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AN EVALUATION METHOD FOR OPEN DISTRIBUTED SPACE SYSTEMS DRIVEN BY THE OPERATIONAL ASPECTS OF THE MISSION: MODEL, SIMULATION AND ANALYSIS

Carlos Leandro Gomes Batista

Doctorate Thesis of the Graduate Course in Space Engineering and Techonology, guided by Drs. Maria de Fatima Mattiello Francisco, and Andras Pataricza, approved in April 26, 2024.

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DEFESA FINAL DE TESE DE CARLOS LEANDRO GOMES BATISTA
BANCA Nº 067/2024, REGISTRO 136115/2019

No dia 26 de abril de 2024, às 10:00 horas, por videoconferência, o(a) aluno(a) mencionado(a) acima defendeu seu trabalho final (apresentação oral seguida de arguição) perante uma Banca Examinadora, cujos membros estão listados abaixo. O(A) aluno(a) foi APROVADO(A) pela Banca Examinadora, por unanimidade, em cumprimento ao requisito exigido para obtenção do Título de Doutor em Engenharia e Tecnologia Espaciais / Engenharia e Gerenciamento de Sistemas Espaciais, com a exigência de que o trabalho final a ser publicado deverá incorporar as correções sugeridas pela Banca Examinadora, com revisão pelo(s) orientador(es).

Observações da banca:
Professor Alessandro Golkar: literature review, scalability issue, questions in the thesis not specific to federation (it can be applied to other architectures) , scientific research question, answer question in the conclusions, future work, compelling results, PhD contribution, harmonization of references.

Professor Viktor Danchev will share his comments to the supervisors. Distinction between methodology for general performance against particular operational scenario tool. Style comments related to equations formulation, figures and citations.

Professor Geilson Loureiros's comments: needs to rewrite Introduction, Theorectical Background, Literature Review, Discussion chapter comparing what he did to what other people did and highlighting the contributions, Conclusions.

Geilson offers to review the final document after the modifications

Novo título: "AN EVALUATION METHOD FOR OPEN DISTRIBUTED SPACE SYSTEMS DRIVEN BY THE OPERATIONAL ASPECTS OF THE MISSION: MODEL, SIMULATION AND ANALYSIS".

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Declaração de aprovação dos membros externos Andras Pataricza, Alessandro Golkar e Viktor Danchev anexa ao processo.

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“The world was all before them, where to choose

Their place of rest, and Providence their guide:

They, hand in hand, with wandering steps and slow,

Through Eden took their solitary way”.

John Milton
in *“Paradise Lost (Book XII:646-649)”*, 1674

*To my parents, **Batista** and **Regina**, and to my brother,
Leonardo.*

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ABSTRACT

This thesis focuses on the intricacies of modeling, analyzing, and verifying resource sharing capabilities in a Distributed Space System of Systems (DSSoS) composed of different operating satellites. A DSSoS is a specific cooperative form of a Distributed Space System, DSS, which exhibits a unique composition of several satellites under the design, control, and management of different owners and stakeholders. Despite this diversity, they collaborate to pursue common goals through a collaborative mode of interaction. The growth of technologies based on CubeSats has significantly revitalized discussions about constellations, transforming them into more practical and cost-effective systems for government agencies and private companies. The sharing of resources through cooperation agreements between different institutions increases the possibilities for configuring and operating satellites for specific missions, paving the way for a whole new range of endeavors. DSSoS has a dynamic topology due to its independence of the design and control of the orbital trajectories of its space components, as well as their possible failure. One faced challenge is to establish resource sharing while ensuring the minimum allocation to meet the primary demands of individual missions. To this end, this work introduces a method that uses the Model-Based Systems Engineering approach, MBSE, to represent the architectural structure of the DSSoS, defining the parameters for the simulation and analysis steps. The method explores the DSSoS in terms of mission and its demands, mission segments, considered resources, and constituent systems, considered services. The inputs for defining the simulation needs and the analysis strategy are the demands that the services should fulfill and the evaluation metrics derived by the method. Finally, it explains how to conduct the qualitative and quantitative evaluation of the DSSoS, allowing the designer to understand the systems' capability to achieve a common goal by sharing their resources.

Keywords: DSS. FSS. DSSoS. CSRM. MS&A.

UMA AVALIACAO PARA SISTEMAS ESPACIAIS DISTRIBUIDOS ABERTOS ORIENTADO AO ASPECTO OPERACIONAL DA MISSAO: MODELO, SIMULACAO E ANALISE

RESUMO

Esta tese concentra-se nos meandros da modelagem, análise e verificação das capacidades de compartilhamento de recursos em um Sistema de Sistemas Espaciais Distribuídos (DSSoS) composto por diferentes satélites operacionais. Um DSSoS é uma forma cooperativa específica de um Sistema Espacial Distribuído, DSS, que apresenta uma composição única de vários satélites sob o projeto, controle e gerenciamento de diferentes proprietários e partes interessadas. Apesar desta diversidade, eles colaboram para perseguir objetivos comuns através de um modo colaborativo de interação. O crescimento das tecnologias baseadas em CubeSats revitalizou significativamente as discussões sobre constelações, transformando-as em sistemas mais práticos e econômicos para órgãos governamentais e empresas privadas. A partilha de recursos através de acordos de cooperação entre diferentes instituições aumenta as possibilidades de configuração e operação de satélites para missões específicas, abrindo caminho para todo um novo leque de empreendimentos. DSSoS possui uma topologia dinâmica devido à sua independência em termos de projeto e controle das trajetórias orbitais de seus componentes espaciais, bem como de sua possível falha. O principal objectivo é estabelecer a partilha de recursos, assegurando ao mesmo tempo a alocação mínima para satisfazer as necessidades primárias de missões individuais. Para tanto, este trabalho adota a abordagem da Model-Based Systems Engineering, MBSE, para representar a estrutura arquitetural do DSSoS, definindo os parâmetros para as etapas de simulação e análise. O método explora o DSSoS em termos de missão e suas demandas, segmentos de missão, considerados recursos, e sistemas constituintes, considerados serviços. Os insumos para definir as necessidades de simulação e a estratégia de análise são as demandas que os serviços deverão atender e as métricas de avaliação derivadas do método. Ele finalmente explica como conduzir a avaliação qualitativa e quantitativa do DSSoS, permitindo ao projetista compreender a capacidade dos sistemas de atingir um objetivo comum através do compartilhamento de seus recursos.

Palavras-chave: DSS. FSS. DSSoS. CSRM. MS&A.

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LIST OF ABBREVIATIONS

CS	–	Constituent System
FSS	–	Federated Satellite System
DSM	–	Distributed Spacecraft Mission
DSS	–	Distributed Space System
DSSoS	–	Distributed Space System of Systems
MoE	–	Measures of Effectiveness
MoP	–	Measures of Performance
KPP	–	Key Performance Parameters
QoS	–	Quality of Service
TPM	–	Technical Performance Measures

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1 INTRODUCTION

In recent decades, access to space has become easier and cheaper. Playing a great part in that is the development of reusable rocket stages, which considerably reduced the price of launching objects into space, and the advent of the CubeSats, with the standardization of components and deployers.

CubeSats, the largest representative of the nanosatellite category, are more than 2323 in-orbit objects nowadays. These numbers show that more than 5% of all objects in orbit today are nanosatellites, including *debris* (Space Track, Nanosats DataBase).

The advent of the so-called New Space also contributed to this scenario of low-cost satellite popularization. Not only limited by the space segment (i.e. spacecrafts), but also the development of new and cheaper launchers, piggy bag launches, streamlined CubeSat development, assembly, and testing, and ground segment development focused on on-demand operations.

A vast range of applications are being studied using the CubeSat standard (POGHOSYAN; GOLKAR, 2016; SELVA; KREJCI, 2012; NATIONAL ACADEMIES OF SCIENCE, ENGINEERING AND MEDICINE, 2016), especially due to its rapid development process and relatively low launch cost. This creates new perspectives on the feasibility of different types of space missions. Constellation is the most common term in this context with many successful examples of constellations from space agencies and private entities using traditional satellites (i.e. GNSS, Sentinel, Iridium, PlanetScope) (HOFMANN-WELLENHOF et al., 2007; ATTEMA et al., 2010; MAINE et al., 1995; GRIESBACH; MUKIMOVA, 2023), and dozens of proposed constellations with the advent of CubeSats (KULU, 2023).

According to Moigne et al. (2020), a “constellation” is a reference to a space mission that, from its inception, is composed of two or more spacecraft that are placed in specific orbit(s) to serve a common objective. Distributed Spacecraft Missions, DSM, on the other hand, is a more general definition of a multi-satellite system in which the satellites currently share a common goal but might have been designed independently and even by different institutions.

With the standardization of the platforms (e.g. CubeSats), the subsystems development, the expansion of systems informatization (e.g. IoT), concepts of Satellites swarms, constellations, inter-satellite communication networks, flight formation, are becoming more tangible. Not so far, also global terrestrial networks (e.g. AWS Ground Station) for tracking, monitoring, and commanding spacecrafts are now a reality in the business.

Such scalability and integration were unfeasible decades ago because of its intrinsic high cost and being delegated mostly to big governmental space agencies.

Discussing and studying new ways of distributed systems is a must in terms of the actual evolutionary stage of the space missions development.

1.1 Scope

Some ideas in the direction of new distributed solutions have been enlightened in recent years.

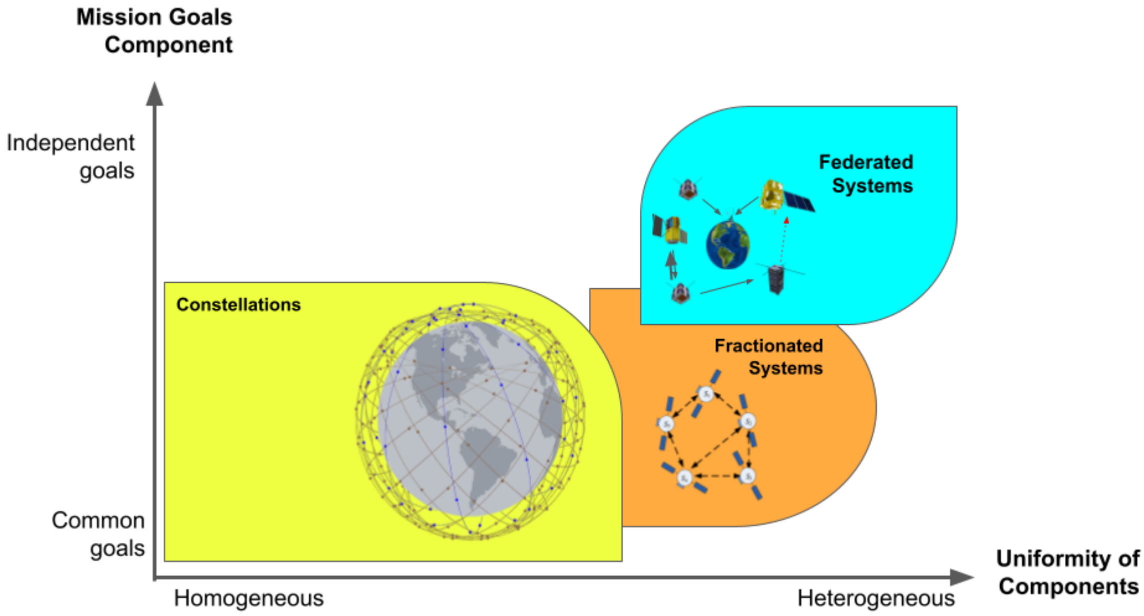
To start, the main definition of a Distributed Spacecraft Mission given by (MOIGNE et al., 2020) is: “a mission that involves multiple spacecraft to achieve one or more common goals”. As a general definition, the DSM does not specify whether these multiple spacecraft are launched together, achieve common goals by design or in an *ad-hoc* fashion, or if the common goals are scientific (ARAGUZ et al., 2018). The authors say that “Multiple” in this case refers to “two or more” and can refer to tethered or untethered satellites, although very few tethered concepts have been proposed so far.

Another example is the Fractioned Spacecraft Missions, where a spacecraft system is decomposed into modularized individual spacecrafts that can communicate wirelessly in formation instead of using a single monolithic spacecraft (BROWN; EREMENKO, 2006). Here, the spacecraft system can compose a cluster or fly-formation architecture where each individual satellite performs a specific function, a module, allowing flexibility in terms of scalability, evolvability, maintainability and adaptability (BROWN; EREMENKO, 2008).

Going further into the idea of distributed systems, inspired by cloud computing ideas, the Federated Satellite Systems (FSS) paradigm foresees the use of independent spacecraft as a network to trade unused resources and commodities, also to achieve a common goal (GOLKAR, 2013; GOLKAR; CRUZ, 2015). FSS envisions a space-based resource market, where missions dynamically offer, to the federation, any underutilized capabilities, such as communication channels, processing power, or data storage, and access to such resources depending on their needs (CRUZ; GOLKAR, 2014). From the users’ perspective, in-orbit services, in this sense, the payload data, become commodities that can be exploited and shared, the dawn of the "Satellite-as-a-Service". Most ideas on sharing resources in an FSS are based on the possibility and feasibility of an Inter-Satellite Network, which should be present in all elements of the FSS of this heterogeneous constellation in the form of Inter-Satellite Links (LLUCH; GOLKAR, 2019).

The Figure 1.1 exemplifies the differences between distributed spacecraft architectures in terms of form uniformity and goals.

Figure 1.1 - Notional map of distributed mission architectures.



SOURCE: Adapted from Golkar and Cruz (2015).

Using these complementary ideas, we can overcome and add more to this cauldron, Graziano (2012) and Leitner (2002) bring the general purpose of not only dealing with the space segment elements but also exploring the concept of a full collaborative Space System.

1.2 Motivation

Considering the growing trend on heterogeneous architectures for space missions, the motivation of this work is to study ways to evaluate the effective contributions which a Constituent System can bring to a collaborative federation when it makes resources available for sharing.

In this sense, in this thesis, the term Distributed Space System (DSS) is adopted to express the complete meaning of a space mission, not restricted to the concept of space segment as focused in the DSM definition (MOIGNE et al., 2020), but including ground and user segment facilities involved in the entire space mission operation. In this context, the term Distributed Space System of Systems (DSSoS) expresses the composition of different satellite missions, under the design, control, and management of different owners and stakeholders. Despite this diversity of CSs in the DSSoS, they collaborate in order to pursue common goals through a cooperative mode of interaction. DSSoS has a dynamic topology due to the independence of the design and control of the orbital trajectories of its space components, known as CSs, as well as their possible failure.

To give some context, a system of systems (SoS) refers to a collection of interconnected and independent systems that work together toward a common goal (*sup.*), often exhibiting behavior and complexity beyond the individual systems (JAMSHIDI, 2008). This concept fits very well when talking about DSS because SoS thinking reduces complexity by considering functional behavior and situation-sensitive approaches, aiding in the design and adaptation of behavior in complex adaptive systems (BARACHINI; STARY, 2022).

In this way, not only are in-orbit resources shared, but also ground and user segment resources and services can be shared and exploited (SCHMIDT; SCHILLING, 2013). The goal is to switch from monolithic and isolated space missions to a highly dynamic evolving Cyber-Physical System of Systems capable of supporting different goals with constant deployment of new constituent systems. In other words, “an integration of a finite number of Constituent Systems (CS) which are independent and operable and which are networked together for a period of time to achieve a certain higher goal” (BONDAVALLI et al., 2016).

This whole scenario of a Distributed Space System of Systems (DSSoS) can also be claimed as “Space-as-a-service”.

1.3 Research question and objectives

Given that context, motivation, and space for new applications, distributed space SoS open a wide range of possibilities. And, also, the constant rearrangement of different constituent systems drives to the question:

“How are Distributed Space Systems of Systems affected in constant reconfiguration scenarios when dealing with heterogeneous Constituent Systems ?”

The orchestration of the Constituent Systems is the core idea when searching for this answer. But it is also the most challenging task due to the intrinsic heterogeneity of a DSSoS. We will explain some of the pain points when describing our problem.

Among them, we have: a. Sharing resources; b. Provisioning of services; c. Scalability of demands; d. Emergent Behavior and; e. Quality levels.

1.3.1 Sharing resources

It is crucial for the DSSoS that the different CS are capable of sharing their resources. Capabilities such as contact time between spacecraft and ground stations, data storage, and communication links are examples of precious resources when we try to coordinate the operation of such a system.

