18th International Conference on Space Operations, Montreal, Canada, 26 - 30 May 2025.

SpaceOps-2025, ID # 474

Enhancing Space Resilience: An Integrated Maintenance and Routing Optimization Framework for On-Orbit Servicing Missions

Nathan Claret[a], Adam Abdin[b]*

[a] *Concordia University, Montreal, Canada, nathan.claret@mail.concordia.ca*
[b] *University of Paris-Saclay, CentraleSupélec Engineering School, Department of Industrial Engineering, Gif-sur-Yvette, 91190, France, adam.abdin@centralesupelec.fr*
* Corresponding Author

Abstract

On-orbit servicing (OOS) is an emerging capability for extending satellite lifespans and enhancing the resilience of space infrastructure through in-situ maintenance, repair, and refueling. As OOS operations grow in scale and complexity, efficient mission planning becomes essential to ensure both cost-effectiveness and mission operational reliability. A growing body of research has begun to address optimization of OOS mission planning, particularly for refueling scenarios; however, planning OOS missions that are particularly focused on satellite maintenance—especially the coordination of preventive and corrective interventions—remains largely unexplored. Satellite maintenance, such as component replacement, station keeping, pointing correction and other forms of operational corrections, plays a critical role in sustaining satellite functionality and avoiding costly failures that often lead to full asset replacement or loss of service continuity.

To fill this gap, this paper introduces a novel framework for the Integrated Maintenance and Routing Optimization for On-Orbit Servicing, referred to as IMROOS. The problem is formulated as a mixed-integer linear program that jointly schedules OOS maintenance tasks and optimizes the routing of refuelable servicing spacecraft. IMROOS models the orbital environment as a time-expanded network, capturing the motion of satellites, service vehicles, and refueling depots across multiple orbital regimes. Orbital maneuvers, propellant constraints, and temporal dynamics are incorporated to ensure realistic and efficient mission planning. A particular emphasis is given to differentiate between routine preventive maintenance (conducted to avoid failure) and corrective maintenance (conducted prior to failure). Maintenance scheduling is tightly coupled with routing decisions to reduce service disruptions and avoid costly post-failure interventions. Initial results to validate the framework suitability demonstrate that coordinated planning of maintenance and routing can indeed improve the efficiency and sustainability of OOS operations. These initial findings offer practical guidance for the design of future servicing missions and resilient space infrastructure.

Keywords: On-Orbit servicing, Maintenance Planing, Space Resilience, Space Sustainability, Spacecraft Routing.

Nomenclature

Sets

T	Set of time period
N	Set of nodes
B	Set of tasks, $v \in B_v$
B_v	Set of sub-tasks with $v \in B,\ k \in B_v$
A	Set of arcs with starting node $i \in N$ and final node $j \in N$, $(i,j) \in A$
A_t^R	Set of refueling arcs at time $t \in T$, $A_t^R \subset A$
D	Set of robot servicers, $d \in D$
Γ	Set of refueling depots, $r \in \Gamma$

Parameters

E	Super sink node, $E \in N$
w_v	Weight of task $v \in B$
n_{vk}	Node location of sub-task $k \in B_v$ of task $v \in B$
t_{vk}	Time period of sub-task $k \in B_v$ of task $v \in B$
τ_{ij}	Time periods to traverse arc $(i,j) \in A$, in ΔV

Ψ_{ij}	Fuel per time period needed to traverse arc $(i,j) \in A$, in ΔV
s_d	Starting node of servicer $d \in D$
F_d	Maximum fuel capacity of servicer $d \in D$ in ΔV
R_d^F	Number of time periods for servicer d ∈ D to completely refuel to fuel level F_d
F_{dij}	$\frac{\tau_{ij}}{R_d^F} \times F_d$ (Refueling time on arc (i,j))
H	Failure threshold (operating time)
h	Length of the PM time window
c_{PM}	Cost of conducting a PM operation
c_{CM}	Cost of conducting a CM operation
c_{OP}	Opportunity cost paid each time a satellite remains failed

Decision Variables
β_{vk} = 1 if subtask k of task $v \in B$ is completed; 0 otherwise
y_{dijt} = 1 if robot servicer d initiates move on arc $(i,j) \in A$ at time $t \in T$; 0 otherwise
x_{vt}^{PM} = 1 if preventive maintenance is scheduled for task v ∈ B at time t ∈ T; 0 otherwise
x_{vt}^{CM} = 1 if corrective maintenance is scheduled for task v ∈ B at time t ∈ T; 0 otherwise
f_{vt} = 1 if satellite associated with task v ∈ B is planned as failed at time t ∈ T; 0 otherwise
f_{dt} = fuel level of robot d ∈ D at time t ∈ T

Acronyms/Abbreviations

- IMROOS : Integrated Maintenance and Routing Optimization for On-Orbit Servicing
- OOS : On-Orbit servicing
- NASA : National Aeronautics and Space Administration
- ESA : European Space Agency
- CNSA : China National Space Administration
- LEO : Low Earth Orbit
- MEO : Medium Earth Orbit
- GEO : Geosynchronous Earth Orbit
- MILP : Mixed Integer Linear Programming
- CM : Corrective Maintenance
- PM : Preventive Maintenance
- TSP : Traveling Salesman Problem
- VRP : Vehicle Routing Problem

1. Introduction

The evolution of space infrastructure is undergoing significant transformation, driven by technological advancements from both governmental space agencies (NASA, ESA, CNSA) and commercial entities (SpaceX, Amazon). This development has facilitated satellite deployment across all orbital regimes, with distinct strategic importance for each: Low Earth Orbit (LEO) for Earth observation and telecommunications constellations, Medium Earth Orbit (MEO) for navigation systems, and Geosynchronous Earth Orbit (GEO) for high-value communications assets. Current orbital infrastructure comprises thousands of operational satellites, with projections indicating substantial growth from mega-constellation deployments in coming years.

