TotalEnergies software (see reference [3]). Predicate Petri nets are used to model the system's behaviour (considering equipment failures, redundancies, etc.), and the calculation is performed using Monte Carlo simulation, a random number simulation method. Associated with the stochastic laws governing the transition of an element from one state to another (and therefore the transition from one state of the system to another), this method calculates the probability of the system being in a given state, for example, being in the "Fully operational constellation" state, and thus the system's availability.

2. Presentation of the simulator

2.1. *Hypotheses*

To model the CMIM constellation, the following assumptions have been made:

- Satellite lifetime: 5 or 7.5 years; modelled by a normal distribution with a mean of 5 or 7.5 years and a standard deviation of 0.5 years;
- Deployment delay: 2 months;
- Vega-C launch reliability: 0.90;
- Platform reliability at 7.5 years: 0.90;
- Payload reliability at 7.5 years: 0.72 for a non-redundant configuration and 0.85 for a redundant configuration (with passive redundancy);
- Simulations are performed over a total duration of 15 years of operational life + N years for the initial deployment phase (depending on the launch frequency for the initial deployment);
- Availability is calculated by excluding the theoretical initial deployment delay;
- Launch frequency: varies between 9 months, 1 year, 15 months, and 2 years depending on the scenario;
- Last launch is performed at Total simulation duration minus satellite lifetime (because the project aims to account for residual availability without renewal during the final years of the constellation);
- Deployment and renewal for each plane are carried out through separate launches.

2.2. *Structure of the simulator*

2.2.1. *Global presentation*

The model of the satellite constellation deployment and renewal simulator is divided into two parts, as shown on Figure 3:

- A *Plane N°* part that models each constellation plane with two submodels:
    - A *Launch Management* submodel to model all launches of the plane;
    - *Satellite* submodels to model each satellite in the plane;
- An *Availability* part to calculate availability.

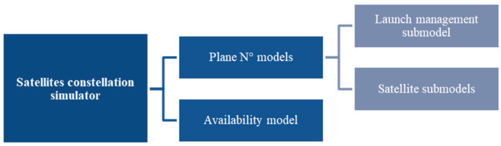

Fig. 3. Simulator’s structure

Each of these parts is parameterized to observe the evolution of the constellation. All simulations are run over a period of 15 operational years plus N (theoretical) years for the initial deployment, 100 000 times to extract a statistical trend.

2.2.2. *Constellation plane model*

Each of the four constellation planes is modeled by the set of positions of the operational satellites (two per plane in the reference scenario), as well as by individual launch management, since each launch is always associated with a single orbital plane.

2.2.2.1. Launch management submodel

This sub-model, presented in Figure 4, represents the acquisition of satellites from the factory stock to their deployment in orbit.
The top branch represents the initial launch. The parameter *Vega_sat_capacity* is set to 2, considering that two satellites are carried by a small launcher such as Vega-C. The parameter *Initial_launch_frequency* represents the frequency of launches at which the initial deployment is planned. It includes the time required to produce the satellite, transport it to the launch site, and prepare the campaign until the launch. During this period, only one launch can be in preparation at a time. The probability of launch success is modeled as a "shot at solicitation" law with the success rate based on the historical performance of Vega and Vega-C launches (0.90). In case of failure, a new initial launch is performed. In case of success, the variable *Initial_deploy_px* is set to true for the plane N°*x*, allowing the initial launch of the next orbital plane. The two satellites successfully launched reach their orbit after the deployment delay *Launcher_to_orbit_duration* (set at two months).
The bottom branch represents the renewal launches. Success and failure transitions are handled in the same way as the initial launch. The transition *Beginning_renewal_launch_Vega_px* can only be triggered once the initial deployment of all planes has been completed. The priority associated with this transition, *Priority_px*, ensures that renewal is prioritized for the plane with the fewest satellites in orbit, which is the highest priority plane (with priority updated in real-time).