This creates a full dependency on a well-defined Concept of Operations, ConOps, for the constellation (LARSON; WERTZ, 1999). As each CS has decentralized development and operations, the DSSoS operation itself cannot rely on the optimal delivery of resources, as the CS may have other priorities or even not be prepared to share its infrastructure.

So, it is a limited access to a limited amount of resources that must be managed by the DSSoS operations as a whole.

Identifying and quantifying these resources is one of the objectives of this thesis.

1.3.2 Provisioning of services

The services, or functionalities, that each resource can provide to the system must be manageable by the DSSoS operations in order to correctly allocate them to fulfill the mission goals or demands. When a new satellite or ground station enters the Distributed System, it will come with a set of available services that can be exploited by the system. The Constellation Operations shall then be capable of quickly adapting its behavior to better make use of these services. Also, the same is true when we think about a spacecraft or a ground element leaving the Space System.

Dealing with these scenarios on a reconfiguration of constituent systems is one of the objectives of this thesis.

1.3.3 Scalability of demands

Orchestrating the operations can be easily performed when dealing with a small number of spacecraft and ground stations. But this may not be true with a full and well-developed operation that may collapse with an increasing number of space and ground elements to manage. It is because the underlying architecture for operations does not scale to large constellations (BEN-LARBI et al., 2021).

However, demands from different stakeholders may start to increase exponentially as the number of CS increases and conflicts on expectations may arise.

Finding ways to upscale a solution is one of the objectives of this thesis.

1.3.4 Emergent behavior

It is a common trait of the CPSoS to deal with emergent phenomena. These are behaviors that were not expected during the concept of a system of systems. Emergent behaviors become active or evident only when the CS begins to collaborate in the SoS ("The whole is larger than the sum of its parts"), it has the potential to offer new services (IVO et al., 2023). Furthermore, there are unwanted emergent behaviors that may introduce risks or dependencies essential to SoS capabilities (DAHMANN et al., 2011).

Dealing with unwanted emergent behavior, evaluating them and qualifying them is one of the objectives of this thesis.

1.3.5 Quality levels

Quality can be defined as ‘how well’ a system performs on a scalar, quantitative, measurable level (HAUSE, 2011). These same levels can be traded off. The focus is on how to measure these levels in such a heterogeneous system. With constant reconfiguration, these measures can be used, in the context of SoS implementation, to assess the status and progress of it in meeting the objectives, goals, and/or demands (KASLOW et al., 2022).

Quantifying and Qualifying the Levels of Performance of a DSSoS is one of the objectives of this thesis.

1.4 Structure of the Thesis

The thesis is structured as follows: Chapter 2 with a theoretical background on the subjects relevant to this work, Chapter 3 with a literature review of recent and past research works that are the subject of this thesis. Chapter 4 presents the modeling, simulation, and analysis method, the main topic of this thesis. The Global Open Collection Data System, GOLDS, is the case study for the application of this method, and it is presented in Chapter 5. Chapter 6 presents the results analysis from the method and its application on a real distributed system. As the Chapter 7 summarizes the conclusions, contributions, limitations, and future works from this thesis. The Appendices A and B are the compiled version of the SysML model generated for this thesis and the parametric values used for the simulation, respectively. Annexes A and B bring two accepted papers and presented in two different symposiums during the realization of this PhD.

2 THEORETICAL BACKGROUND

To establish a common ground of terms in this work, we will refer to this concept of an open DSSoS where the constituent systems (CS) of the whole space mission (space ground and user segments) work together and collaboratively to achieve a common goal. Using the taxonomy from (MOIGNE et al., 2020) defining it as: (a) heterogeneous; (b) *ad-hoc* Mission (c) reconfigurable; (d) deployable and; (e) collaborative.

Heterogeneous, as each CS may not comply in form factor or primary goal. They can also have different owners or stakeholders. *Ad-hoc* mission, in terms of spatial relationship, as we do not have control over the launch and deployment of the CS; Reconfigurable, new CS can come and go from the DSSoS as they intend to share and support the mission. Deployable, derived from its reconfigurable capabilities, the different CS can be part of the system at different points in the mission life cycle. Collaborative, the DSSoS mission goal can only be achieved by the cooperation of the different CS, on how much they collaborate to the quality of service delivered. The sharing of resources to fulfill a set of demands from the mission is the key concept of a Distributed Space Mission, and also for the DSSoS.

The aim is to break down the DSSoS structure in terms of a mission Concept of Operation, ConOps, its demands, available resources, and offered services. And be able to evaluate these aspects in a distributed way of operations. This shared and limited amount of resources plays a role in satisfying mission demands, characterizing the quality of service provided by the Distributed Space System.

DSSoS is a space mission paradigm that instantiates the Cyber-Physical System of Systems, CPSoS, concept in the space domain (UNITED STATES. DEPARTMENT OD DEFENSE, 2011), aiming to switch from independent, isolated space missions to a highly dynamic, constantly evolving in-orbit infrastructure capable of supporting different missions. DSSoS constitutes the dawn of cloud computing environments in space, which will significantly change the way space missions are conceived and operated.

2.1 Constellations and other distributed systems

Space systems, in special constellations, CubeSat based or not, may be classified as System of Systems, SoS (TIPALDI; GLIELMO, 2017), as their constituent parts are characterized by: operation and management independence (e.g. space and ground segments), geographical distribution (e.g. tracking, telemetry, and commanding stations), emergent behaviours (e.g. mission exploitation), and evolving development (e.g. recurring missions with short life cycle). One example is the use of CubeSats as a constellation for the Space Internet of Things. (KAK; AKYILDIZ, 2020; AKYILDIZ; KAK, 2019) analyze and conceive an architecture for a LEO constellation to be used as M2M, Machine-to-Machine, communication. They use gateways and ground stations to interface the communication between several different intelligent systems (e.g. smarthouses, smartgrids, internet, and self-driving cars).

Functional requirements are the main aspects to be considered during the specification, development, verification, and validation of complex systems (LARSON; WERTZ, 1999). When we talk about space systems, non-functional requirements are also discussed when analyzing, designing, developing, and operating them. It is crucial to develop new methods and processes to better understand the correlation between functional and nonfunctional aspects as soon as possible in the system life cycle. The point is to minimize the risks of modifications needed in the late stages of the project (SWARTWOUT, 2018).

López et al. (2019) presents a software tool for modeling possible small satellite constellations, in a DSS approach. Those DSS are supposed to be operated with the bare minimum of human interference and intend to be coordinated by inter-satellite communication networks. The aim is to provide multiple services in orbit, increasing their performance and capabilities.

A similar approach is presented by Tipaldi and Glielmo (2017). Besides the scope of this specific work is on autonomous processes for general space missions, it points out specific subjects about constellations, and it cites the Federated Spacecraft Systems (GOLKAR, 2013). Two levels of requirements are observed in this configuration: (i) locally, about one single satellite on the FSS and; (ii) globally, about the operation of the constellation as a whole (i.e. service continuous generation, spacecrafts real-time control, resource sharing optimization, and robust operation in order to deal with possible faults and failures). Such characteristics can be seen and applied to a specific Brazillian context, shown by Mattiello-Francisco (2018).

Another concept that may be added to the aerospace system evaluation context is the one about CyberPhysical Systems, CPS, or CyberPhysical System of Systems, CPSoS. CPS are, in general, systems that present a high interaction between the physical and the computational components, high needs for adaptability, constant data analysis, resiliency, criticality, and they tend to be geographically spread (BON-

DAVALLI et al., 2016; ZHENG et al., 2015). The New Space paradigm has quite a numeorus characteristics in common with CPS and CPSoS: (i) constellations and formation flights are adaptative systems with critical operation; (ii) the presence of faults are inherent behaviors on space systems due to its complexity which demands resilience; (iii) ground station networks for tracking, telemetry, and commanding the spacecrafts are geographically spread around the world (e.g. SatNOGS, AWS Ground Station) and they can act in a coherent way to achieve better service quality and; (iv) the amount of operational data generated that needs to be analyzed to determine and define different operational and degraded modes.

An effort for the conception of CPS on the aerospace context is being done by the project ADVANCE – Addressing Verification and Validation Challenges in Future Cyber-Physical Systems. It is a joint research venture between the National Institute for Space Research (INPE/Brazil), Campinas University (UniCamp/Brazil), Budapest University of Technology and Economics (BME/Hungary), Coimbra University (Portugal), Los Andes University (Colombia), National Inter-university Consortium for Informatics (CINI/Italy), and Resiltech s.r.l. (Italy).] This project uses as one of its case studies the Brazilian Environmental Data Collection System, BEDCS. This system has been working since the 1990s with the satellites SCD-1, SCD-2, and CBERS family. The goal is to conceptualize the BEDCS as an adaptive CPSoS with spacecrafts that share their hosted payload as an Environmental Data Collector (DUARTE et al., 2020; QUEIROZ et al., 2018; LIMA; DUARTE, 2018), user data collection under the IoT approach (LIMA et al., 2018), and a distributed concept for space, ground and user segments, the Global Open coLlecting Data Systems, GOLDS (MATTIELLO-FRANCISCO et al., 2018; SOUTO et al., 2022).

The correlation between GOLDS and the concept of DSSoS brings new and complex points to be studied and analyzed.

2.2 Verification and validation

Despite the notoriety of CubeSats, much of the work is geared towards one-off experiments on specific missions. This makes it difficult to scientifically analyze the results of processes such as V&V, since they are difficult to reproduce.

The studies presented here have been divided into categories that seek to represent the activities inherent in space V&V processes (NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (NASA), 2015a; EUROPEAN COOPERATION FOR SPACE STANDARDIZATION (ECSS), 2018).

2.2.1 Planning

EUROPEAN COOPERATION FOR SPACE STANDARDIZATION (ECSS) (2010) is here to illustrate actions for crossing the ECSS and NASA standards to improve mission processes based on the CubeSat standard. EUROPEAN SPACE AGENCY (2016) specifies the applicability of ECSS Systems Engineering standards to the European Space Agency's In-Orbit Demonstration (IOD) CubeSat nanosatellite projects. NASA has instructions for trimming, tailoring, its processes taking into account: (a) mission type, (b) mission criticality, (c) acceptable risk level, (d) national significance, and (f) complexity (NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (NASA), 2015b).

Bürger (2018) introduces MBSE, Model Based Systems Engineering, to address the challenges of satellite Assembly, Integration and Tests, AIT. The work presents a conceptual framework that considers the use of MBSE to provide input for satellite AIT campaign planning. The application of the framework is demonstrated on the AIT of a small university satellite. The proposed framework has been shown to foster the AIT team's contribution to product design, while capturing in models approximately 91% of the product-related inputs that form the basis of AIT planning.

Kaslow and Madni (2018) brings up the *CubeSat System Reference Model*, CSRM, as an example of a reference developed by the *INCOSE Space Systems Working Group*, SSWG, (OBJECT MANAGEMENT GROUP (OMG), 2022). The aim of the model is to facilitate the design, verification and validation of CubeSat projects. The CSRM has been= developed with sufficient flexibility to allow customization for different missions by different teams.

Conto et al. (2018) presents an integrated systems modeling approach for VCUB1, the first 100% nanosatellite developed by the Brazilian private sector.

VCU1 represents a low-cost alternative to reach higher levels of maturity of these technologies. The development of the satellite is under a partnership between Visiona and the Brazilian applied research institute called SENAI Innovation Institute for Embedded Systems. The main objectives of the VCUB1 mission are to validate the software of the Attitude and Orbit Control System (AOCS) and the On-Board Data Control System (OBDH), the development of a ground station, a test platform for the OBDH (designed to help test the integration of the Embedded Computer with the other subsystems, sensors, and actuators of the VCUB1 nanosatellite), and to test future space missions.

Jacklin (2017) review of the literature reveals that even though simulation and testing have by far the longest legacy, model-based design methods prove useful for software verification and validation. Some work on formal methods, although not widely used in satellites, may offer new ways to improve the verification and validation of small satellite programs. It also takes advantage of and returns to a model philosophy also raised by Eickhoff et al. (2003) using intermediate development platforms, the DevSats and FlatSats.

Weitz (2018) also presents an analysis of two behavior-based methodologies for the V&V of CubeSats in the educational context, CoRE – Consortium Requirements Engineering – and Monterey Phoenix, both approaches based on behavioral models. Using the expected behavior of the satellite, it would be possible for students to abstract design choices into use cases for each stakeholder involved. And, further down the line, translate these behavioral models into specifications and models that would facilitate easy learning about systems engineering, subsystem integration, and software engineering techniques.

Modeling approaches are being used to support mission engineering activities, as demonstrated by (BEERY, 2019; LASORDA et al., 2018; KASLOW et al., 2022). Having a model representation for the DSSoS is mandatory to evaluate its impact and aspects on sharing resources, providing services, demand scalability, emergent behavior, and quality (BATISTA et al., 2023; BATISTA et al., 2022).

2.2.2 Execution

Khan et al. (2012) developed an approach called Model-Based Verification and Validation (MBV&V). It uses SysML to perform early design verification and validation (via software) of the platform, long before the actual hardware exists. The main objective of this study is to reduce verification and validation by simulating real tests using models. The study's simulations focused on the subsystem and equipment level, but the authors suggest that the systemic application of the approach is promising.

Conceicao et al. (2016) The approach presents a Scalable Test Architecture System (STAS) to support the V&V process in the integration of software-intensive embedded subsystems. The approach aims to anticipate, in the nanosatellite development process, possible failures in the interaction of the platform with its payloads and facilitates the reuse of the test architecture in different phases of the same mission or in satellites of the same family, through the combined application of the Model-Driven Engineering and Model-Based Testing approaches. The method developed systematizes: (i) the design of behavioral models of communicating subsystems in order to verify the subsystems' interoperability requirements through model validation (MIL – Model-in-the-loop), (ii) the automatic generation of computer code from the validated models, by MDE tools, allowing the verification of interoperability requirements in a simulated environment, using the real communication bus (SIL - Software-in-the-loop), (iii) the evolution of models so that abstract test cases can be generated by MBT tools, (iv) the execution of test cases to validate real subsystems (HIL - Hardware-in-the-loop) in the integration phase, and (v) the possibility of injecting faults by means of a Fault Emulation Mechanism (FEM), which makes it possible to test the interaction of the real subsystems in terms of the specified robustness requirements. To assist in the specification of robustness requirements, the approach presented uses a dependability spreadsheet, which applies the concepts of dependability tree and cause-effect analysis to fault mitigation.

Fernandez et al. (2015) uses a part of an MDE-based process to automate a Verification and Validation process for software on board satellites. This process is implemented in a software control unit of the energy particle detector, which is the payload of the Solar Orbiter mission. From the design model, a scheduling analysis model and its verification model are generated. The verification is then defined as Finite-Timed Automata constraints. When the system is deployed on the target, the verification evidence is extracted as measurement points. The constraints are placed with the evidence; if any of the constraints are not met, the *scheduling* analysis is not valid.

Batista et al. (2019) presents a framework of a fault emulator mechanism, FEM, to test the robustness of software-intensive interoperable subsystems on board a nanosatellite. The FEM acts in the communication channel as part of the integration test environment in two phases of the nanosatellite project: (i) specification of robustness requirements using model-in-the-loop (MIL) approach and (ii) robustness validation using hardware-in-the-loop (HIL) approach.

The architectural aspects of the proposed FEM structure support its instantiation in any communication channel of the CubeSat standard.

Almeida et al. (2019) develops a meta-model of a CubeSat mission and its Concept of Operations (ConOps). The expected meta-model should be composed of a set of artifacts contained in the Arcadia method, built in the Capella software tool, representing a sum of points of view to serve as a central source of information in the environment of Concurrent Engineering Centers (such as INPE's CPRIME), which can benefit from an integrated system model that contains the flow of information between the disciplines present in the concurrent engineering approach, favoring fast and collaborative work

Sindermann and Golkar (2023) proposes a modular hardware in the loop architecture to simulate space system operations, including satellite simulations, flatsat data, and satellites flying in orbit. Defining a digital shadow for assessing potential evolutions of satellite constellations. It has the potential to be used in the early stages of a project by quickly evaluating different scenarios.

The execution of V&V process when talking about complex systems relies on the simulation aspects of the proposed models, as well as evolving the activities, when possible, from MIL, to SIL and finally HIL approaches. A DSSoS due to its complexity needs to be simulated, not only to validate the quality of the model conception but also to be able to evaluate the representation of the DSSoS capabilities itself.