This expansion of orbital assets is leading to increased interest for On-Orbit Servicing (OOS) capabilities [1]. Satellites represent complex systems requiring periodic maintenance interventions to optimize operational longevity. The OOS framework encompasses multiple service categories: structural inspection, systems maintenance, component repair, propellant replenishment, and technological upgrades. In the absence of regular maintenance protocols, satellites exhibit elevated failure probabilities that may result in complete operational cessation. Maintenance interventions thus serve as critical determinants of satellite operational lifespan, service continuity, and economic performance. Under current operational paradigms, satellite failure remediation necessitates complete asset replacement—a capital-intensive approach with construction expenditures ranging from €100-600 million and launch costs between €40-400 million [2]. Moreover, non-operational satellites contribute to orbital debris accumulation, presenting additional challenges for sustainable space environment management.

These factors collectively underscore the strategic importance OOS will assume in near-term space operations. The orbital environment is evolving toward an ecosystem where commercial entities will likely deploy dedicated refueling facilities and maintainable service vehicles designed for satellite support across all primary orbital regimes. This transition toward serviceable space architecture represents a fundamental shift toward enhancing the resilience and sustainability of critical space infrastructure, enabling longer operational lifespans and reducing orbital debris generation. Consequently, efficient planning and scheduling of complex OOS missions is expected to become an increasingly critical challenge.

Managing OOS operation presents a multifaceted optimization challenge that requires suitable modeling and optimization frameworks to identify optimal operational decisions. To address this, this paper proposes the Integrated Maintenance and Routing Optimization for On-Orbit Servicing (IMROOS) framework as an optimization framework designed to enhance space system reliability while minimizing satellite failures and associated corrective maintenance costs. The IMROOS model aims at finding the optimal scheduling of maintenance activities across a distributed satellite network spanning multiple orbital regimes to execute OOS satellite maintenance tasks. The framework optimizes routing decisions for refuelable orbital service vehicles, determining both trajectory parameters and satellite visitation sequences to minimize aggregate mission expenditures and ensure minimal satellite failures. The model incorporates two distinct maintenance classifications: Corrective Maintenance (CM), which is implemented post-failure of the target satellite, and Preventive Maintenance (PM), which is executed prior to anticipated system degradation. Given that CM operations incur substantially higher costs than their preventive counterparts, the optimization algorithm prioritizes strategic PM scheduling to mitigate potential cost escalation and enhance overall system resilience. The IMROOS framework additionally incorporates orbital refueling infrastructure, allowing service spacecraft to replenish propellant during extended mission operations. This multifaceted problem is mathematically formulated as a Mixed Integer Linear Programming (MILP) model, designed to minimize cumulative operational costs across the mission planning horizon.

The primary complexity of this optimization problem arises from the dynamic orbital environment, where satellites, service vehicles, and refueling depots continuously change positions along their respective trajectories. To address this challenge, we illustrate a network modeling approach with arcs representing distinct orbital maneuvers. We then present generalized algorithms for generating temporal and spatial evolution data for all system elements throughout the planning horizon. Additionally, we demonstrate the integration of maintenance optimization decisions within this framework to establish an effective balance between operational costs and system reliability objectives.

The remainder of this article is structured as follows: the article reviews existing literature focused on optimizing routing and scheduling for OOS missions. It then illustrated the methodological framework underpinning the IMROOS model. It then presents the computational results demonstrating the model's efficacy across various operational scenarios. The paper concludes with a synthesis of key findings and their implications for resilient space infrastructure management.

2. Literature Review

This section reviews research relevant to routing and maintenance optimization for On-Orbit Servicing (OOS) operations. On-Orbit Servicing has emerged as an established domain in space operations research [1], [3], encompassing various in-orbit interventions to extend spacecraft lifespans or enhance capabilities.

Unlike terrestrial routing, OOS involves continuously moving satellites following predetermined trajectories, with significant ΔV penalties for inter-orbital transfers. Several studies have formulated OOS routing as adaptations of classical optimization problems. Bourjolly et al. [4] modeled servicing as a time-dependent "moving-target" TSP to minimize energy or time. Other research has demonstrated modelling frameworks that can account for single servicers to manage multiple orbital planes through optimized transfer sequences [10]. Similarly, the work in [6] propose a TSP formulation for single orbit refueling scenarios. Moreover, since propellant constraint management represents a critical consideration, research works have developed models integrating orbital fuel depots to extend operational ranges [11]. In the work in [7], the authors propose a comprehensive framework for modeling and optimization of OOS operations under demand uncertainties, particularly for refueling missions. The authors use a MILP formulation to find the optimal solution while incorporating orbital fuel depot strategies. In addition, they employ a rolling horizon approach to adapt dynamically to evolving servicing demands, thereby linking short-term routing decisions with long-term strategic planning. In a subsequent study [12], the authors extend their framework to account for the trade-off between high- and low-thrust propulsion systems.

Of particular relevance to our presented work is the work in Sorenson and Pinkley [5] which develops a MILP approach to maximize the weighted task completion of OOS servicing vehicles, subject to orbital transfer, refueling, and temporal constraints. Their formulation enables cross-regime operations spanning LEO, MEO, and GEO through refueling depot integration and it provides the modelling foundation for our current work.

While exact optimization methods ensure optimal solutions, computational complexity increases significantly with problem size. Researchers have addressed scalability through heuristic approaches—Dutta & Tsiotras [8] applied greedy search algorithms to minimize ΔV consumption, while Du et al. [9] implemented a multi-island genetic algorithm for a nonlinear model incorporating the rocket equation. These methodological trade-offs reflect the balance between mathematical rigor and computational efficiency.

While many of these studies provided modelling and optimization frameworks for generic OOS mission planning, or specifically focused on refueling missions, no analysis has yet been performed for modelling and optimizaing other types of OOS maintenance missions. In the OOS context, preventive maintenance (PM) encompasses proactive interventions prior to failure occurrence [13], while corrective maintenance (CM) addresses post-failure scenarios. Preventive strategies are particularly relevant given that approximately 50% of geostationary satellites experience mission-threatening issues due to propellant depletion before hardware failure [14]. This paper extends the framework proposed in [5] to address this limitation through simultaneous optimization of service vehicle routing and maintenance scheduling, employing a time-expanded network formulation that effectively captures the dynamic aspects of satellite movement across multiple orbital regimes.