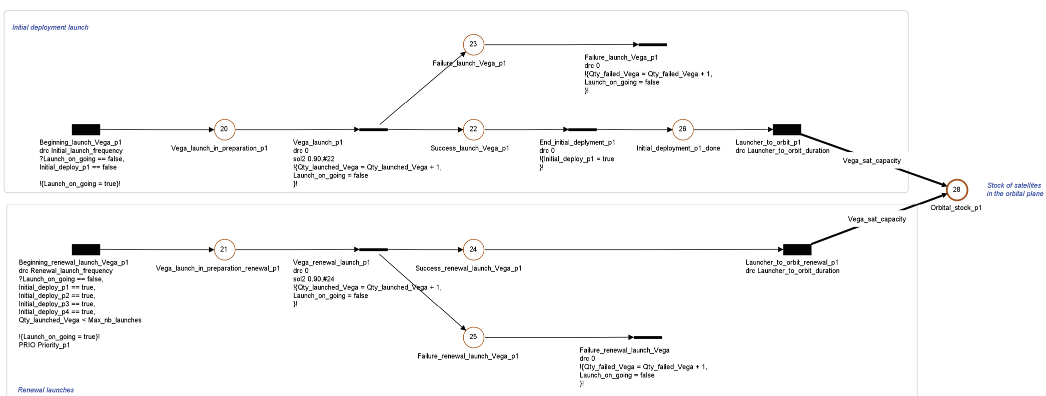

Fig. 4. Plane launch management submodel

2.2.2.2. Satellite submodel

For each operational position in the orbital plane (two per plane in the reference scenario), a satellite is removed from the orbital stock of the plane and placed at its functional operational position *Sat_x_py_position_occupied*.

Operational satellites may cease their functions through two distinct mechanisms: random failure or end-of-life, as shown in Figure 5.

A random failure of the satellite is modeled by a delay transition using an exponential distribution. The failure rate *Lambda_satellite* is set based on the reliability assumptions outlined in the previous section.

The end-of-life of the satellite is modeled by a normal distribution with a mean of 7.5 years (or 5 years, depending on the scenario) and a standard deviation of 6 months.

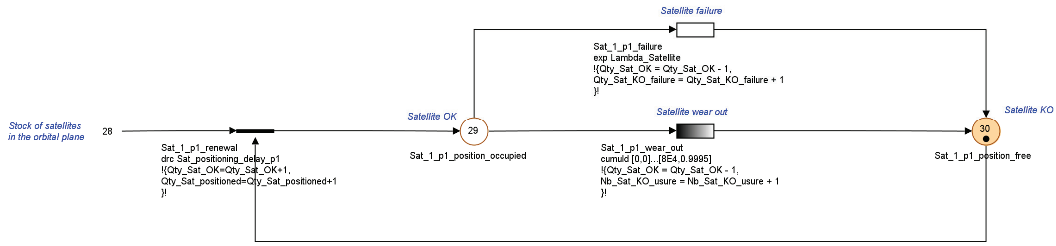

Fig. 5. Satellite submodel

2.2.3. *Availability model*

In order to calculate the availability of the constellation, a small Petri net model was built. The availability threshold (i.e., the number of satellites required for the constellation to be considered available) varies depending on the desired revisit performance of the constellation, as shown below in Table 1. The revisit period of a satellite is the time required for it to pass over the same point again.

Table 1. Revisit of the constellation in function of satellite failure

Constellation architecture	Number of failed satellites	Number of different cases	Best-Worst case of the revisit	Remark
8 satellites on 4 planes	0	1	3h26	None
	1	8	6h27-6h54	Best case: loss of satellites in outer planes Worst case: loss of satellites in inner planes
	2	28	6h53-10h21	Worst case: loss of satellites in inner planes
	3	56	6h54-13h26	Worst case: 3 lost satellites on 3 different planes

The Figure 6 is a simple example for the case where the constellation is considered available when the number of operational satellites is superior or equal to a *Threshold*:

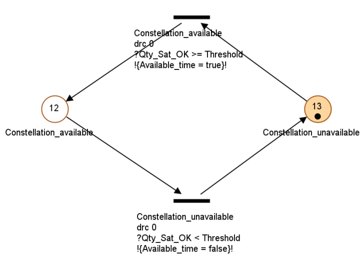

Fig. 6. Example of an availability submodel

This availability model becomes more complex depending on the desired outcome:

- Availability for exactly 6 satellites, 7 satellites, 8 satellites, at least 6 satellites, at least 7 satellites, or at least 8 satellites.
- In the case of active redundancy 2/3 within each plan (12 satellites in total): enumeration of all the cases where the constellation is considered available.

For example, if the goal is to have the availability for 7 or more satellites out of 12, there will be several conditions: for 3 out of 4 planes the number of satellites needs to be superior or equal to 2, and for a 4th plane the number of satellites needs to be superior or equal to 1. In this case, the available can be modelled by the following if-then-else loop (where the | symbol represents a logical OR gate): *ite(((Nb_Sat_Ok_p1 >= 1 & Nb_Sat_Ok_p2 >= 2 & Nb_Sat_Ok_p3 >= 2 & Nb_Sat_Ok_p4 >= 2) | (Nb_Sat_Ok_p1 >= 2 & Nb_Sat_Ok_p2 >= 1 & Nb_Sat_Ok_p3 >= 2 & Nb_Sat_Ok_p4 >= 2) | (Nb_Sat_Ok_p1 >= 2 &Nb_Sat_Ok_p2 >= 2 &Nb_Sat_Ok_p3 >= 1 &Nb_Sat_Ok_p4 >= 2) | (Nb_Sat_Ok_p1 >= 2 &Nb_Sat_Ok_p2 >= 2 &Nb_Sat_Ok_p3 >= 2 &Nb_Sat_Ok_p4 >= 1)), true, false)*

In this case, the available time will be incremented when the conditions on the number of satellites are met, and the variable will be set to True, and it will not be incremented when the variable is False.