2.2.3 Control

Bürger (2014) proposes a systemic AIT method based on the adaptation of European ECSS standards and traditional INPE AIT activities. Through the practical example of applying the method to the AIT of ITA's AESP14 CubeSat, it can be concluded that the method proposed in this work gives the system more reliability by carrying out the minimum set of systemic tests that provide the minimum guarantee that a given peak or nano-satellite is free of potential defects, and guarantees a certain level of tolerance against the space environment. The method uses little documentation, which contains the essential elements for the planning and execution of the AIT, which encourages the recording of lessons learned from each stage, to compensate for the lack of literature observed on the subject.

Feldt et al. (2010) evaluates whether the use of ECSS standards is valid when it comes to cost and whether there are ways to make the V&V process less expensive while maintaining quality. It also seeks to analyze how the V&V activities of two European aerospace companies that use ECSS standards can be optimized. The case studies reported focus on how the adopted standards are used by the companies and how they affect their V&V processes and activities.

Kaslow et al. (2018) enlightens the need for proper modeling of the technical measures in the CSRM. Technical measures are used to determine if the technical solution will meet stakeholder needs, provide early indications if the development effort is not progressing as needed to meet key milestones, predict the likelihood of the delivered solution to meet performance requirements, monitor high-risk items, and assess the effectiveness of risk mitigation actions.

Knowing what expectations are from a specific scenario or mission is a good way to evaluate and attest the quality of the provided service. Translating stakeholders' needs into demands and quantitative measures helps in assessing a DSSoS. Additionally, analyzing these measurements in terms of what is possible, what constrains the mission, what is achievable, and how to reconfigure the SoS to provide the best possible service are intrinsic needs if the objective is to provide a correct evaluation of the DSSoS state.

2.3 Concept of Operations

The Concept of Operation and the Operational Concept are disciplines of Systems Engineering that are very close in their definitions. Both are defined as verbal or graphic statements, in general terms, of an organization's intentions regarding an operation or series of operations (Concept of Operation) of a system or related set of systems (Operational Concept) (INTERNATIONAL COUNCIL ON SYSTEMS ENGINEERING (INCOSE), 2021).

In Space Systems Engineering, ConOps is a discipline (LARSON; WERTZ, 1999) present in satellite design from the beginning of the mission development cycle. There is no differentiation here between Concept of Operation and Operational Concept, as the terms are used by different institutions, *Concept of Operation* by NASA and *Operational Concept* by ECSS. Thus, ConOPS is a description of how the elements of the ground, space, and user segments must interact to meet the mission requirements, thus demonstrating how the mission will work in practice (LARSON; WERTZ, 1999). Critical performance, functional and non-functional requirements are analyzed, as well as the qualitative and quantitative objectives that will lead to mission success. This includes how data will be transferred to the end user, how the mission can be controlled, updated, and exploited, and how each component/subsystem should behave. ConOps is therefore highly relevant to the V&V process because it involves all the mission's constituent systems (space, ground, and user segments) and their interactions and dependencies. And, the development of solid ConOps in the early stages of the project (refining with the requirements of the development and design phases) is critical to the success of V&V activities (NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (NASA), 2015b).

The forementioned work by Almeida et al. (2019) works on the use of a meta-model for CubeSat missions and their ConOps, other initiatives also bring the use of MBSE to the design of space missions with CubeSats (KASLOW; MADNI, 2018; FERNANDEZ et al., 2015; EICKHOFF et al., 2003).

However, these works treat ConOps as just another discipline to be managed during the life cycle or even present the definitions of operation in a succinct and specific way to the needs of the project (VENTURINI et al., 2009; ROSCOE et al., 2018; ASUNDI; FITZ-COY, 2013; MALPHRAS, 2016).

From the point of view of INTERNATIONAL COUNCIL ON SYSTEMS ENGINEERING (INCOSE) (2021), ConOps as a graphic or verbal description of an organization's intentions in view of an operation, at a high level, here we take the liberty of simplifying the definition of this as the expected behaviour of space systems in view of providing services, *space-as-a-service*.

In this way, other systems, already known to use this assumption of services, use different approaches to: (i) communication with *stakeholders*; (ii) deriving objectives, targets, and technical measures; (iii) generating clear documentation with subjectivity that allows for consumer validation and developer verification; and; (iV) continuous integration and maintenance of the system.

This is the case with the techniques used in so-called agile projects, i.e. eXtreme Programing (ANWER; AFTAB, 2017). Test-based approaches are part of agile development, Test Driven Development (TDD), Acceptance Test Driven Development (ATDD), and Behaviour Driven Development (BDD) are focused on software development, but their approaches can be adapted to space product development processes. They emphasize the decentralization of documents, better communication with stakeholders, aiming for cohesive tests, simplification of the project, constant revision and continuous iterations (GÓMEZ et al., 2018). Like the SCRUM methodology, which focuses on management processes, XP is useful in technical processes (KAZEROUNI et al., 2019; GÓMEZ et al., 2018; SOLÍS; WANG, 2011).

An application of TDD and BDD techniques in the space environment can be found in Mwakyanjala et al. (2020), where these techniques are used to develop an SDR (Software Designed Radio) for a Satellite Operating Ground Station. Despite the difficulties encountered in the implementation of TDD / BDD, the authors highlight the advantages of *test-first* over *test-last* practices in terms of systematic fault finding, ensuring compatibility and modularity.

As described above, ConOps is how the space, ground, and user segments work together to meet the requirements (LARSON; WERTZ, 1999). It demonstrates how the mission must work to fulfill the mission demands. In a federated-based system operation that is mandatory. Orchestrating the resource sharing, reconfiguring the aspects of the system, and up/downscaling the DSSoS based on the availability of its constituent systems are the core points. And the ConOps definition plays a big role at this point.

3 LITERATURE REVIEW

As commented in the previous sections, mainly in Chapter 2, the concept of an Open Distributed Space System still lacks a comprehensive approach to its verification and validation.

Once we cannot literally verify, there is no specification to be verified; what is aimed is not to approve or reject the constellation as a solution, but to evaluate its capabilities as its distributed aspect allows us to do.

What it means is that, given the intrinsic heterogeneity of the system and the absence of control over the design and management of the constituent systems, an DSSoS cannot be fully a subject of verification activities. It is closer to what the US Department of Defense is going to call Operational Test and Evaluation (UNITED STATES. DEPARTMENT OD DEFENSE, 2011) than a verification.

Of course, some specifications, for example, in interface level, that allow the constituent system to be incorporated into the system (e.g. uplink and downlink frequencies), can be verified *a priori* to the admission of such a system. The evaluation is not based on the binary idea of verification correctness, but on the validation uncertainty of conformity (INTERNATIONAL COUNCIL ON SYSTEMS ENGINEERING (INCOSE), 2021). What needs to be verified is if all the constraints defined by the Mission's Concept of Operations are satisfied. Then, to evaluate, within the constraints met, how far the actual (or future) configuration of the DSSoS is from the stakeholder expectations.

Nowadays solutions can provide support on this matter, but additional work is needed to modify the current state of the art and, in some cases, create entirely new ones (KASLOW et al., 2022).

In fact, a whole scientific area is dedicated to dealing with this kind of 'unstructured' problems.

In this section, we are going to explore some of the works that already tried to deal with the intrinsic problems of distributed space systems and their verification and validation.

3.1 V&V on distributed space systems

Verification and validation of distributed systems in space is crucial due to the complexity and cost of deploying constituent systems. Various techniques like model checking, theorem proving, and runtime verification are employed to ensure system-wide verification, especially in modular autonomous systems (CARDOSO et al., 2021; PECHEUR, 2000; PECHEUR, 2006). Traditional testing methods are considered inefficient for these kinds of systems, leading to the exploration of advanced V&V techniques such as static analysis, model checking, and compositional verification to enhance trust in model-based systems (BRAT et al., 2006). NASA, for example, shifts toward distributed, intelligent, and autonomous systems for future missions that require the development of new V&V techniques tailored to highly parallel and nondeterministic systems, departing from conventional approaches designed for monolithic systems (HINCHEY et al., 2001). These advancements in V&V methodologies are essential to ensure the reliability and efficiency of distributed and autonomous systems deployed in space.

Huisman and Seceleanu (2020) and Huisman and Seceleanu (2022) focus on formal methods for heterogeneous system verification, emphasizing the challenges in verifying distributed systems driven by failure domains. However, they lack consistency due to failure domain issues, difficulty developing correct and reliable distributed systems, and the requirement for new models, notations, and techniques for such challenging systems.

3.2 Operational Research for space applications

Operational Research is “a discipline that deals with the application of advanced analytical methods to help make better decisions” [1].

OR, for short, has a relationship with the space industry since the begging of the space rush (FLIEGE et al., 2012). Planning and Scheduling, Constellation and ‘ad-hoc’ network optimization are some of most common applications of OR in the space sector.

Current advancements in operational research techniques for space systems include the development of multimodel approaches for operational diagnosis (CHRISTOFI et al., 2023), the use of adaptive planning and scheduling methods for groups of satellites (GALUZIN et al., 2020), the proposal of Space-based Operationally Responsive

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[1] https://www.informs.org/Explore/What-is-O.R.-Analytics/What-is-O.R.

Systems to handle exceptional cases in space systems (CHANG et al., 2015), the investigation of orbit control in multi-debris removal through far-range trajectory optimization (WANG et al., 2018), and the integration of machine learning capabilities and autonomous agent architectures in operational research for space systems (CHIEN et al., 2005). These advancements aim to enhance the performance, reliability, and adaptability of space systems by addressing issues such as complexity management, resource allocation, maneuverability, and response to uncertainties, ultimately improving the overall operational efficiency and effectiveness of space missions.

Vladimirova et al. (2006) presents a conceptual model for a heterogeneous picosatellite constellation. In fact, the idea is to deploy several picosatellites to work as relays for a bigger constellation, improving communication, processing power, and reconfiguration. The solution relies on the existence of an inter-satellite communication network and this solution is specific for the scenario.

In Bianchessi et al. (2007) an algorithm is presented to solve a Multi-Satellite, Multi-Orbit Problem for scheduling an Earth Observation Mission. The idea is to orchestrate several satellites to fulfill user requests (imaging). Although this solution is well-defined, it is limited by the earth observation scenario and is focused on scheduling the requests based on the available orbits.

Zhu et al. (2010) also shows a solution for planning and scheduling several satellites for Earth Observation. In the paper, they demonstrate an analysis to maximize coverage and minimize fuel consumption. In addition, solar radiation and local time are requirements for the imaging that must be fulfilled, in this case, operational constraints. Again, it is limited by the application scenario, and it is single-satellite focused. But driving the analysis by the concept of fulfilling a demand at the same time as dealing with operational constraints is a good approach when we talk about dealing with multiple actors, multiple perspectives, incommensurable and/or conflicting interests, and key uncertainties (MINGERS; ROSENHEAD, 2004).

3.3 Problem Structuring

Problem Structuring Methods, PSM, are a group of model-based problem handling approaches offering OR access, with the purpose of helping in the structuring of problems where the elements are connected by interrelationships (GASS; FU, 2013; SMITH; SHAW, 2019).

Mingers and Rosenhead (2004) provides a review and evaluation of different PSM. It elects some of the elements that a PSM must do, such as enable different perspectives, interactive operation, and allow improvements to be identified.

More recently, GOMES JUNIOR and Schramm (2022) has also reviewed the PSM in the last decade. It shows that not only is the PSM widely used for different application areas, but also the Soft System Methodology, SSM, is the most used. Used also as a multimethodological approach that is combined with other methodologies, such as simulation for resource planning and allocation (LEHANEY; HLUPIC, 1995). Even though the OR approaches are being used in the space sector, PSM is not. GOMES JUNIOR and Schramm (2022) performs a statistical review of the PSM application, and the aerospace sector does not even appear, even if we can exploit the application on system design and resource allocation.

Smith and Shaw (2019) presents a framework for reviewing PSM methodologies based on four pillars: system characteristics, knowledge, values of model building, and structure analysis. For all these pillars SSM demonstrates a good and solid basis, for understanding the system model, representative knowledge about the area of concern, quality of service judgment, and convergent and divergent thinking.

PSM focuses on how to analyze a problem, with models as integrated representations that help to negotiate and gain new understanding (SMITH; SHAW, 2019). That is why the fit between MBSE approaches, operational simulations, and analytical methods is a feasible solution for dealing with DSSoS. Mainly due to its intrinsic characteristics: heterogeneity, ‘ad-hoc’ mission, reconfiguration, continuous deployment, and collaboration.

4 METHOD

In this section, it is going to be discussed the comprehensive method and its environment. The concept is to use MBSE to complement a Problem-Structure-like method and bring up a solution for the performance evaluation of an Open Distributed Space System of Systems. This can be used for redesign of legacy space systems with the addition of newcomers, and to be able to simulate different scenario configurations in a complex pluralistic context.

4.1 Modeling

Model-Based System Engineering, MBSE, is a formal application of Systems Engineering using the system model as a central artifact to support activities, including requirements definition, design, analysis, verification and validation (BORKY; BRADLEY, 2019). MBSE focuses on evolving and refining the model to achieve the desired representation of the system (FRIEDENTHAL et al., 2014). Based on the works for the CSRM (OBJECT MANAGEMENT GROUP (OMG), 2022), the intended system model uses the concept of different diagrams that can represent different aspects or views of the SoS.

The Figure 4.1 presents the profiles used that can better represent the Concept of Operation in a DSSoS.

Here, the focus will be on the architectural concept of the system (see Figure 4.2), the one which is going to have more modifications compared to the original CSRM. This architectural structure of the DSSoS will be the main input for the future phases, on simulation and analysis.

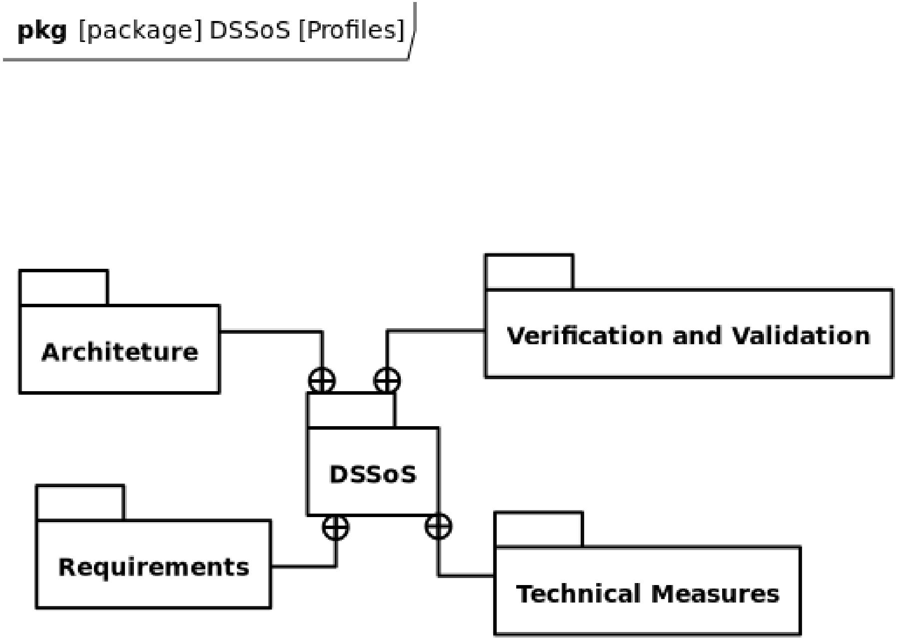
The mission $m(T)$ has its demands $d(m, T)$, which can be derived from the expectations of the stakeholders.

In the same sense, each segment can be defined as a resource, $r(T)$, with its CS as services, $s(r, T)$. These services should be shared to fulfill one specific mission demand, see Figure 4.2

The demand is independent of the available service. By any means, there is always a demand. And the systems are trying to fulfill it within the resources at hand.