3. Methodology

3.1 Problem Formulation

The Integrated Maintenance and Routing Optimization for On-Orbit Servicing (IMROOS) framework addresses the challenge of scheduling maintenance activities for satellites while optimizing the routing of service vehicles. We consider a set of satellites distributed across multiple orbits requiring either preventive or corrective maintenance operations. The model routes a refuelable orbital service vehicle such that its trajectory and visitation sequence minimize total mission costs and ensure system reliability.

3.2 Network Model and Orbital Environment

To generate a computationally tractable representation of the dynamic orbital environment, we follow a similar methodology as the one presented in [5] to implement a network model comprising nodes and arcs. We consider a set of Earth orbits, O, on which satellites may require maintenance. Nodes, N, are placed at fixed positions on these orbits, characterized by specific true anomaly values. These nodes are connected by arcs, A, representing possible orbital maneuvers between positions.

Each arc is represented by a starting node i and an ending node j such that $(\mathrm{i}, \mathrm{j}) \in \mathrm{A}$. An arc is created only if an orbital maneuver is feasible according to the criteria defined below. An orbital maneuver is defined by a change in a service vehicles's trajectory or velocity, to transfer it from one orbit to another. In this study, four types of orbital maneuvers have been considered to connect two nodes:

- Orbital Maneuver: Two nodes (i, j) are connected by an orbital maneuver if they are located on the same orbit and are adjacent in the direction of the orbit's rotation.

- Phase Maneuver: Two nodes (i, j) are connected by a phase maneuver if they are located on the same orbit but are not adjacent in the direction of the orbit's rotation.

- Hohmann transfer: Two nodes (i, j) are connected by a “Hohmann transfer maneuver” if they are not on the same orbit but share the same orbital plane (i.e., they have identical inclination), and if the difference in their true anomaly is 180°.

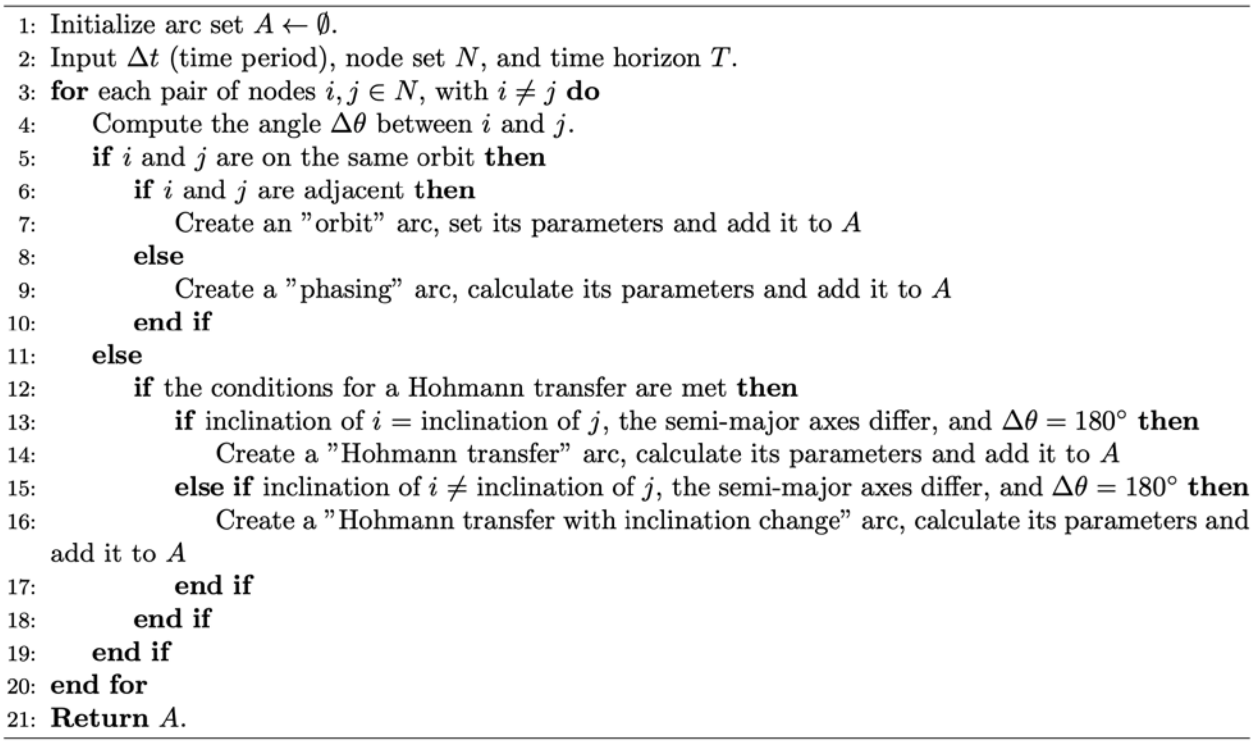
- Hohmann transfer with inclination change: Two nodes (i, j) are connected by a Hohmann transfer with inclination change maneuver if they are neither on the same orbit nor in the same plane, and if the difference in their true anomaly is 180°.

Each arc (i, j) is associated with the following parameters:

- τ_{ij} : Time required to traverse arc (i, j).
- ϕ_{ij} : Propellant consumption, expressed as ΔV, required to traverse arc (i, j).
- Ψ_{ij} : Per time period propellant consumption required to traverse arc(i, j), where $\phi_{ij} = \Psi_{ij}\tau_{ij}$

Algorithm 1 summarizes how to generate the network by creating arcs between nodes and calculating associated maneuver parameters for each feasible orbital maneuver [5].