3. CMIM scenarios study

3.1. *First simulations set*

The Table 2 presents the different scenarios and results of the first simulations set. The goal of this first simulations set was to test several envisaged hypotheses (satellite lifetime, launch frequency, redundancies, etc.) and define a reference scenario for the second simulations set.

Table 2. Synthesis of the hypotheses and results of the first simulations set

Scenarios	**Hypotheses**				**Results**			
	Satellite lifetime	**Launch frequency**	**Redundancy in the payload**	**Redundancy in the constellation**	**Constellation availability**		**Launched satellites**	**Launches**
					Case ≥ 6/8	Case 8/8		
1.a	5 years	9 months	No	No	98,2%	70,1%	36	18
1.b	5 years	15 months	No	No	52,1%	4,6%	24	12
2.a	7,5 years	1 year	No	No	89,9%	43,5%	24	12
2.b	7,5 years	2 years	No	No	24,4%	2,6%	16	8
2.c	7,5 years	2 years	Yes	No	32,8%	5%	16	8
2.d	7,5 years	2 years	No	Yes	62,0%	19,5%	24	8

3.2. *Second simulations set*

The results of the first simulations set allowed the project to choose a reference scenario with a deployment and renewal strategy that optimized the availability performance:

- Satellite lifetime: 7.5 years;
- Initial deployment: launches every six months of two satellites;
- Renewal: launches every year of two satellites
- Simulations to be run for 15 years (operational lifetime) + 2 years (theoretical deployment not accounted for the availability calculation): total of 17 years;
- The last launch is done at 10 years.

Two variant scenarios were derived from this reference scenario to test redundancy hypotheses:

- Variant 1 with passive redundancy in the payload;

- Variant 2 with active redundancy in the constellation: 2 out of 3 satellites only required in the same plane to be available.

For the second variant scenario, the availability for 6 or more satellites actually corresponds to counting all states where there are two planes with at least 2 satellites and two others with at least 1 satellite. The availability for 7 or more satellites corresponds to counting all states where there are three planes with at least 2 satellites and one with at least 1 satellite.

The Table 3 presents the different scenarios and results of the second simulations set.

Table 3. Synthesis of the hypotheses and results of the second simulations set

Scenario	Hypotheses							Results				
	Satellite lifetime	**Initial deployment frequency**	**Renewal frequency**	**Redundancy in the payload**	**Payload reliability at 7.5 years**	**Platform reliability at 7.5 years**	**2/3 satellite redundancy**	**Constellation availability**			**Launched satellites**	**Launches**
								≥ 6 sats	≥ 7 sats	= 8 sats		
Reference	7.5 years	6 months	1 year	No	0.72	0.9	No	92.6%	78.2%	54.5%	24	12
First variant	7.5 years	6 months	1 year	Yes	0.85	0.9	No	96.9%	86.8%	67.3%	24	12
Second variant	7.5 years	6 months	1 year	No	0.72	0.9	Yes	100 %	89.4%	78.7%	36	12

3.3. Synthesis of the results

For the reference scenario with a total of 24 satellites regularly launched without payload redundancy, the availability of the complete constellation of 8 operational satellites over 15 years is very low (< 55%); it is only satisfactory for an incomplete constellation of 6 satellites (> 90%). To achieve a reasonable availability (> 70%) for the complete constellation of 8 operational satellites over 15 years, it is necessary to consider either the 2/3 redundancy between satellites in each plane, or a redundancy in the payload.

The first option is more effective in terms of availability, but it requires one-third more satellites to be launched: a cost comparison between 24 "expensive" satellites (with redundant payload) and 36 "cheaper" satellites (without payload redundancy) is needed to conclude.

4. Conclusion

During the phase 0 of a project, this simulation approach allows a comparison of availability performance and costs between several envisaged scenarios, leading to an optimization of the constellation regarding factors as deployment and renewal strategy, redundancies strategy, satellite lifetime, etc.

Depending on the technical and technological choices that are made at the end of this phase, it is then possible to refine the working hypotheses taken within the framework of this study and to precise the trends that are emerging.

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