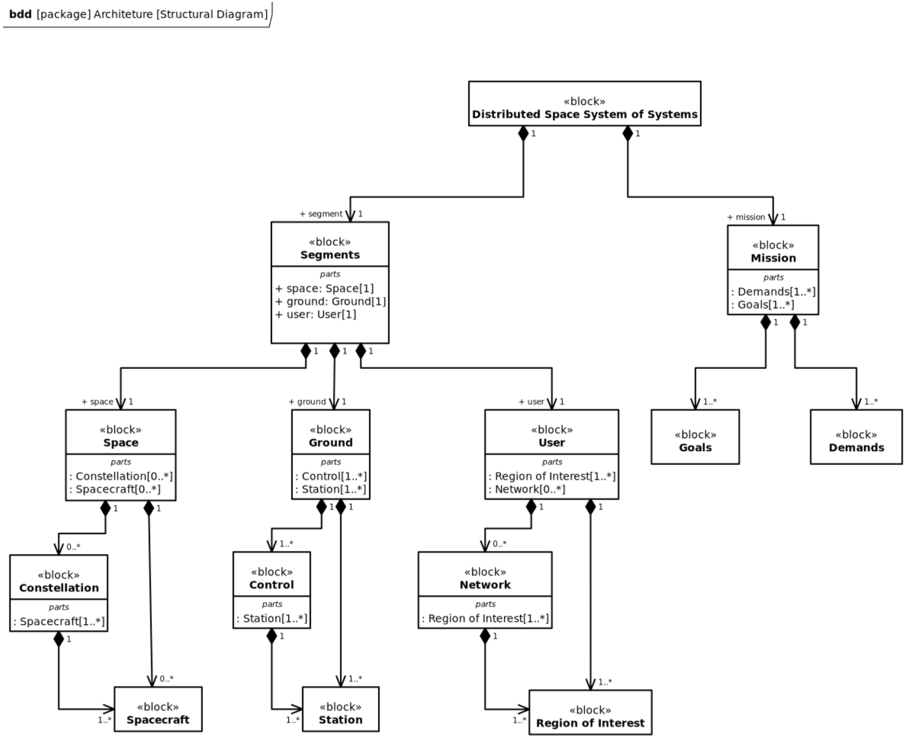
The mission goal should be a function of which demand needs to be fulfilled, and it will drive the evaluation in terms of what technical measure should be taken into

Figure 4.1 - DSSoS modeling profiles.



SOURCE: Author.

Figure 4.2 - DSSoS Architectural Profile.



SOURCE: Author.

account for each T, time fragment of the system.

Each of these technical measures is related to one specific level of the mission.

KPP, Key Performance Parameters, gives the list of what needs to be measured in order to accomplish the stakeholder needs, e.g. downlink baudrate and space-to-ground contact time give us the data download capacity per day (Eq. 4.1). TPM, Technical Performance Measures, is the measure itself from a single CS, e.g. the ground station A is capable of downloading 100 MB of data per day as function of one or more *kpp* (Eq. 4.2). MoP, Measures of Performance, is the system performance measure, the sum of *tpm* from a service s to fulfill a demand d. The value that needs to satisfy the MoE, e.g. the ground stations are capable of downloading 2 GB of data per day (Eq. 4.3 and 4.4). MoE, Measures of Effectiveness, are the levels of satisfaction that need to be met by the DSSoS (e.g. 1 GB of data downloaded per day).

$$KPP = \{kpp_i\},\ \forall\ i \in [1..I] \tag{4.1}$$

$$TPM = \{tpm(s, d, T)\ \rightarrow\ f(kpp)\} \tag{4.2}$$

$$MoP\ \rightarrow\ f(r, d, T) = \sum TPM(s, d, T) \tag{4.3}$$

$$MoP\ \rightarrow\ f(r, d, T)\ \vdash\ MoE\ \rightarrow\ f(m, T) \tag{4.4}$$

In a specific time fragment, T_0, when evaluating the DSSoS, from a set of CS, $r(T_0)$ which have each service, $s(r, T_0)$, providing TPMs to achieve a demand, $d(m, T_0)$, $TPM \rightarrow f(s, d, T_0)$.

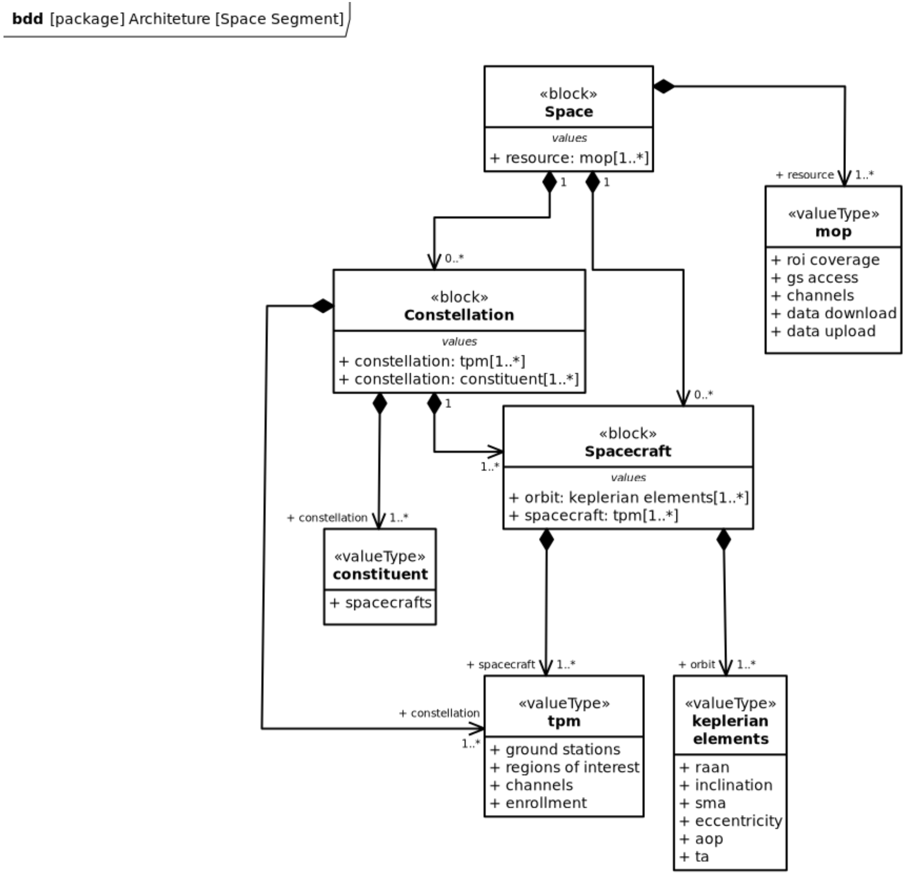
The sum of these services becomes the MOPs of a given resource, $r(T_0)$, to fulfill the same demand, $d(T_0)$ now as SoS – $MoP \rightarrow f(r, d, T_0)$.

The set of MOPs from each resource involved to fulfill the demand, $d(T_0)$, are compared to the KPPs, or the constraints of the mission – $KPP \rightarrow f(d, m, T_0)$.

The sum of demands fulfilled by the DSSoS, represents the MoEs of the DSSoS, moreover, the Quality of Service provided by the DSSoS for that given mission in a given time – $MoE \rightarrow f(m, T_0)$.

The Figure 4.3 presents an example of how to represent the elements present in a space segment, and what are the technical measures available on that service, all the diagrams in SysML used for this thesis are available in the Appendix A.

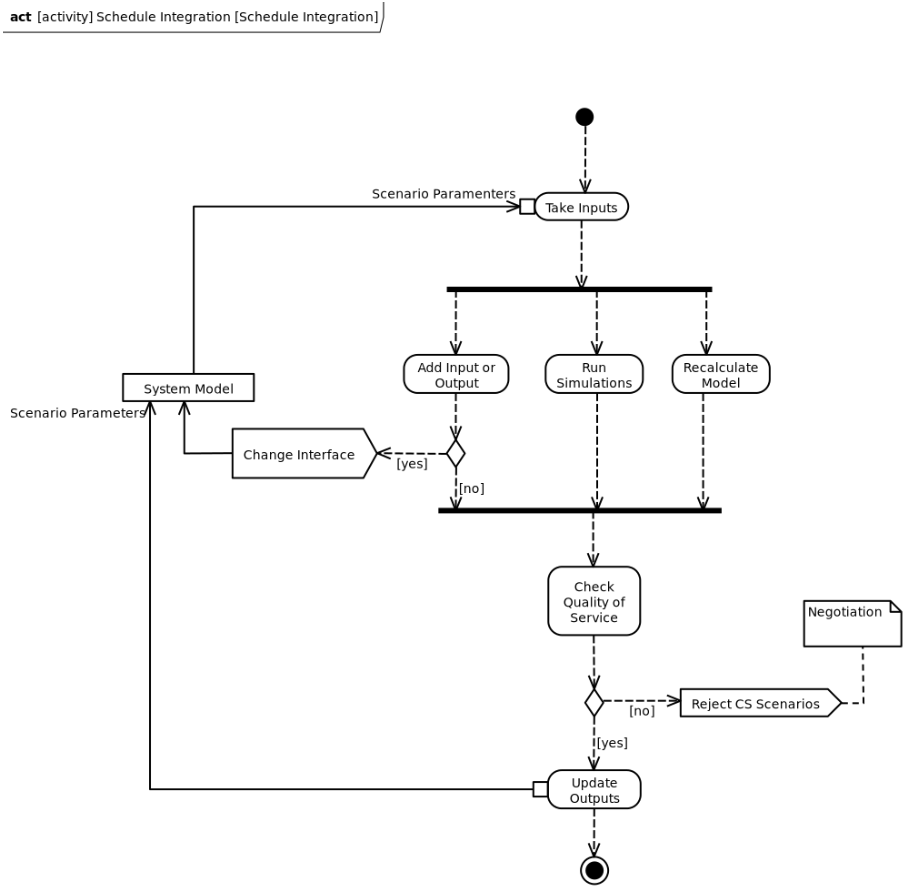
Figure 4.3 - Example Space Segment Structure with its parameters and TPM.



SOURCE: Author.

From these physical and functional measurements, it is possible to determine baselines for the mission. To know exactly how the DSSoS is being successful in achieving the mission demands as-is, and what the improvement is on the quality levels with the addition of a new CS or a new configuration. Even so, evaluate a fault case or unavailability of a single or more CS.

Figure 4.4 - Schedule Integration Activity Diagram placing the role of Simulation.



SOURCE: Author.

4.2 Simulation

The simulation aspect of this method is based on the operational level of abstraction (BORKY; BRADLEY, 2019). Which examines the modeled architecture from the system operator’s point of view. Scenarios, events, and procedures are all implemented to mimic the perspective concerning the accomplishment of tasks.

With that in mind, the choice of the simulation tool will be based on what is needed to be measured.

Figure 4.4 demonstrates where in the method the simulation is placed. As long as its relationship with the scenario model through the CS parametric values and how the other system model elements will feed the analytical model in a later stage, in an Update Descipline model (KNOLL et al., 2021).

In terms of available tools it is not the scope of this work to define which tool to use but to give the necessary point to take into account when choosing the specific simulator.

The Generic Mission Analysis tool, GMAT (HUGHES, 2016), presents an open source solution with a good set of parameters that can be adapted to your specific needs. GMAT has a script-based language and interfaces with MATLAB and Python languages to open even more possibilities for customization of your mission. (BATISTA, 2024) is used to interface and automate the integration between modeling artifacts and script generation for GMAT applications.

The Satellite ToolKit, STK by AGI, (FUNADA, 2023; SHAHAT; YOUSEF, 2022) is a well-known simulation tool used by most of the aerospace industry. The STK even in its free version is capable of ConOps simulation and also has integration with MATLAB and Pyhton Languages. Its paid version has even more adaptability and enables the introduction to more details and more fidelity to your representation during the simulation.

Other tools were developed within internal interests for the INPE concurrent engineering group, CPRIME, in order to verify Operational Analysis (CHAGAS et al., 2019), the FOrPlan. Such tool was used to verify the modeling approach developed by (ALMEIDA et al., 2019) and verify the concept of operation for one single spacecraft.

In the same sense, (CARVALHO et al., 2023) presents the COSCAT (ConOps Satellite Constellation Analysis Tool). This simulation and analysis tool enables the capabilities of FOrPlan to be exploited in the sense of an operational constellation. With a wide range of customization, the COSCAT is able to simulate and generate data about individual spacecraft behavior at the same time it analyzes the interaction between n-numbered constituent systems during simulation time.

The choice of the simulation tool is much more about what is familiar and what needs to be evaluated. More precision and fidelity can usually be achieved by paid-commercial solutions as the flexibility of open-source solutions can be tailored to the analysis needs. The simulation is an enabling element for the analytical method.

4.3 Analysis

Simulation establishes the system state in the individual time instances corresponding to the events at the merged timeline.[1]

The design space can be defined by setting mission demand requirements as constraints. We currently consider only four mission demands on a simplified system model without loss of generality. Although simplification is achieved in the system, this model can be easily extended with additional parameters, constraints, and optimization criteria. Introducing more constraints leads to more efficient cuts in the search space, thus facilitating a reduced choice of possible parameters.

In the model, $s_i \in resource(space, T)$ is the i-th space resources for the given time fragment, and $g_j \in resource(ground, T)$ is the j-th ground resource (ground stations (gs_j), RoIs (roi_j)) for the given time fragment. The duration of a time fragment, i.e., the length of the corresponding time interval T $(T \in \mathcal{T})$ is denoted by τ_T. Between a space (s_i) and ground (g_j) resource for a given time fragment T, the visibility is denoted by the binary variable $v_{ij}(T)$, and the active connection is denoted by $c_{ij}(T)$. Accordingly, a connection between s_i and g_j corresponds to $v_{ij}(T) = 1$ and $c_{ij}(T) = 1$.

In the simplified model, the following general assumptions were made:

- A ground resource (g_j) can connect to a maximum of one space resource (s_i):

$$\sum_{i=1}^{|resource(space,T)|} c_{ij}(T) \leq 1 \tag{4.5}$$

- A space resource(s_i) can connect to a maximum of one ground resource (g_j):

$$\sum_{j=1}^{|resource(ground,T)|} c_{ij}(T) \leq 1 \tag{4.6}$$

- Only there can be an active connection between the space (s_i) and ground

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[1] Note we assume that all faults are fatal in the running example. Thus we neglect repair actions like the potential recharge of the energy storage after its exhaustion.

resources (g_j) if there is visibility between them:

$$c_{ij}(T) \leq v_{ij}(T) \tag{4.7}$$

This kind of connections can describe both taking pictures of RoIs (roi_j) and transferring it to the ground station (gs_j).

The four examined mission demands are the following:

a) *Data download*: One of the most important requirements is that data generated from space resources can be transferred to the ground. This is possible when there is an active connection between a space and ground resource. We assume that the ground station can receive the transfer from any satellite (it has at least such a bandwidth as any satellite). If we assume for simplicity that there is the same data rate between all resources then we can calculate by using the number of connections without explicitly transforming it to the actual download bandwidth. The following constraints can be formulated:

   The goal is to maximize the number of active connections ($c_{ij}(T)$) between the space (s_i) and ground resources (g_j) for all time fragments ($T \in \mathcal{T}$). The result gives an upper estimate of the global active connections:

$$\forall T \in \mathcal{T} : max \sum_i \sum_j c_{ij}(T) \tag{4.8}$$

   The optimization criteria can be easily extended with the duration of the time fragment, which gives an upper estimate of the available time for the information exchange (which is proportional to the amount of data downloaded under the simplifying assumption of identical communication speed between all elements).

$$\forall T \in \mathcal{T} : max \sum_i \sum_j \tau_T * c_{ij}(T) \tag{4.9}$$

   Note that the model is quite flexible to include different model parametrizations. For instance, if we relax the identity of data rates between all devices thus there is a different data rate between the resources, the model can be extended to include the data rate between two resources ($datarate_{ij}$). In this case, the objective function determines the maximum possible transfer rate in a given time fragment.

$$\forall T \in \mathcal{T} : max \sum_i \sum_j \tau_T * datarate_{ij} * c_{ij}(T) \tag{4.10}$$

Besides the current objective function, which is based on time, it can easily be supplemented with other metrics such as energy consumption, less channel switching, and more efficient satellite intercom.

b) *Data storage*: The satellites ($\{s_i\}$) store the pictures of RoIs ($\{roi_j\}$) in their internal storage memory ($m_{s_i}(T)$, which varies along the time due to new pictures taken and the download process). The information can be downloaded to ground stations ($\{gs_j\}$) in chunks, and the already downloaded data chunks can be deleted. The current memory for all time fragments can be calculated by (memory size in the previous time fragment - downloaded data in the current time fragment if there is a connection between a satellite and ground station or memory size in the previous time fragment + size of the collected information from RoI):

$$m_{s_i}(T) = \begin{cases} m_{s_i}(T-1) - c_{ij}(T) * datarate_{ij} * \tau_T & \forall \text{ comm } s_i \text{ and } gs_j \\ m_{s_i}(T-1) + c_{ij}(T) * informationsize & \forall \text{ comm } s_i \text{ and } roi_j \end{cases} \tag{4.11}$$

For all time fragment, the used memory ($m_{s_i}(T)$) should be less or equal to the storage capacity (sc_i) of satellite (s_i) for all time fragments ($T \in \mathcal{T}$).

$$\forall T \in \mathcal{T}, \forall s_i \in S : m_{s_i}(T) \leq sc_i \tag{4.12}$$

c) *Revisit time*: Revisit time ($\Delta_j\ (T)$) gives the time elapsed since the last visit to RoI (roi_j) at the time fragment T.

$$\Delta_j\ (T) = (1 - c_{ij}(T))(\Delta_j\ (T-1) + \tau_T), \tag{4.13}$$

Elapsed time between two consecutive contacts between any RoI (roi_j) and a satellite (s_i) should not exceed a time limit (tl) predefined by the stakeholders.