Algorithm 1 Network Creation Algorithm (adapted from [5])



```
Initialize arc set $A \leftarrow \emptyset$.
Input $\Delta t$ (time period), node set $N$, and time horizon $T$.
for each pair of nodes $i, j \in N$, with $i \neq j$ do
    Compute the angle $\Delta\theta$ between $i$ and $j$.
    if $i$ and $j$ are on the same orbit then
        if $i$ and $j$ are adjacent then
            Create an "orbit" arc, set its parameters and add it to $A$
        else
            Create a "phasing" arc, calculate its parameters and add it to $A$
        end if
    else
        if the conditions for a Hohmann transfer are met then
            if inclination of $i$ = inclination of $j$, the semi-major axes differ, and $\Delta\theta = 180°$ then
                Create a "Hohmann transfer" arc, calculate its parameters and add it to $A$
            else if inclination of $i \neq$ inclination of $j$, the semi-major axes differ, and $\Delta\theta = 180°$ then
                Create a "Hohmann transfer with inclination change" arc, calculate its parameters and add it to $A$
            end if
        end if
    end if
end for
Return $A$.
```

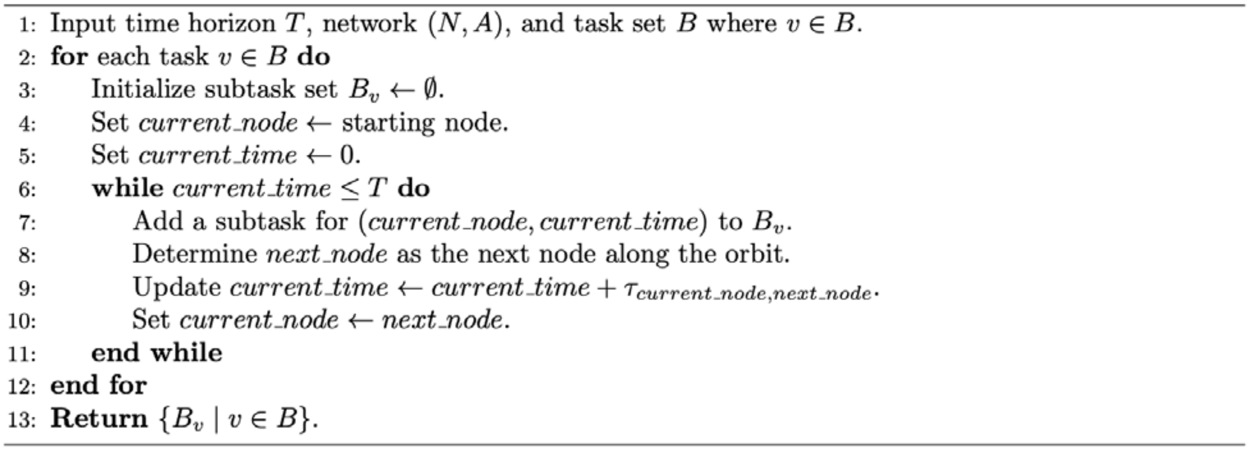
3.3 Modeling the temporal evolution

To capture the temporal evolution of the system, we introduce a discrete time horizon divided into multiple intervals: $t = 0, \ldots, |T|$, representing the maximum duration available for maintenance operations.

We define a set of tasks B where each task $v \in B$ corresponds to a satellite requiring maintenance. To model satellite movement, each task is associated with a set of sub-tasks B_v. Each sub-task $v_k \in B_v$ is represented by a node-time pair: (n_{vk}, t_{vk}), indicating that task v will be located at node n_{vk} at time t_{vk}.

Algorithm 2 describes how to generate the sub-tasks associated with each satellite, mapping their positions throughout the planning horizon [5].

Algorithm 2 Sub-Task Creation Algorithm (adapted from [5])



```
Input time horizon $T$, network $(N, A)$, and task set $B$ where $v \in B$.
for each task $v \in B$ do
    Initialize subtask set $B_v \leftarrow \emptyset$.
    Set $current\_node \leftarrow$ starting node.
    Set $current\_time \leftarrow 0$.
    while $current\_time \leq T$ do
        Add a subtask for $(current\_node, current\_time)$ to $B_v$.
        Determine $next\_node$ as the next node along the orbit.
        Update $current\_time \leftarrow current\_time + \tau_{current\_node, next\_node}$.
        Set $current\_node \leftarrow next\_node$.
    end while
end for
Return $\{B_v \mid v \in B\}$.
```

A task v is considered completed (i.e., maintenance has been performed) if at least one of its sub-tasks v_k is completed. To complete a sub-task, the service vehicle must arrive at node n_{vk} at time t_{vk}, which requires departing from a starting node i along arc (i, n_{vk}) at time $t_{vk} - \tau_{in_{vk}}$.

3.4 Mathematical Formulation

The IMROOS problem is formulated as a MILP that integrates satellite maintenance scheduling with service vehicle routing decisions. The formulation incorporates several key components:

3.4.1 Service Vehicle Representation

The service vehicle, denoted as d, moves through the network along arcs $(i, j) \in A$ over time. At $t = 0$, the vehicle begins at the starting node $\mathrm{s_d} \in \mathrm{N}$. The optimization model determines the sequence of arcs traversed throughout the mission duration. The vehicle's movements are modeled as a flow through the network, obeying flow conservation principles. The vehicle requires propellant to perform orbital maneuvers, with fuel level f_{dt} representing the propellant quantity possessed by vehicle d at time t. A vehicle can traverse an arc (i, j) only if its current fuel level satisfies $\mathrm{f_{dt}} \geq \phi_{ij}$.

3.4.2 Refueling Infrastructure

The model incorporates refueling depots that enable service vehicle propellant replenishment. These depots orbit Earth along with satellites and maintain specific positions at defined times. Refueling depots are modeled as arc positions rather than node positions, as they move exclusively along orbital maneuver arcs. We define $\mathrm{A_t^R}$ as the set of refueling opportunities, comprising triplets $(\mathrm{i, j, t})$ indicating that arc (i, j) permits refueling at time t. Parameter $\mathrm{R_d^F}$ represents the time periods required for vehicle d to recharge from zero to maximum capacity $\mathrm{F_d}$. The parameter $\mathrm{F_{dij}}$ defines the maximum propellant quantity that vehicle d can acquire while traversing arc $(\mathrm{i, j, t}) \in \mathrm{A_t^R}$ between time t and $t + \tau_{ij}$.

3.4.3 Maintenance Operations

Satellites experience degradation due to environmental factors, component wear, and operational stress. This degradation eventually leads to failure, interrupting service provision and resulting in revenue loss.

For computational tractability, we model each satellite as a single-component system subject to failure. Two maintenance categories are considered:

- Corrective Maintenance (CM): Performed after satellite failure to restore functionality.
- Preventive Maintenance (PM): Conducted before failure to proactively replace degraded components.

After any maintenance intervention, we consider the satellite restored to “as-new” condition. The respective costs are denoted as $\mathrm{c_{CM}}$ and $\mathrm{c_{PM}}$, with $\mathrm{c_{CM}}$ significantly exceeding $\mathrm{c_{PM}}$ due to the complexity of restoring failed systems.

We introduce operating time as the duration a satellite has functioned since either initial deployment or the most recent maintenance operation. A satellite is considered failed when its operating time reaches threshold H. Revenue loss due to satellite failure is modeled using an opportunity cost $\mathrm{c_{OP}}$, representing ungenerated revenue per time unit.

To prevent premature maintenance that would waste remaining useful life, we constrain PM operations to a specific window. A PM operation can only be performed when the satellite's operating time a satisfies:

$$\mathrm{H - h \leq a \leq H}$$

where h represents the width of the maintenance window.

We define $\mathrm{t^f = max(1, H - a_v^0)}$ as the time at which satellite v will fail in the absence of maintenance, based on its initial operating time $\mathrm{a_v^0}$.

Based on these key considerations, we now proceed to formulate the complete MILP problem. The proposed mathematical model addresses the optimal mission planning of OOS through a systematic formulation of the routing and maintenance scheduling problem. The constraints that capture the routing dynamics are largely based on the work in []. The full model formulation is presented in the next section.

3.4.4 Objective Function

$$min \sum_{t\in T} \sum_{v\in B} (f_{vt} c_{OP} + x_{vt}^{PM} c_{PM} + x_{vt}^{CM} c_{CM}) + \sum_{t\in T} \sum_{(i,j)\in A} y_{dijt} \Psi_{ij} \tag{1}$$

The objective function minimizes the sum of opportunity costs from satellite failures, preventive and corrective maintenance costs, and propellant consumption costs associated with service vehicle maneuvers.

3.4.5 Constraints

Eq.(2) tracks the operational state of satellites:

$$f_{vt} \geq 1 - \sum_{t} (x_{vt}^{PM} + x_{vt}^{CM}) \qquad \forall v \in B, \forall t \in [\![t_v^f, T]\!] \tag{2}$$

Eq.(3) ensures that at most one sub-task is completed per satellite:

$$\sum_{k\in B_v} \beta_{vk} \leq 1 \qquad \forall v \in B \tag{3}$$

Eq.(4) links service vehicle movement with sub-task completion:

$$\sum_{d\in D} \sum_{\substack{i:(i,n_{vk})\in A \\ t_{vk}-\tau_{in_{vk}}\geq 0}} y_{din_{vk}t_{vk}-\tau_{in_{vk}}} \geq \beta_{vk} \qquad \forall v \in B, k \in B_v \tag{4}$$

Eq. (5) ensures flow conservation for service vehicles:

$$\sum_{\substack{j:(j,i)\in A \\ t-\tau_{ji}\geq 0}} y_{dijt-\tau_{ij}} - \sum_{j:(i,j)\in A} y_{dijt} = \begin{cases} -1, & if\ i = s_d\ and\ t = 0 \\ 1, & if\ j = E\ and\ t = |T| \\ 0, & otherwise \end{cases} \qquad \forall i \in N, d \in D, t \in T \tag{5}$$

Eq.(6) updates service vehicle propellant levels:

$$f_{dj} \leq f_{dt-1} - \left(\sum_{(i,j)\in A} \sum_{s=\max\{t-\tau_{ij},0\}}^{t} \left(y_{dijs} \times \Psi_{ij}\right) - \sum_{\substack{(i,j)\in A_{t-1}^{R} \\ t-\tau_{ij}\geq 0}} \left(y_{dijt-\tau_{ij}} \times F_{dij}\right) \right) \qquad \forall t \in T \backslash |T|, d \in D \tag{6}$$

Eq.(7) links sub-task completion with maintenance operations:

$$\beta_{vk} \geq x_{vt}^{PM} + x_{vt}^{CM} \qquad \forall v \in B, k \in B_v, t \in T \tag{7}$$

Eq.(8) constrains propellant levels:

$$0 \leq f_{dt} \leq F_d \qquad \forall d \in D, t \in T \tag{8}$$

Eq.(9) restricts PM to functioning satellites:

$$x_{vt}^{PM} = 0 \qquad \forall v \in B, \forall t \in [\![t_v^f, T]\!] \tag{9}$$

Eq.(10) restricts CM to failed satellites:

$$x_{vt}^{CM} = 0 \qquad \forall v \in B, \forall t \in [\![1, t_v^f - 1]\!] \tag{10}$$

Eq.(11) enforces PM time window constraints:

$$x_{vt}^{PM} = 0 \qquad \forall v \in B, \forall t \in [\![1, \max(H - a_v^0 - h, 1) - 1]\!] \tag{11}$$

Eq.(12) enforces PM time window constraints:

$$f_{d0} = F_d \qquad \forall d \in D \tag{12}$$

4. Results and discussion

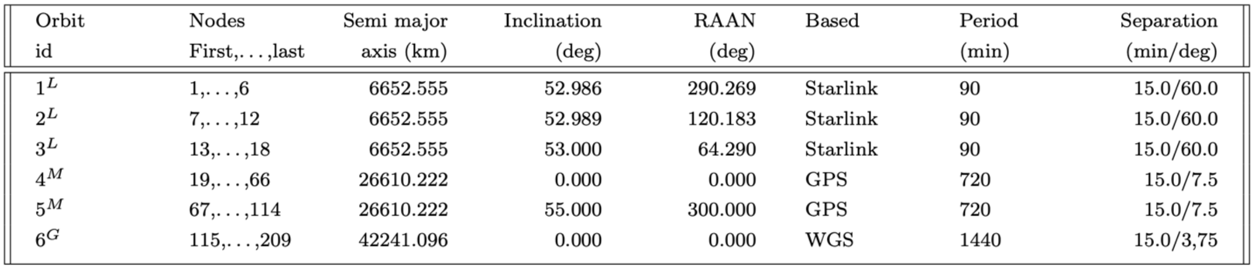
In this section, we present initial results that demonstrate the model's effectiveness at optimizing OOS maintenance routing and scheduling decisions across operational scenarios.