The Revisit Time constraint ensures that the stakeholder, or any other entity interested in the generated data by the DSSoS, may have access to data that is 1-hour-old maximum from the time that it was acquired. Reducing the time interval between consecutive data acquisitions from the same RoI enables the construction of better representative time series. Such more detailed time series may create better models to foresee and help the decision-making actions, for example in the case of accidents, deforestation, natural disasters, etc.

$$\forall roi_j, \forall T \in \mathcal{T} : \Delta_j \ (T) \leq tl \tag{4.14}$$

d) *Coverage*: cov_j represent the coverage ratio for a RoI roi_j. If the RoI (roi_j) is visible from any satellite then $v_j(T) = \bigvee_i (v_{ij}(T)) = 1$.

$$cov_j = \frac{\sum_t \tau_T v_j(T)}{\sum_t \tau_T} \tag{4.15}$$

The goal is to maximize the coverage for all the regions:

$$\forall g_j : max \ cov_j \tag{4.16}$$

Even with low values of revisit time on one specific RoI, we cannot assure that we do not have gaps where there is no contact between the spacecraft and the RoI. In this sense, the percentage of coverage, may help on understanding, at least on average, how much of time do we have with this RoI being monitored. Maximize the coverage means more close to real-time data access.

Naturally, the constraint logic description of the system can be extended by several resources together with their associated requirements, usage constraints, and preferences. In the case of the objective function, there are several ways to reflect multi-aspect objectives:

a) One solution could be the exploration of the design space by calculating the particular solutions by taking into account only the individual aspects (e.g., the solution requiring the minimum number of satellites involved) and neglecting the distribution of the utilization of the individual resources of the elements in the configuration. Out of these marginal solutions, the design space is well-defined and can serve as a tradeoff.

b) On the other hand, combining the different objectives by introducing penalty and benefit functions to the exploitation of the resources allows a global optimization by introducing weights by the individual subobjectives.

4.3.1 Qualitative evaluation

Qualitative evaluation is based on an abstract model of the system. The purpose of this abstract model is to represent the system in a simpler but faithful way. Abstraction can be done, among others, by abstraction of structures and values. With structure abstraction, certain system elements can be aggregated (e.g., ground resources) and treated as a unit. Value abstraction can be done by categorizing continuous metrics or by aggregating certain (even categorical) values. Using qualitative models makes discrete validation and verification techniques available, and logic reasoning can be performed on the model.

4.3.1.1 Dependability

An abstract qualitative model can serve as a basis for evaluating the dependability of a system. The evaluation process uses a logic reasoning-based dependability analysis method to investigate cases where mission objectives may be compromised.

In dependability evaluation, logic reasoning on a qualitative system model is used for fault detection, fault diagnosis (WOTAWA, 2020), error propagation analysis, and evaluation of system architecture configurations.

The dependability evaluation of the systems can be based on examining how fault-tolerant the system is, i.e., whether the failure of some resources in the system could cause degradation of the mission requirements.

For example, if a ground resource fails during data transmission (Ground Resource - Satellite communication). The satellite should switch to another ground resource if there is available capacity. Also, additional mission-critical constraints and conditions for reconfiguration can be integrated into the model for optimization. Both qualitative logical constraint satisfaction and optimal selection of options play a role in the analysis.

In the general case, a failover necessitates transferring the data to the backup resource and, afterward, triggering its operation. The time needed for the failover depends on the type of backup strategy used. (1) In the case of a cold backup, the resource substituting the failed one has to be initiated. For example, data to be transferred to the ground station has to be submitted to this satellite (and afterward starting the operation). (2) In time-critical cases, the synchronization of the candidate backup resource is continuous, and thus, nearly immediately after activating it, it can start functioning and substituting the failed one. Note that this later strategy continuously needs resources to ensure synchronization.

4.3.1.2 Complexity

Scheduling the resource usage in large systems is a complex task (SHUIB; KAMARUDIN, 2019). One of the main reasons for the complexity of the approach used for evaluation is that the possibility of assigning tasks in time fragments based on visibility information is extremely high. This is highly dependent on the number of resources and visibilities.

There are several ways to deal with complexity. 1. By using model abstraction, one way of doing this is to aggregate certain elements in the model (e.g., aggregation of ground resources); 2. by specifying partial solutions for how parts of a particular solution should look (e.g., continuous resource use).

These methods can help reduce the search space for the scheduling task. Using abstraction, we can be sure that what was not a solution in the upper approximation will not be a solution in our original model. However, due to abstraction, false solutions may also emerge (PATARICZA, 2008). These solutions can be filtered by model refinement.

Another advantage of the approach is that qualitative rules can be used to describe soft constraints, including scheduling constraints. This way, partial solutions can be generated, which reduces the search space and makes the evaluation more accurate.

Using the known constraints, the possible resource allocation combinations can be sorted into a weighted solution space, and the configuration can be examined by evaluating the different solutions.

4.3.2 Quantitative evaluation

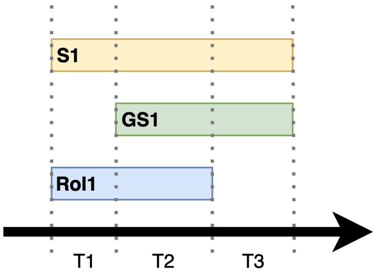
Given the constraints and scheduling information, the quantitative evaluation aims to quantify the relevant indicator metrics (e.g., available data download time) for the mission to be achieved. There are four main aspects of quantitative evaluation:

- *Available capacity*: The already-in-service satellites were used from the simulation data. It shows the current capacity of the available resources.
- *Virtual capacity gain*: It considered the new planned satellite constellations and compared the capacity with the current one. It shows the capacity gain by increasing the number of resources.
- *Failover*: Failing satellites can cause the system will not to fulfill the QoS requirements. The evaluation environment supports the analysis of cases where satellites fail at a given time fragment and can not operate anymore. This way, a "what-if" type analysis can be carried out.
- *Resource Evaluation*: Any additional resources (e.g., satellite storage, satellite power) can be tested during the analysis. This step allows a more detailed assessment of whether the configuration meets the requirements and constraints.

4.3.3 Evaluation workflow

The evaluation workflow consists of five main steps. The workflow first identifies and defines the evaluation inputs (time fragments, constraints, and objectives). Based on the inputs, it uses constraints and objective functions to construct a near-optimal schedule for allocating satellite and ground resources (photo creation, data download). The process ends with a qualitative and quantitative evaluation, including a dependability analysis.

Figure 4.5 - Example visibility of the resources.



SOURCE: Author.

a) Identification of time fragments: To define the time fragments from the simulation data, we have considered that the visibility between ground resources and satellites does not change in a fragment. Three time fragments can be identified in the small example in Figure 4.5. In T1, there is visibility between S1 and RoI1. In T2, for S1, both the GS1 and RoI1 resources are available. In T3, for S1, only GS1 resource is available. This way, each time fragment includes the possible connections of the space and ground resources. These time fragments are the basis for the evaluation. In the examples, we have made use of the assumption that in a time fragment, resources do not switch tasks.

b) Definition of constraints: The constraints include the limitations for the possible connections between the space and ground resources (e.g., one space resource can connect to a maximum of one ground resource). Moreover, this is where the various cost metrics are defined. These cost metrics may include the data rate between space and ground resources. Specifying the loss of satellites due to a fault is also possible. This can be used to evaluate how the QoS changes in case of failures, i.e., how the performing satellites can take over the task of the failed ones.

c) Definition of objectives: Mission objectives define the optimization criteria. For example, maximizing the download capacity and coverage and minimizing the revisit time.

d) Optimization/Scheduling: The scheduler provides a near-optimal solution for scheduling mission tasks. It defines the tasks of resources in each time fragment. Note that the optimizer/scheduler used in this paper is not to present the best possible scheduling algorithm but to present an evaluation approach for mission analysis.

e) Qualitative and Quantitative Evaluation: On the one hand, the evaluation examines the output provided by the scheduler using quantitative metrics (e.g., total time available to download data, useful time spent over RoIs). It also examines the configuration from a dependability perspective (e.g., how QoS changes when satellites are down/new satellites are deployed or how many satellites need to be down to fail to meet mission objectives).

5 GOLDS

As presented at the 2018 UN/Brazil Symposium on Basic Space Technologies, the Global Open cOLection Data System, a.k.a. GOLDS, constellation is an international collaboration initiative (MATTIELLO-FRANCISCO, 2018). It aims at creating an international cubesat-based constellation, ground stations, and data collection platforms working together to ensure quick accessibility to environmental data (SOUTO et al., 2022). GOLDS is an enhancement and an upgrade from the Brazilian Environmental Data Collection, started in the 1990s using two LEO satellites (SCD1 and SCD2), Data Collection Platforms spread over all Brazilian territory using ARGOS communication technology, and two ground stations located in Cuiaba, (central region), and Alcantara (north region) (YAMAGUTI et al., 2009).

Four points make GOLDS an excellent example of a DSSoS in this work (SOUTO et al., 2022):

- For GOLDS, the satellite design is not a concern for the GOLDS operation;
- quality assurance about the system must be in the GOLDS requirements to achieve a satisfactory level of service;
- GOLDS is an open constellation, not restricted and defined to the number of members and their characteristics and;
- GOLDS still needs to be modeled at a lower abstraction level to reveal the challenges of sharing infrastructure between the missions.

Figure 5.1 shows GOLDS operational scenarios. Where the scientific community can access the data acquired by GOLDS through independent missions.

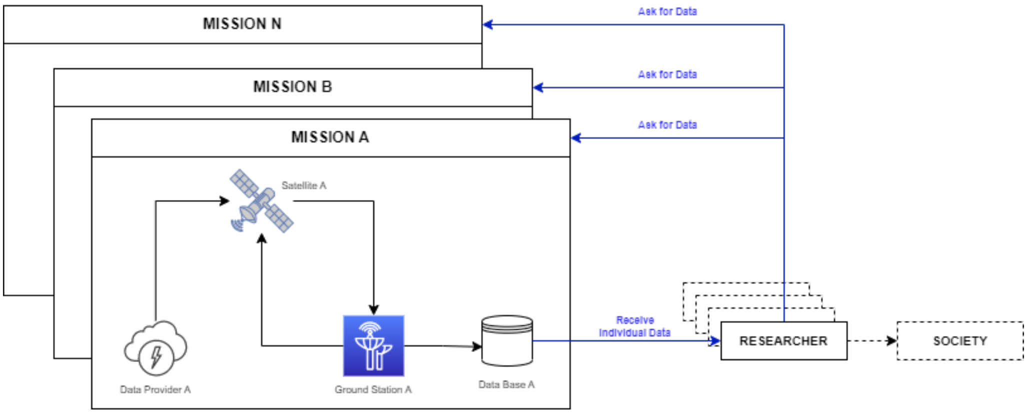
5.1 Modeling

In order to model the GOLDS as a DSSoS, we first have to determine the Domain Space in a given time fragment for the system, $Domain(T)$, see Figure 5.2.

$$\begin{aligned} DOMAIN(T) = [&mission(golds, T), resource(space, T),\ \ldots \\ &\ldots resource(ground, T), resource(user, T)] \end{aligned} \tag{5.1}$$

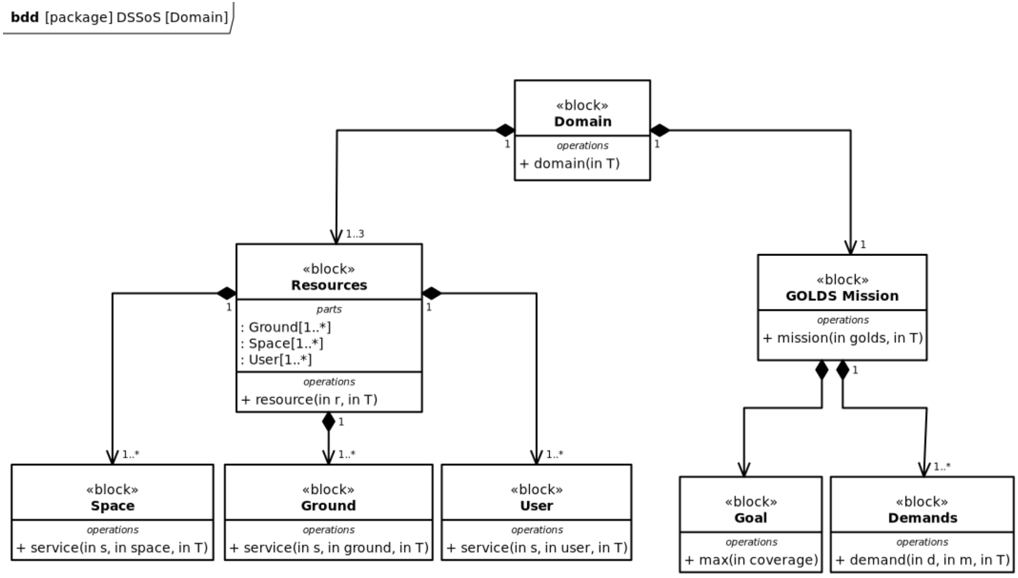
Where:

Figure 5.1 - GOLDS operational scenarios.



SOURCE: Adapted from Souto et al. (2022).

Figure 5.2 - Domain space for the GOLDS ideal DSSoS.



SOURCE: Author.

mission(golds,T) is the set of demands for the GOLDS mission, that assures the quality of service delivered for given time fragment.

resource(space,T) is the set of services, spacecrafts available for the DSSoS in a given time fragment.

resource(ground,T) is the set of services, ground segment available for the DSSoS in a given time fragment.

resource(user,T) is the set of services, user segment available for the DSSoS in a given time fragment.

The time fragments, T, are defined as a specific time fragment in which the visibility between the entities does not change.

So, for the specific mission goals and stakeholders' expectations that GOLDS has, we have different parametric demands. These demands exemplify the MoEs for GOLDS mission, and the more of them that are fulfilled, we can assume a better quality of service provided.

For the segments, or in this case, resources that we have available for the DSSoS, each of them has its available services.

Each service on the space segment, $service \in resource(space, T)$, is a satellite, a family of satellites, or a constellation available on that given time fragment, T.

Each service on the ground segment, $service \in resource(ground, T)$, is an available ground station/operation control for the DSSoS on that given time fragment, T. It is a fact that each ground station is attached to a specific satellite or set of satellites being that a limitation inherent of this heterogeneous system.

Each service on the user segment, $service \in resource(user, T)$, is one Data Collection Platform network responsible for acquiring the environmental data (hydrological, meteorological, or geological) from a specific region and normally owned by a specific user, stakeholder, client on that given time fragment, T.