4.1 Experimental Design

The computational framework developed in previous sections enables the generation of various operational scenarios for evaluating the IMROOS model. To systematically assess model performance, we conduct a series of case studies that explore variations in key parameters, including refueling depot distribution, propellant capacity constraints, and initial positions of satellites, servicing vehicles, and refueling depots.

To ensure consistent comparison across scenarios, we establish a standardized network topology comprising nodes and arcs that remains fixed throughout all simulations. To facilitate tractable evaluation and enable consistent comparisons across scenarios, we define a fixed planning horizon of 24 hours, discretized into 96 intervals of 15 minutes each. Table 1 presents the orbital parameters defining the operational environment for the initial case study.

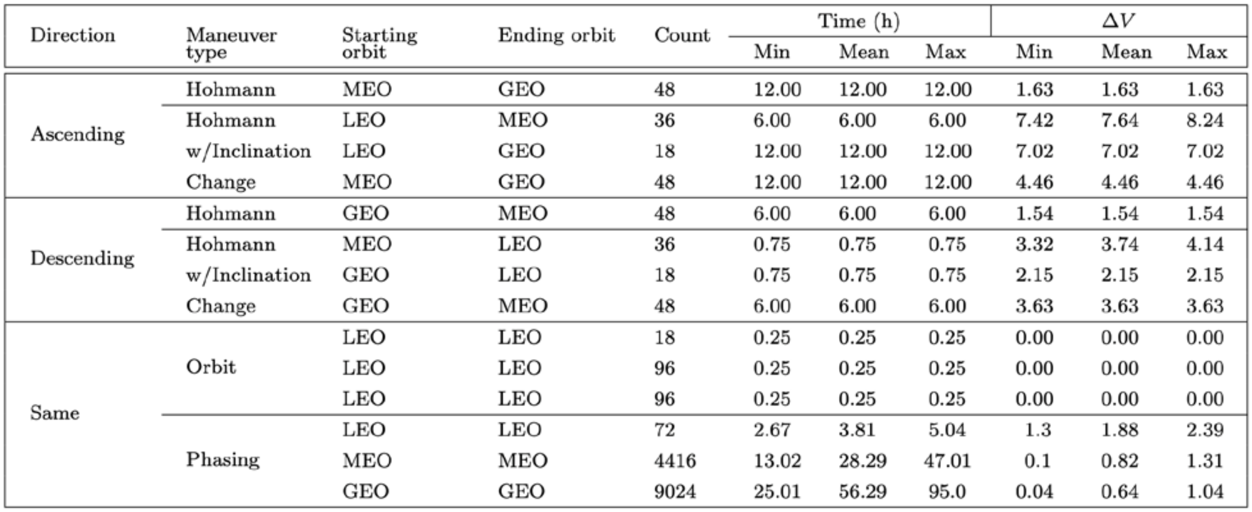
It should be noted that while the chosen mission duration is shorter than what would be required for realistic OOS mission execution—especially when accounting for multi-orbital maneuvers and maintenance operations—we use it as a prileminary setting for model validation. Additionally, for simplicity, we assume that maintenance tasks are executed instantaneously upon service vehicle arrival. These assumptions allow us to isolate and assess the core routing and scheduling logic of the IMROOS framework. Future work will extend the model to accommodate longer planning horizons and explicitly model time-dependent maintenance activities.



Orbit id	Nodes First,...,last	Semi major axis (km)	Inclination (deg)	RAAN (deg)	Based	Period (min)	Separation (min/deg)
1^L	1,...,6	6652.555	52.986	290.269	Starlink	90	15.0/60.0
2^L	7,...,12	6652.555	52.989	120.183	Starlink	90	15.0/60.0
3^L	13,...,18	6652.555	53.000	64.290	Starlink	90	15.0/60.0
4^M	19,...,66	26610.222	0.000	0.000	GPS	720	15.0/7.5
5^M	67,...,114	26610.222	55.000	300.000	GPS	720	15.0/7.5
6^G	115,...,209	42241.096	0.000	0.000	WGS	1440	15.0/3,75

Table 1: Orbital parameters defining the operational environment for the case studies

Table 2 summarizes the complete set of feasible maneuvers for the orbital environment specified in Table 1. For each maneuver classification, the table presents both the required execution time and associated propellant consumption (expressed as ΔV).



Direction	Maneuver type	Starting orbit	Ending orbit	Count	Time (h)			ΔV		
					Min	Mean	Max	Min	Mean	Max
Ascending	Hohmann	MEO	GEO	48	12.00	12.00	12.00	1.63	1.63	1.63
	Hohmann	LEO	MEO	36	6.00	6.00	6.00	7.42	7.64	8.24
	w/Inclination	LEO	GEO	18	12.00	12.00	12.00	7.02	7.02	7.02
	Change	MEO	GEO	48	12.00	12.00	12.00	4.46	4.46	4.46
Descending	Hohmann	GEO	MEO	48	6.00	6.00	6.00	1.54	1.54	1.54
	Hohmann	MEO	LEO	36	0.75	0.75	0.75	3.32	3.74	4.14
	w/Inclination	GEO	LEO	18	0.75	0.75	0.75	2.15	2.15	2.15
	Change	GEO	MEO	48	6.00	6.00	6.00	3.63	3.63	3.63
Same	Orbit	LEO	LEO	18	0.25	0.25	0.25	0.00	0.00	0.00
		LEO	LEO	96	0.25	0.25	0.25	0.00	0.00	0.00
		LEO	LEO	96	0.25	0.25	0.25	0.00	0.00	0.00
	Phasing	LEO	LEO	72	2.67	3.81	5.04	1.3	1.88	2.39
		MEO	MEO	4416	13.02	28.29	47.01	0.1	0.82	1.31
		GEO	GEO	9024	25.01	56.29	95.0	0.04	0.64	1.04

Table 2: Orbital maneuver classifications with associated time requirements and propellant consumption ΔV for the case studies

Figure 1 shows a graphical representation of network topology with the respective nodes and arcs, in which the six orbits used are visible.

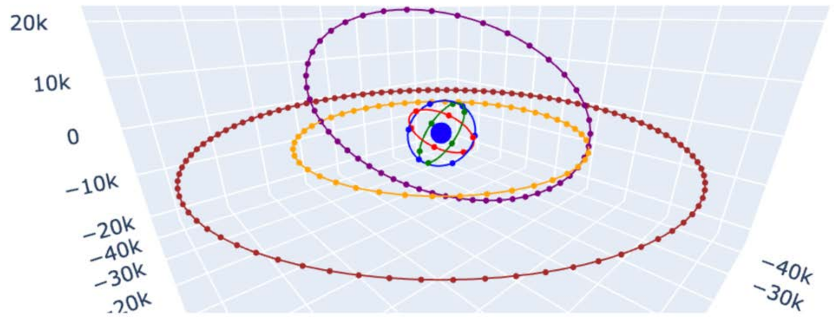


Figure 1: Spatial representation of the six orbital trajectories utilized in the experiments

4.2 Results and Discussion

We first examine the relationship between initial available propellant capacity for the servicing vehicles the and the total mission cost (as captured by the objective function value). Lower values indicate superior solutions in this minimization framework. Subsequently, we quantify the economic impact of the proposed maintenance optimization approach by comparing system costs under two scenarios: (1) no maintenance interventions and (2) optimized maintenance scheduling as determined by the IMROOS framework.

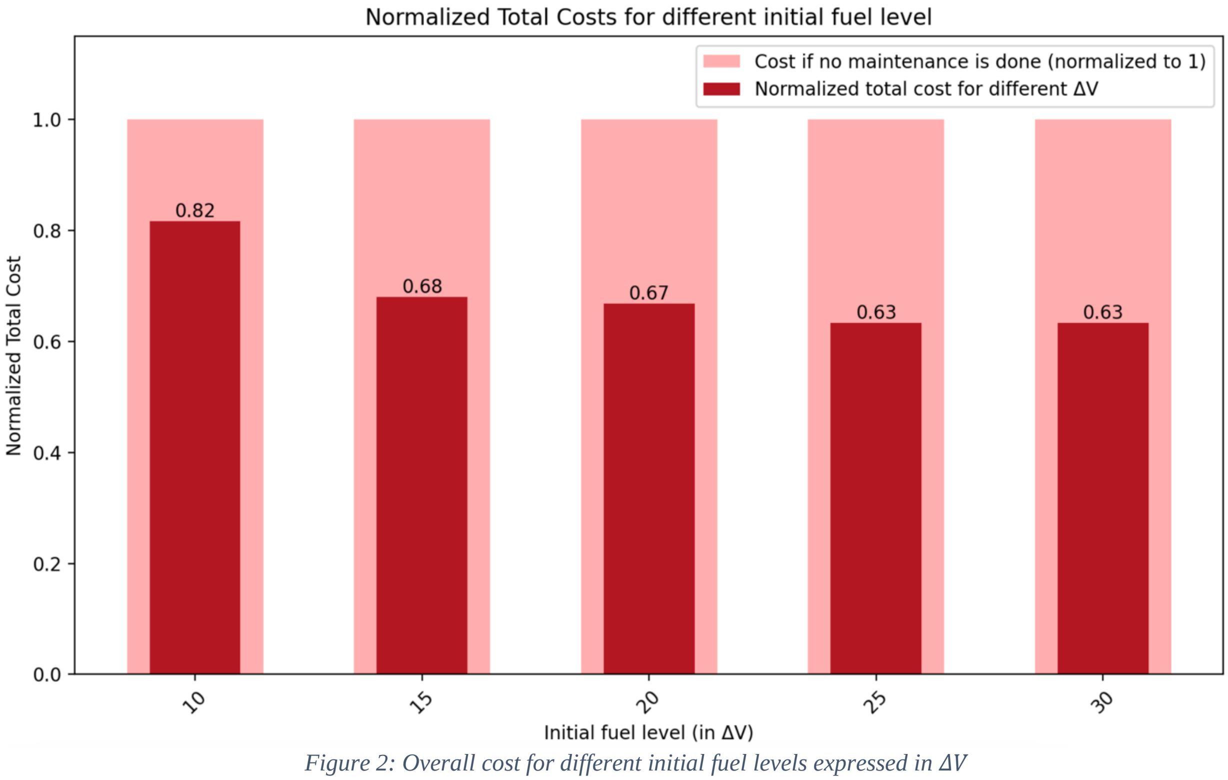


Figure 2: Overall cost for different initial fuel levels expressed in ΔV

Figure 2 illustrates the impact of maintenance optimization on total system costs. To improve the accuracy of the results, the initial positions of the satellites, the maintenance robot, and the refueling depots were randomly changed, and an average of the results was calculated, while remaining within the first case study using the orbital parameters presented in Table 1 and the node-arc network described in Table 2. The results demonstrate that across all initial propellant configurations, the optimized maintenance scenario (depicted in red) yields considerably lower total system costs compared to the no-maintenance baseline (depicted in pink). In the presented case study, this cost reduction reaches a maximum of 37% under optimal conditions, specifically at initial propellant capacities of 25 ΔV and 30 ΔV.

The analysis of propellant capacity influence reveals a decreasing relationship with system cost reduction. Incremental increases in initial propellant capacity produce diminishing marginal returns on cost reduction. For example, augmenting initial propellant of servicers from 10 ΔV to 15 ΔV yields a 14% reduction in total system cost, while the transition from 25 ΔV to 30 ΔV produces no measurable cost improvement. This indicates the existence of a propellant capacity threshold beyond which additional capacity offers no economic advantage within the current operational parameters.

The observed diminishing returns on propellant capacity can be attributed primarily to temporal constraints rather than fuel availability. As evidenced in Table 2, a substantial proportion of feasible maneuvers requires execution times that exceed the 24-hour time horizon established for Case Study 1. Specifically, phasing maneuvers in MEO and GEO regimes exhibit mean execution times of 28 and 56 hours respectively, while ascending Hohmann transfer maneuvers typically require 12 hours, representing 50% of the available planning window.