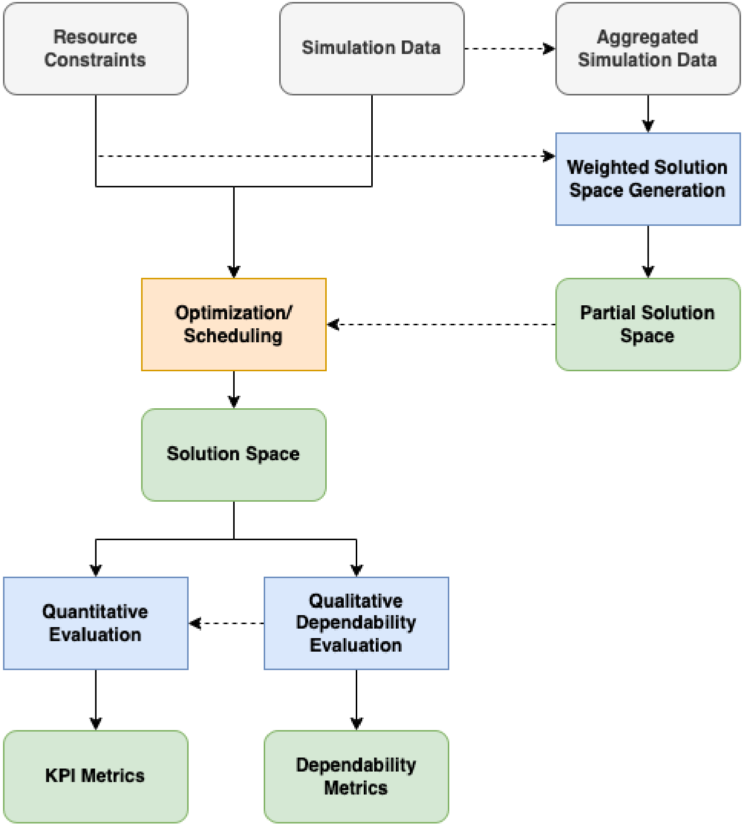
5.2 Evaluation objectives

Evaluation of mission demands and constraints was performed on simulation data from actual orbital satellite data, that is, SCD-1, SCD-2 and CBERS4A TLEs. And from an idealized, still under design, orbital parameters of new satellites, the project is called CONASAT (CARVALHO et al., 2016). It envisions the update of the BEDCS with the use of a CubeSat constellation, for our simulation purposes 6 satellites, Polar LEO, with 60 degrees of phase difference. It was also used as input for the simulation of the location and pointing characteristics of the Brazilian Ground Stations, located in Cuiaba (ETC), Alcantara (ETA), and Natal (EMMN). For the RoI, it was assumed that each of the Brazilian states was one DCP, a simplification to reduce to 27 RoI instead of dealing with more than one thousand DCPs in the real scenario. Detailed information on satellite keplerian elements, ground station locations, and example DCP locations can be found in B.1, B.2, and B.3, respectively.

The goal of the evaluation is to verify whether the different configurations for the GOLDS as a DSSoS are capable of ensuring the expected quality of service. Its tasks were designed according to two main approaches, namely, qualitative and quantitative analysis.

Figure 5.3 summarizes the overview of the Quality of Service evaluation. The inputs to the evaluation are resource requirements and simulation data. These can be used to design a near-optimal task scheduling. This process can be supported by providing partial solutions on an abstract model of the system (weighted solution space generation), which can be used in further evaluation and make the complexity of the task more manageable. Qualitative QoS and quantitative dependability evaluation solutions are provided to evaluate configuration and scheduling results.

Figure 5.3 - Evaluation Overview.



SOURCE: Author.

First, qualitative evaluation performs an analysis on an abstract system model, where it is not necessary to evaluate the details, but only to focus on the main operational processes. Qualitative abstraction also makes the complexity of the task more manageable.

In the case of quantitative evaluation, it is essentially a parameterization of the abstract model (concrete configuration). This allows a detailed analysis of different mission objectives, constraints, and QoS parameters.

In our approach, the evaluation is presented in the form of Jupyter Notebooks as they are reusable with different parametrizations and provide an easy-to-follow structure (including both the code and the textual documentation/findings of the results).

For scheduling, we used Google OR-Tools (PERRON; FURNON, 2019), which is an open-source software designed for combinatorial optimization, offering a range of optimization techniques to address specific problems.

For the qualitative dependability evaluation, Answer Set Programming (ASP) (LIFSCHITZ, 2019) is used. ASP is a declarative programming method designed to model and solve combinatorial search and optimization problems. It integrates a language with expressive representation capabilities, a methodology for specifying problems based on models, and powerful solution tools. Within the ASP language, domain-specific knowledge, including incomplete information, defaults, and preferences, can be used. This property makes ASP valuable for representing and reasoning about abstract qualitative models.

6 RESULTS AND DISCUSSIONS

The simulation is based on the GOLDS constellation, running over the GMAT/NASAv. It covers seven complete days, during which the mutual visibility of satellites and ground/user resources (ground stations, RoIs) was monitored.

(BATISTA et al., 2023) and (CARVALHO et al., 2023) present more results using the method presented here in this work.

6.1 Quantitative evaluation of GOLDS mission

One of the mission goals of this example is to access as much download time as possible. In addition to the maximum available download time, the evaluation examined the time available over RoIs. Three scenarios were considered: In *Scenario A*, the already-in-service satellites were used from the simulation data. It shows the current capacity of the available resources. The evaluation of *Scanario B* includes the new incoming satellite constellation, CONASAT, and compares the capacity with the current one. It shows the gain in capacity as the number of resources increases. *Scenario C* introduces the failover behavior. Failing satellites can cause the system not to fulfill the QoS requirements. The evaluation environment supports the analysis of cases where satellites fail at a given time fragment and cannot operate anymore. This way, a "what-if" type analysis can be carried out.

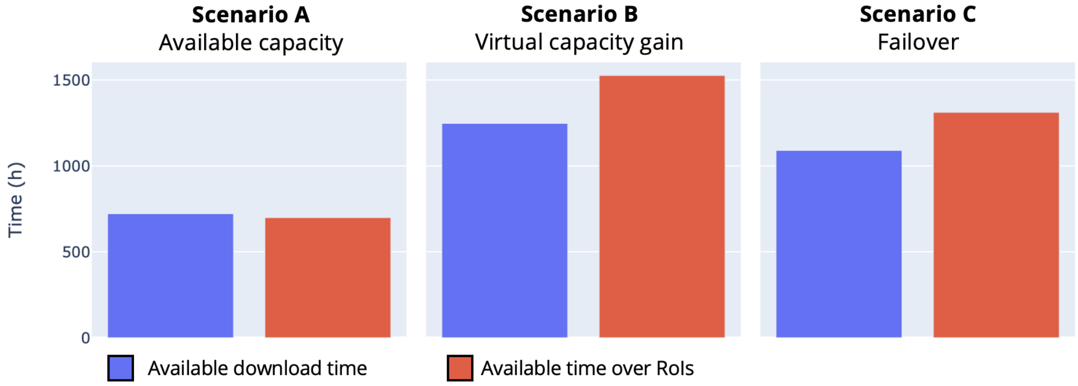
The GOLDS mission is characterized by a high number of regions of interest, where the contact constraint is limited just by the elevation angle between the target and the satellite and the spacecraft capability on storing this data. The goal in our study is to maximize the data acquisition, this is the main drive for the evaluation.

In Figure 6.1, the blue bars indicate how much time is available for satellites to exchange information with the ground stations in each scenario. This available time can be used to exchange mission data between the satellite and the ground station or to download operational data (telemetry). This example gives an upper estimate of the time available as it does not consider cases where a task with a higher priority opposes the connection.

The red bars show the available time (in hours) over the RoIs. It can be observed that since the first priority is to download as much data as possible, the time spent on RoIs is less. However, a shorter time is also sufficient to collect sufficient data.

The first scenario shows that the time spent over the ground stations and RoIs

Figure 6.1 - Available download time and over RoI time for the evaluated scenarios.



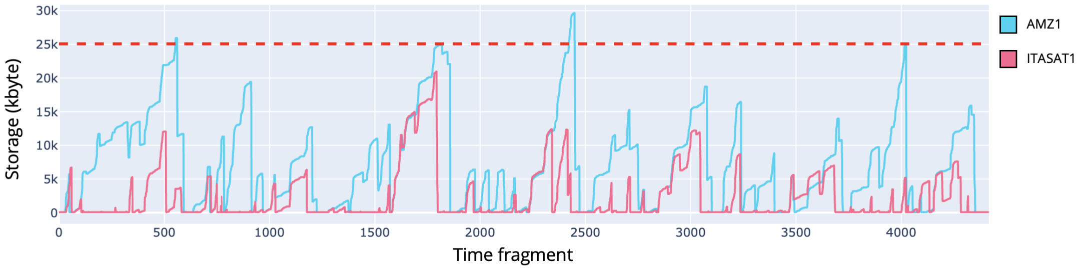
SOURCE: Author.

is almost the same for a given schedule. For example, in this case, if these times are distributed almost uniformly across the satellites and symmetric upload and download times are assumed, then the resource capacity of the internal storage of a satellite is not a problem.

Between Scenario A and Scenario B, both metrics nearly doubled by adding the six new CONASAT satellites. In this case, under the previous assumptions, the storage capacity of the satellites may already be a problem, and further investigation may be needed.

Scenario C in Figure 6.1 shows the failover scenario where the CONASAT5 satellite went down at the 500th time fragment and CONASAT6 at the 600th time fragment.

Figure 6.2 - Evaluation of the data storage of AMZ1 and ITASAT1 satellites.



SOURCE: Author.

Figure 6.2 shows the amount of data (in kilobytes) stored on ITASAT1 and AMZ1 satellites. When a satellite is working over a RoI, the amount of data stored increases. When it is able to send data to a ground station, the amount of stored data decreases. In this case, it can be seen that for a given schedule, the storage used by AMZ1 does not go above 25000 kilobytes, whereas for the ITASAT1 satellite, it goes above it multiple times. This leads to the conclusion that with the given configuration and schedule, the satellite cannot use the allocated time because it cannot receive more data. The solution may be to allocate more memory to the satellite in the configuration or to use a different schedule.

6.2 EXTRA: qualitative evaluation of EO mission

In order to demonstrate some of the flexibility of this proposed work. It was decided to also perform some analysis on a different mission, in this case, an Earth Observation mission.

The idea is to exemplify what can be the differences in terms of modeling constraints and demands in this different scenario.

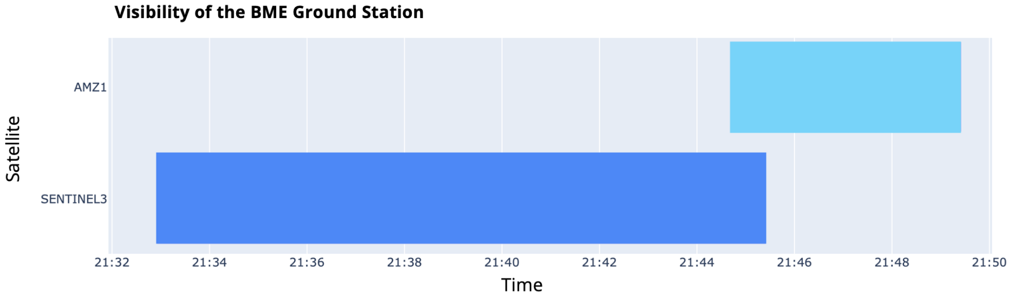
For this scenario, the characteristics change from the previous one, where here there is a low number of target regions of interest but they are constrained by geometry for the image acquisition (elevation angle over 45 degrees). The goal is to emulate the coordinated operation of the AMZ1 and SENTINEL satellites considering the ETC, ETA, EMMN, and BME (in Hungary) ground stations. What drives the service here is also the mission goal, which aims to minimize the revisit time to the target and maximize the data download over the ground stations.

In addition to explicit values differences, in the same qualitative and quantitative analysis, one thing that points out is the explosion of possible solutions when the number of CS increases. An increase in complexity increases the search space complexity, which leads to possible suboptimal solutions from the technical perspective.

An aspect that was exploited to reduce complexity is the preference for continuous connections in resource usage, i.e., cases where a connection built in a previous time frame can be continued in subsequent steps (no resource is switched).

For example, a rule can be defined so that, if in the previous time fragment there was a scheduled task where consumer A used resource B, and in the current time, fragment scheduling A-B is also possible (there is visibility between A and B), the system chooses that option.

Figure 6.3 - Complexity on Evaluation of Contact Scheduling.



SOURCE: Author.

If the rule is considered a hard constraint, the solution will only include this scheduling option. Another possible solution could be to use so-called soft constraints to weigh the solutions, in this case giving preference to the one where the connection is continuous. Using soft constraints, we can get the whole solution space or the Top N solution. In this case, comparing the best solution (which may not be the optimal solution) with the other options is possible.

Figure 6.3 shows the visibilities between the AMZ1 and SENTINEL3 satellites and the BME ground station. This subtask can be divided into three time fragments. One with the SENTINEL3 connection to BME, a second with both satellites, AMZ1 and SENTINEL3 visible by the ground station, and a third one with only AMZ1 visible.

Based on visibility information, two different schedules are possible in the second time fragment. However, if we apply the continuity rule to generate the sub-solution, the SENTINEL3 satellite will continue communicating with the ground station. The use of these sub-solutions, if more scheduling options arise, greatly reduces the search space.

7 CONCLUSIONS

This work presented the results of congregating different ideas that were only possible due to the rapid escalation in space technology and access, mainly due to CubeSat-based missions.

DSM, DSS, and FSS are topics that have been discussed for a long time, but only now can we foresee that nonmonolithic design missions are feasible. And new ways of thinking about how to exploit these unused available resources are on the rise.

Evaluating the impacts of different systems working together is a must due to the heterogeneity of their operations. Different resources can work together to increase the Quality of Service delivered by a mission but can also be problematic as they demand infrastructure and other resource allocation.

The functionalities and enabling features of the use of MBSE in coordination with Simulation and Analysis (MS&A) in a soft-system-like methodology give us a perfect match to support the concept, evaluation, and optimization of a DSSoS (BORKY; BRADLEY, 2019).

Technically, reallocation is a problem that must be solved on the ground. The long-term vision of large satellite configurations requires well-scalable algorithms. Note that the peculiarities of cube/nanosatellites require the operation design of such communication plans. The reliability of nanosatellites is significantly lower than that of traditional ones (SWARTWOUT, 2016; SWARTWOUT, 2019). In this way, the “disposable” nature of nanosatellites results in frequent faults, which requires redesigning the task allocation of the individual elements of a satellite configuration.

Resource reallocation is one of the biggest challenges in our modern resource-limited world. Being aware of the great problems that space debris can cause and the amount of resources that are unused around the world, future space technologies must be able to cooperate and reconfigure in orbit.

Adding a new CS is not subject to a better Quality of Service provided. Conflicts between operational needs and the CS will be always presented as we upscale the system. The method presented here presents a way to evaluate the impacts of the reconfiguration of an SoS in terms of what resources can be shared and what services are available to cooperate to achieve a specific demand.

Moreover, new business models can take advantage of the easy access to space that

CubeSats provide. Collaborative missions in a federated paradigm can be exploited on these shared satellite platforms (SWARTWOUT, 2022). The possibility of collaboration between different mission segments can be an advantage in future business models. Standardizing inter-satellite communication channels, open-source hosted payloads, and cloud-based ground services are examples of feasible nanosatellite mission capabilities that can exploit the Distributed Space System (of Systems) concept.

7.1 Achievement of objectives

Regarding the objectives of this thesis (Sections 1.3), on providing a way to evaluate the performance of DSSoS in constant reconfiguration, some points need to be highlighted.

The method answers the objective questions using a structured model-driven approach to quantitatively describe what the resources are to be shared and how the services interact, and which demands can be prioritized when the system upscales.

CS involved in a DSSoS paradigm are shareable resources, which are modeled, measured, and analyzed. Those resources provide services that can also be measured in terms of performance and mission enrollment. The system model, based over the CSRM, answers this question with a comprehensive parametric technical measurement. As the system grows, its demands also grow. Demands can be modeled, simulated, and evaluated in the same sense as constraints that rule the success of the mission. The modeling approach enables the scalability of those demands without lacking of details but also requires more on the analytical point of view.

In the face of emergent faulty behaviors, the evaluation method presents a current planning and scheduling action to constantly update the model and simulation scenarios to tackle, at runtime, the heterogeneity of the DSSoS. Based on looking for the most suitable scenario to cover the faulty situation with the current CS configuration.

The integrated model, simulation, and constraint analysis method enables quick and efficient decision-making in DSSoS in terms of determining the quality levels of the services provided. The method enables top-down decision making based on measurable parameters to determine the quality level of such DSSoS, also to evaluate with different CS configurations which one can best offer a solution for a specific and already known goal.