While these results reflect a modeling limitation of considering only a 24h mission planning horizon introduced for this initial framework validation, they also provide insight into real-world operational challenges. In particular, short planning horizons are relevant for urgent maintenance interventions—such as those required in response to unexpected system failures—where rapid servicing decisions must be made under tight temporal constraints. The model demonstrates how limited time availability restricts maneuver flexibility and may reduce the effectiveness of added propellant for the servicers, underscoring the need to tightly couple temporal and energy considerations in short-term OOS planning. These findings reinforce the utility of the IMROOS framework as a decision-support tool for both reactive and proactive mission contexts and motivate future extensions to accommodate multi-day or longer planning for long-lead preventive servicing campaigns.

These temporal constraints suggest that further performance improvements would require expanding the planning horizon, particularly for scenarios involving long-lead preventive maintenance and complex inter-orbital maneuvers. Extending the temporal scope would enable the optimization model to exploit the full range of efficient transfer options, thereby more accurately reflecting the operational timelines of real-world OOS missions, which often span several days or weeks. While the current model provides valuable insights into short-term responsiveness and mission feasibility under urgency, future extensions will aim to integrate longer planning horizons to support comprehensive servicing strategies across both reactive and strategic contexts.

5. Conclusion

This paper introduces the Integrated Maintenance and Routing Optimization for On-Orbit Servicing (IMROOS) framework, a novel approach to jointly optimize satellite maintenance and spacecraft servicer vehicle routing in OOS operations. The problem is formulated as a Mixed Integer Linear Programming model that minimizes total mission costs while balancing preventive and corrective interventions to client satellites across multiple orbital regimes.

A key contribution of the IMROOS framework lies in its integration of differentiated maintenance strategies (preventive vs corrective) with fuel-constrained trajectory planning, enabling the coordination of complex servicing operations within a dynamic orbital environment. Refueling infrastructure is incorporated to support extended mission durations for servicing vehicles and enhance operational flexibility.

Initial computational experiments validate the model's ability to reduce failure-related costs and improve overall servicing efficiency. Sensitivity analyses reveal diminishing returns with respect to increased propellant capacity for the servicers, where additional fuel does not consistently translate into improved mission outcomes due to time constraints on maneuver execution. These findings highlight the critical role of temporal constraints and demonstrate the relevance of IMROOS to evaluate mission planning both in short-term, urgent intervention scenarios and for future long-horizon planning tools.

While the current implementation adopts simplified assumptions on failure modeling and mission duration, the framework is adaptable to more complex degradation models and long horizon considerations. Future research will extend the model to accommodate longer planning horizons, time-explicit maintenance execution, and expanded orbital scenarios to further support the design of resilient and scalable OOS missions.

Acknowledgements

This work was supported by the *Agence Nationale de la Recherche (ANR)*, France, under the project **ANR-23-CE10-0006** (Resilient and Sustainable Planning and Management of Future Space Industry Infrastructure with On-Orbit Servicing), for which Adam Abdin serves as the Principal Investigator.

References

[1] Flores-Abad, A., Ma, O., Pham, K., & Ulrich, S. «A review of space robotics technologies for on-orbit servicing,» *Progress in Aerospace Sciences, Volume 68,* pp. Pages 1-26, July 2014.

[2] Rousso, P., Samsam, S., & Chhabra, R. «A mission architecture for on-orbit servicing industrialization,» *In 2021 IEEE Aerospace Conference (50100). IEEE.,* pp. pp. 1-14, 2021, March.

[3] Tatsch, A., Fitz-Coy, N., & Gladun, S. «On-orbit Servicing: A Brief Survey,» *In Proceedings of the IEEE International Workshop on Safety, Security, and Rescue Robotics (SSRR'06). New York: Inst. of Electrical and Electronics Engineers.,* pp. pp. 276-281, 2006, August.

[4] Bourjolly, J. M., Gurtuna, O., & Lyngvi, A. «On-orbit servicing: a time-dependent, moving-target traveling salesman problem,» *International Transactions in Operational Research, 13(5),* pp. 461-481, 2006.

[5] Sorenson, S. E., & Pinkley, S. G. N. «Multi-orbit routing and scheduling of refuellable on-orbit servicing space robots,» *Computers & Industrial Engineering, 176, 108852.,* 2023.

[6] Alfriend, K. T., Lee, D. J., & Creamer, N. G. «Optimal servicing of geosynchronous satellites,» *Journal of Guidance, Control, and Dynamics, 29(1),* pp. 203-206, 2006.

[7] Sarton du Jonchay, T., Chen, H., Gunasekara, O., & Ho, K. «Framework for modeling and optimization of on-orbit servicing operations under demand uncertainties,» *Journal of Spacecraft and Rockets, 58(4),* pp. 1157-1173, 2021.

[8] Dutta, A., & Tsiotras, P. «A greedy random adaptive search procedure for optimal scheduling of p2p satellite refueling,» *In AAS/AIAA Space Flight Mechanics Meeting,* pp. pp. 07-150, 2007, January.

[9] Du, B., Zhao, Y., Dutta, A., Yu, J., & Chen, X. «Optimal scheduling of multispacecraft refueling based on cooperative maneuver,» *Advances in Space Research, 55(12),* pp. 2808-2819, 2015.

[10] Gürtuna, Ö., & Trépanier, J. «On-orbit satellite servicing: a space-based vehicle routing problem,» *Operations research in space and air,* pp. 123-141, 2003.

[11] Zhou, Y., Yan, Y., Huang, X., & Yang, Y. «Multi-objective planning of a multiple geostationary spacecraft refuelling mission,» *Engineering Optimization, 49(3),* pp. 531-548, 2017.

[12] Sarton du Jonchay, T., Chen, H., Isaji, M., Shimane, Y., & Ho, K. «On-orbit servicing optimization framework with high-and low-thrust propulsion tradeoff,» *Journal of Spacecraft and Rockets, 59(1),* pp. 33-48, 2022.

[13] Abhishek, K., Muzikayise Clive, S., Viet Hoang, D., Ryota, Y., Qingqing, W., Florent, R. «In-Orbit maintenance: the future of the satellite industry, » 2016.

[14] Davis, J. P., Mayberry, J. P., & Penn, J. P. «On-orbit servicing: Inspection repair refuel upgrade and assembly of satellites in space,» The Aerospace Corporation, report, 25., 2019.