7.2 Contributions

The main contribution is an integrated method for evaluating DSSoS in a heterogeneous architecture. The method explores overlapping ideas on Model-Based Systems Engineering Approach, Concept of Operation Scenarios Simulation, and Logic-mathematical Analysis, for a better understanding, planning, scheduling, and execution of Distributed Space Systems.

Those contributions foresee the incoming of a new space systems architecture, where we will increasingly rely on more efficient, interactive, and optimized space systems in the near future. The resources are limited, so our solutions need to be clever.

7.3 Limitations

However, no solution is a panacea. This solution is not meant to be the method "to rule them all". A method is always limited by its scope and domain, and every model is a simplification of the real world. It is not meant to solve every single aspect of a distributed space system, but it is limited only to the Concept of Operation aspects of it. Trying to abstract the individual constituent systems in terms of what are the available resources and which services can be provided to fulfill a set of demands in a specific mission. Individual designing decisions on each of these systems are not taken into account, as they cannot be fully modeled, they are not in control of the mission concept, and due to its intrinsic heterogeneity, it would be a never-ending work.

7.4 Future works

Science is continuous and never an end in itself.

It was an initial desire to have an implemented integration between the different aspects of the method that would simplify the execution. Integrating, in a tool, the SysML model, Simulation Scripting, and Results Analysis. Since these three aspects are directly correlated and integrated at a theoretical level, a systematic tool would help with a better realization of the intended evaluation.

The use of open-source tools is part of this intent. Gaphor, for SysML modeling, GMAT for simulation of scenarios and Jupyter Notebooks for logic-mathematical analysis.

Of course, more work needs to be done in order to expand the SysML profiles and extension on the CubeSat Reference Model to better represent the DSSoS, in terms of Mission Engineering, Planning, and Scheduling.

Collaborative Distributed Space Systems (of Systems) are a reality, it is up to us if they are going to be something that will propel us to the future of space missions or if they will remain in the science fiction books.

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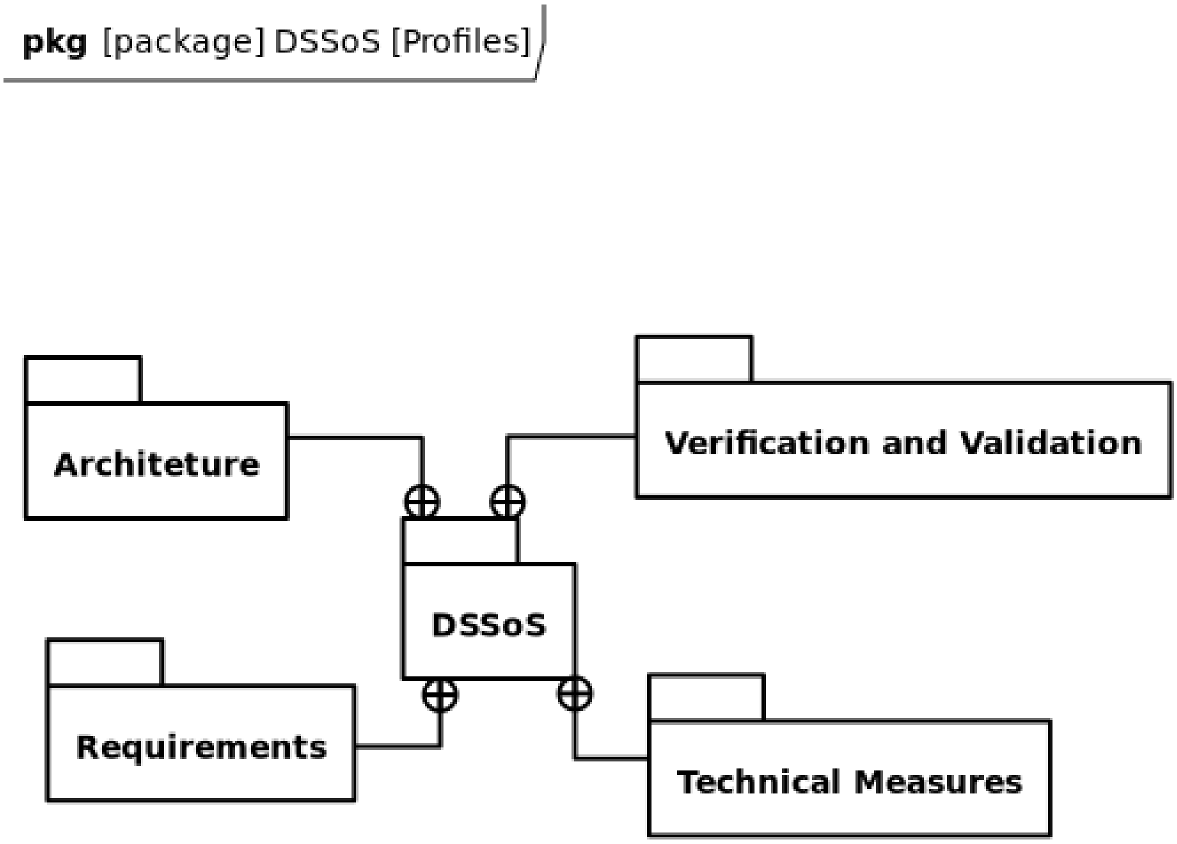
APPENDIX A - DSSoS MODEL IN SYSML

A.1 Profiles diagram

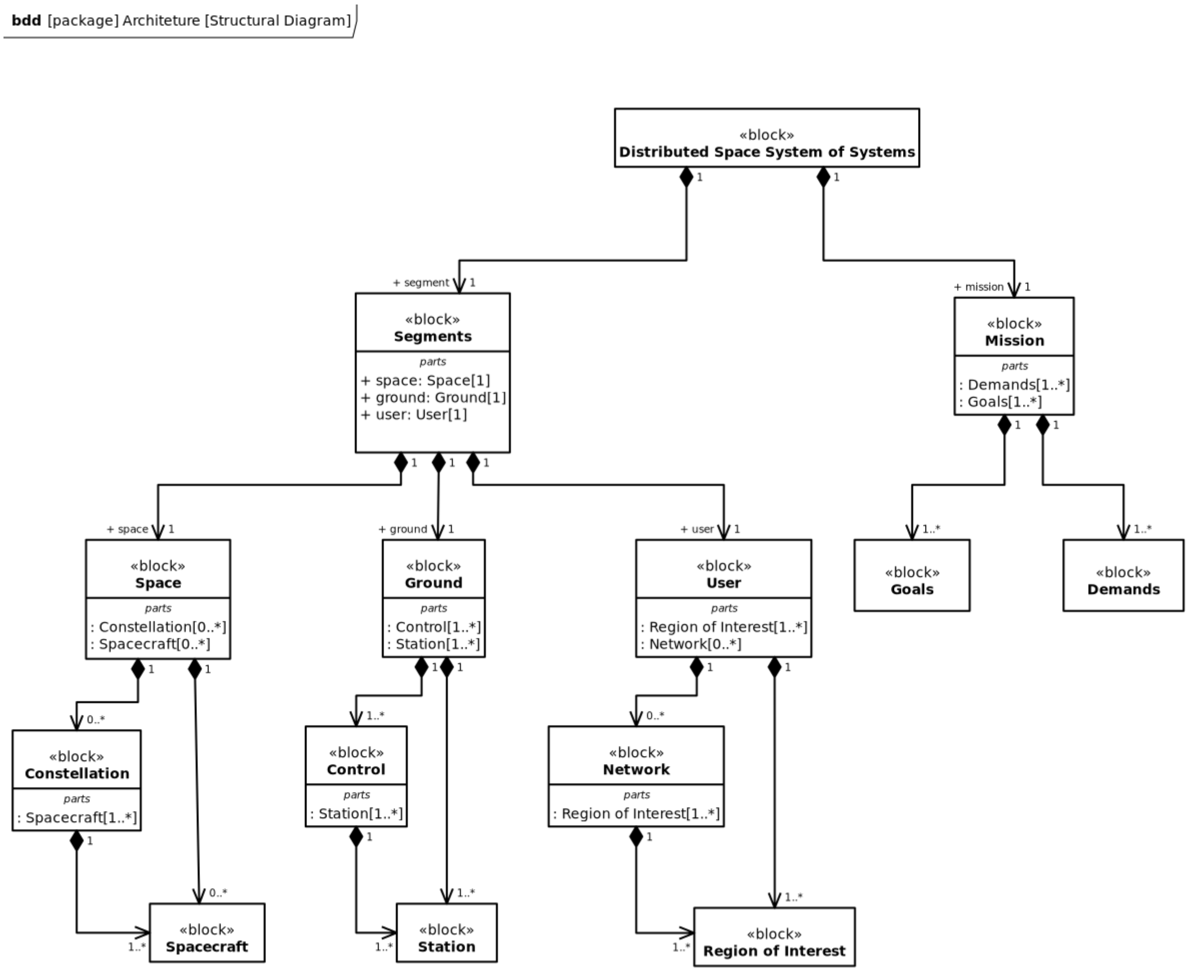
Figure A.1 - Profiles used for the DSSoS modeling.



SOURCE: Author.

A.2 Architectural diagram

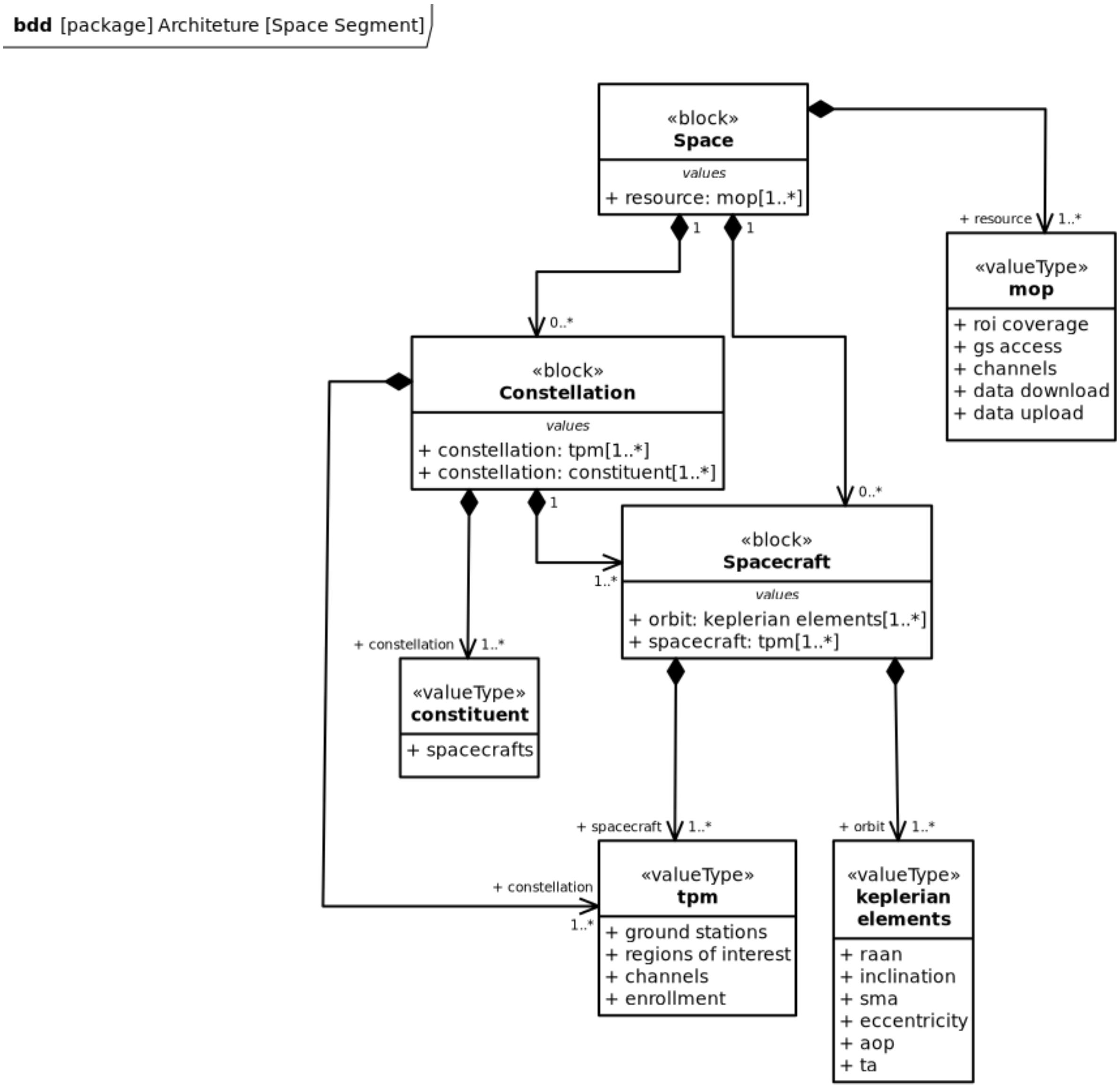
Figure A.2 - Structural Diagram for DSSoS modeling.



SOURCE: Author.

A.3 Space segment diagram

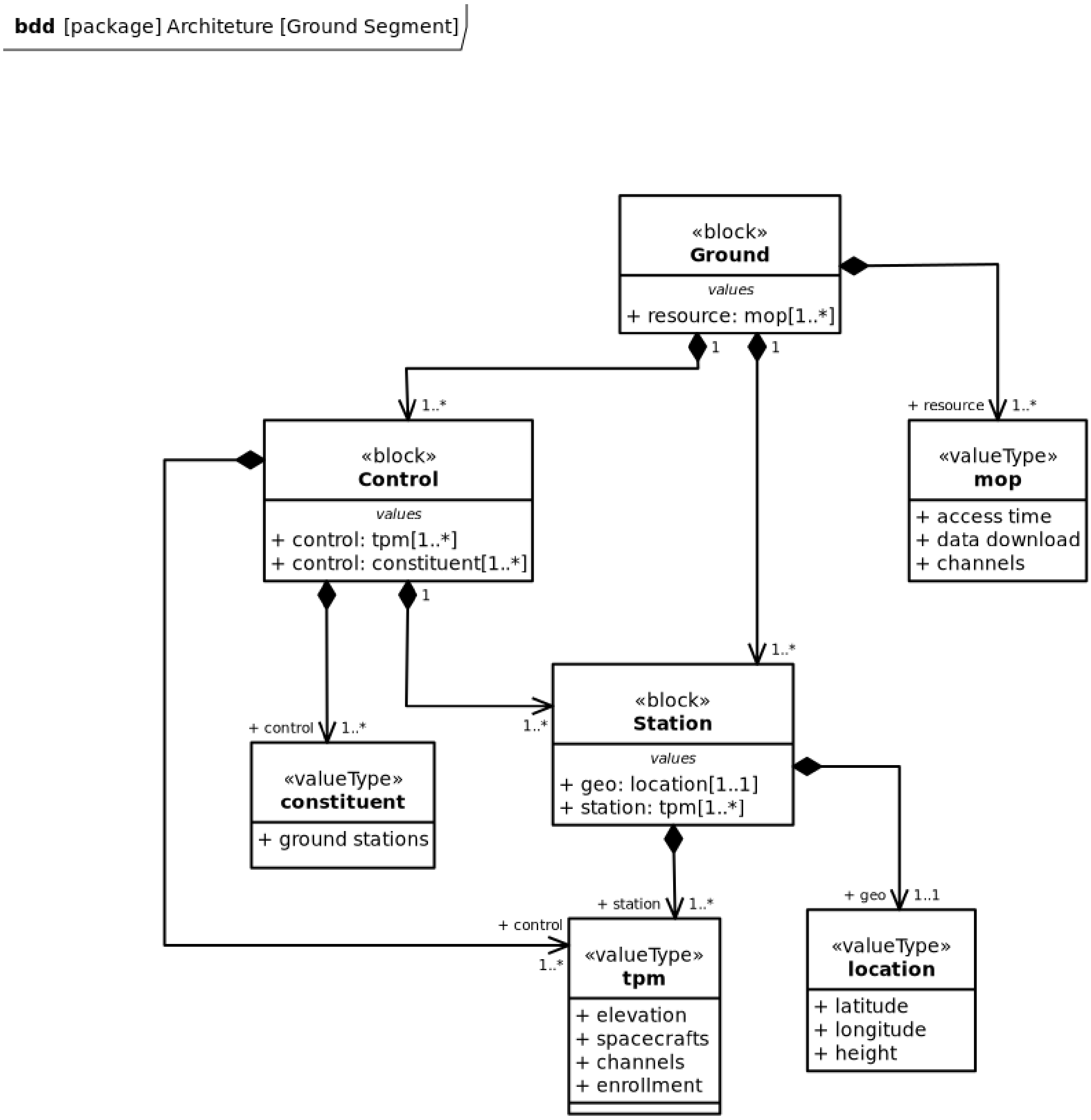
Figure A.3 - Structural Diagram for DSSoS Space Segment modeling.



SOURCE: Author.

A.4 Ground segment diagram

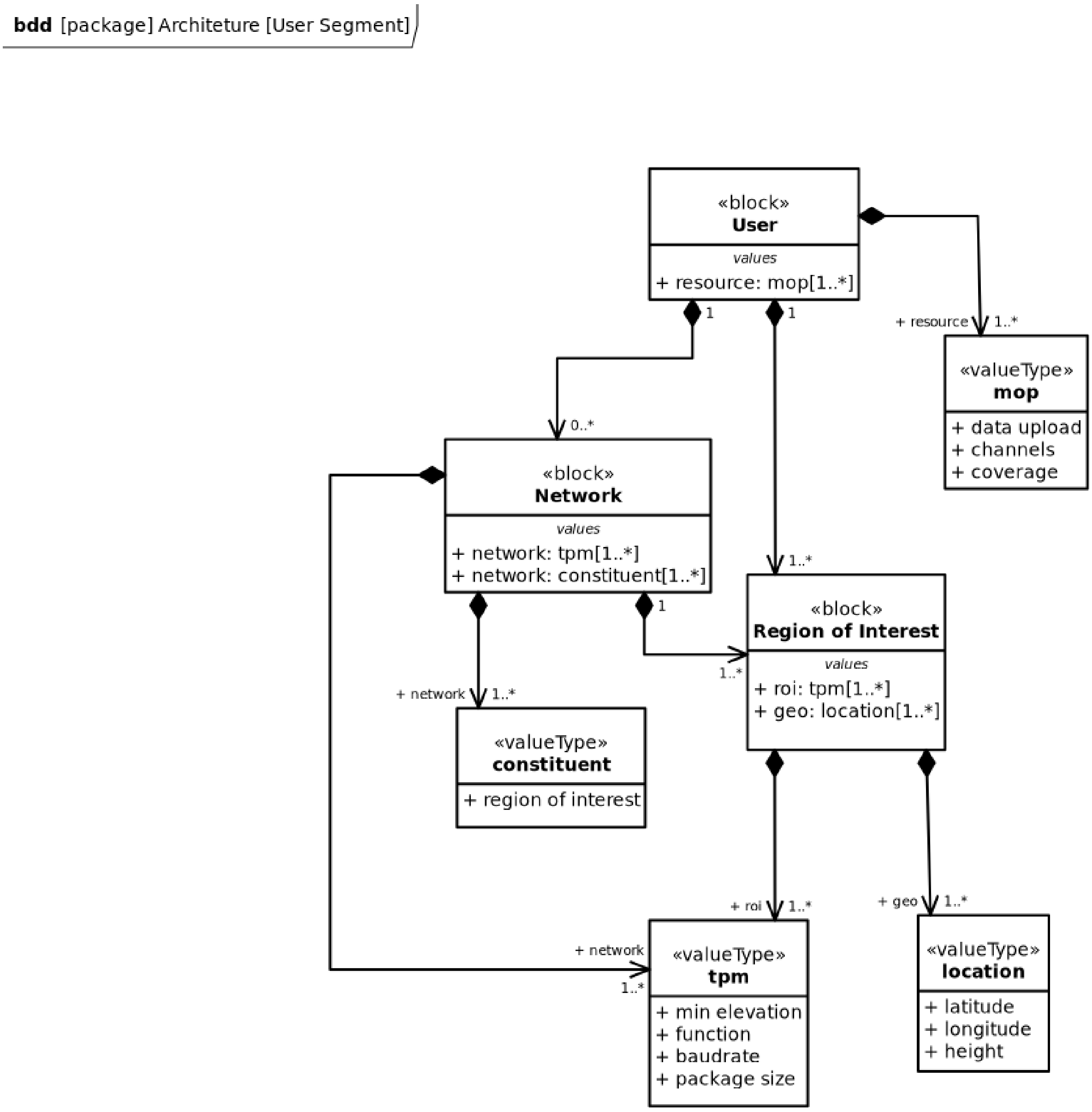
Figure A.4 - Structural Diagram for DSSoS Ground Segment modeling.



SOURCE: Author.

A.5 User segment diagram

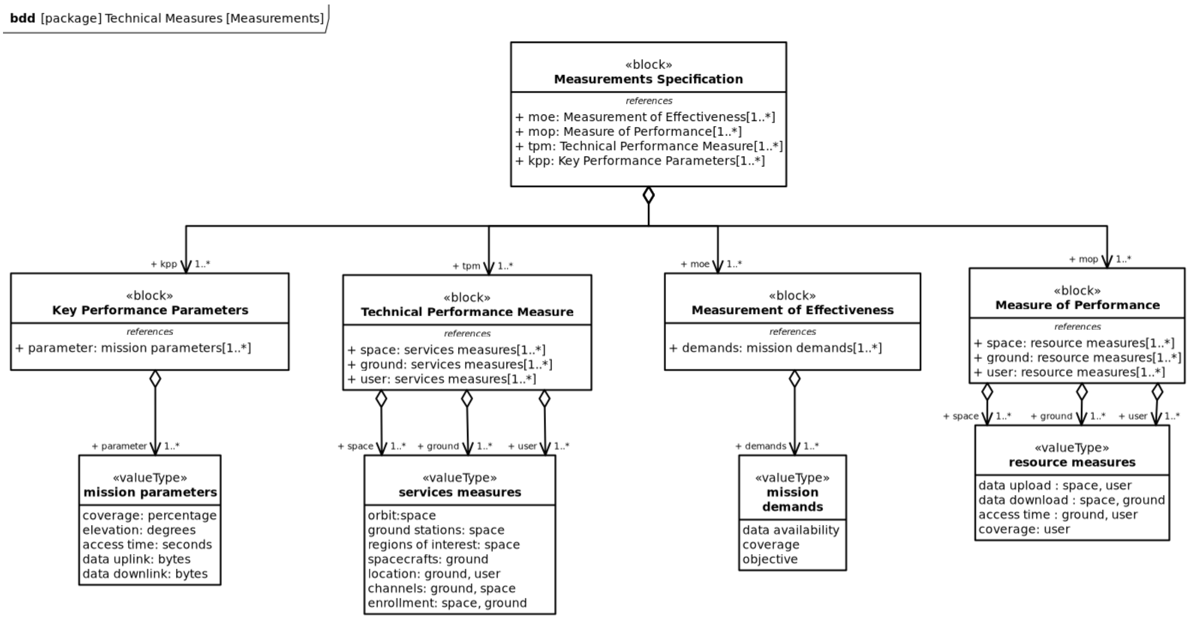
Figure A.5 - Structural Diagram for DSSoS User Segment modeling.



SOURCE: Author.

A.6 Technical measurements diagram

Figure A.6 - Technical Measurements Diagram for DSSoS modeling.



SOURCE: Author.

APPENDIX B - PARAMETRIC DATA FOR THE RESOURCES

The next sections will exemplify the parametric data for the different resources (space, ground, and user) used for the different evaluation scenarios.

B.1 Keplerian elements for the spacecrafts

Table B.1 - Spacecraft Keplerian Elements used on the scenarios.

NAME	SMA(km)	ECC	INC(deg)	RAAN(deg)	AOP(deg)	TA(deg)
CONASAT1	6921.00000	0.00200	97.70000	360.00000	152.00000	360.00000
CONASAT2	6921.00000	0.00200	97.70000	300.00000	152.00000	360.00000
CONASAT3	6921.00000	0.00200	97.70000	240.00000	152.00000	360.00000
CONASAT4	6921.00000	0.00200	97.70000	180.00000	152.00000	360.00000
CONASAT5	6921.00000	0.00200	97.70000	120.00000	152.00000	360.00000
CONASAT6	6921.00000	0.00200	97.70000	60.00000	152.00000	360.00000
SCD1	7121.00000	0.00400	24.97000	25.53000	91.60000	360.00000
SCD2	7123.00000	0.00100	25.00000	150.27000	331.79000	360.00000
CBERS4A	7151.00000	0.00200	98.50000	138.61000	283.20000	0.00000
ITASAT1	6946.00000	0.00180	97.53000	61.18000	180.44000	182.76000
AMZ1	7127.00000	0.01108	98.5089	135.0747	261.1190	98.8578

B.2 Ground station locations

Table B.2 - Ground Station locations used on the scenarios.

NAME	LATITUDE(deg)	LONGITUDE(deg)	HEIGHT(m)
EMMN	-5.835	-35.209	51
ETC	-15.550	-56.067	0
ETA	-2.530	-44.400	0
BME	47.470	19.060	0

B.3 Data collection platforms locations

Table B.3 - Example used for the DCPs Locations.

STATE	STATE NAME	LAT(deg)	LON(deg)
SP	São Paulo	-23.5587	-46.625
RJ	Rio de Janeiro	-22.925	-43.225
MG	Minas Gerais	-19.915	-43.915
RS	Rio Grande do Sul	-30.05	-51.2
PE	Pernambuco	-8.0756	-34.9156
CE	Ceará	-3.75	-38.58
BA	Bahia	-12.97	-38.48
PR	Paraná	-25.42	-49.32
PA	Pará	-1.45	-48.48
GO	Goiás	-16.72	-49.3
AM	Amazonas	-3.1	-60.0
ES	Espírito Santo	-20.324	-40.366
AL	Alagoas	-9.62	-35.73
RN	Rio Grande do Norte	-5.78	-35.24
MA	Maranhão	-2.516	-44.266
SC	Santa Catarina	-27.58	-48.52
PB	Paraíba	-7.1011	-34.8761
PI	Piauí	-5.095	-42.78
MT	Mato Grosso	-15.5696	-56.085
MS	Mato Grosso do Sul	-20.45	-54.6166
SE	Sergipe	-10.9	-37.12
AP	Amapá	0.033	-51.05
RO	Rondônia	-8.75	-63.9
AC	Acre	-9.9666	-67.8
TO	Tocantins	-10.2377	-48.2878
RR	Roraima	2.8161	-60.666

ANNEX A - PAPER ACCEPTED AND PRESENTED AT THE 17TH INTERNATIONAL CONFERENCE ON SPACE OPERATIONS 2023, DUBAI, UAE

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Resources/Services/Demands Relationship on a Federated Cubesat Constellation System Operation

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Abstract

This paper addresses the problem of orchestrating resource sharing in Federated Satellite Systems under heterogeneous ownership of components. Federated Satellite Systems, FSS, are a particular case of cooperative Distributed Satellite Systems because their constituent systems are under the control of different owners and/or stakeholders. However, at the same time, they share one or more common goals, an emergent behavior. Additionally, the increasing availability and affordability of the CubeSat technologies and market open an opportunity to enroll different players for quick access to space. Sharing resources regulated by cooperation agreements between different institutions may increase the capabilities of a satellite configuration for a particular mission. This way, sharing different segments (space, ground, and user) enlightens the path to a qualitatively new range of missions. Services could be provided not by a single entity but by the totality of the activities of many spacecraft, payloads, and ground stations, even if they were initially not planned to cooperate. The core question in such a distributed configuration of heterogeneous ownership is the proper orchestration of resource sharing. The FSS has a dynamic topology originating in the independently designed and controlled orbital trajectories, occasional dropouts due to faults, etc. The challenge is to compose and maintain a proper allocation of resource-sharing schemes to fulfill the demands of the particular missions. The quality of the service provided by an ideal FSS shall be evaluated based on the relationship between the service offered by the resources and needed by the missions under the constraints originating in shared resources (e.g., access time, data generation/storage) in the constituent systems. Does the optimization address how we can manage the limited resources in orbit to better achieve the proposed goal? The paper presents for this purpose a constraint-driven evaluation, or in a more precise way, deals with the operation of such a System of Systems as a Constraint Satisfaction/Optimization Problem.

Keywords: CubeSat, FSS, DSS, CSP, Constellation, Modelling

Acronyms/Abbreviations

DSM	Distributed Spacecraft Mission	MoE	Measures of Effectiveness
DSS	Distributed Space System	KPP	Key Performance Parameter
FSS	Federated Space System	MoP	Measures of Performance
FCS	Federated CubeSat System	TPM	Technical Performance Measures

1. Introduction

Satellite constellation is the most general term for defining a distributed spacecraft mission (DSM). A DSM is a mission that involves multiple spacecraft to achieve one or more common goals. This main definition does not specify if the multiple spacecraft are launched together, achieve common goals by design or in an ad hoc fashion, or if the common goals are scientific. “Multiple” means “two or more” and can refer to tethered or nontethered satellites. For example, a DSM conceived with two or more satellites to achieve particular requirements can count on

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other satellites later and refer as a “constellation,” or it can become a DSM after the fact, in which case it is an “ad hoc” DSM or a “virtual” mission [1, 2].

The concept of DSM has not been systematically traded when designing mainstream missions. Given cost considerations, miniaturization using CubeSats, SmallSats modular satellite architecture, and standardized payload orbital delivery (POD), the constellation concept is coming in the last 10 years more common in the space sector (space agencies, industry, and academia) due to many technical and programmatic changes in the development of satellite missions. Satellite constellations are an efficient pathway to technological development. Building a distributed mission adds complexity beyond the development phase of each spacecraft of the mission. Significative costs and risks to the mission are due to the complexity of the operational phase.

Inspired by cloud computing nodes, the Federated Satellite Systems (FSS) paradigm introduced by Golkar and Cruz [3] consists of spacecraft networks trading unused resources and commodities to achieve a common goal. FSS envisions a space-based resources market, where missions dynamically offer to the federation any underutilized capabilities such as bandwidth, processing power, or data storage, and access to such resources depending on their needs. FSS can be classified as heterogenous, reconfigurable, deployable, and collaborative space missions [1]. Heterogenous, as the constituent systems have different owners and stakeholders and they do not, a priori, need to share their primary goal or form factor. Reconfigurable, as long as new partners can come and go from the system, as also the demands may change over time, its configuration can change over time with quite a high frequency, based on how much the constituent systems can share and support the FSS. Deployable, because each element of a space/ground/user segment may be deployed into the system as demanded by its owners. Collaborative, by means that the FSS goal achievement is based on the active cooperation between all the constituent systems, on how much they collaborate to the quality of service.

This paper addresses the core question of a Federated Constellation composed of a network of independent satellites Cubesat-based, aiming at formalizing the Resources/Services/Demands Relationship in a distributed configuration of heterogeneous ownership as the proper orchestration of resource sharing.

FSS is a space mission paradigm that instantiates the CPSoS concept in the space domain [4], aiming to switch from independent, isolated space missions to a highly dynamic, constantly evolving in-orbit infrastructure capable of supporting different missions and even deploying software-based, virtual missions. FSS constitutes the dawn of cloud computing environments in space, which will significantly change the way space missions are conceived and operated.

Using the approach of CPSoS, we aim to break down the FSS structure in terms of mission, demands, resources, and services shared between the constituent systems of this Distributed Space System. This shared, and limited, amount of resources plays a role in satisfying the mission demands, characterizing the quality of service as a Constraint Logic Satisfaction Problem. Also, we use the example of the idealized GOLDS Constellation [5] as a study case for our proposed problem model, in the context of the ADVANCE Project.

2. Problems Description and Modeling Method

The orchestration of a CubeSat-based FSS Constellation, from now on Federated CubeSat Constellation System (FCS, for short), is the core idea when we talk about this kind of DSS. A classification system for categorizing constellations, which takes into account the workload related to operational tasks, as well as the scalability of these tasks can be used to identify and prioritize operational tasks.

2.1. Problem Description

This orchestration can be challenging due to the intrinsic heterogeneity of a Federated Constellation. So, managing the sharing of resources, the provisioning of services, and the scalability of demands are the pain points and main problems in this symphony.

2.1.1. Sharing Resources

Sharing resources in an FCS is crucial for the success of the mission. Once the constituent systems do not share, in most cases, the same owner, main goal, or form factor, their capabilities on access time, coverage, and data accessibility are precious resources in the coordinate operation.

As each Constituent systems (CS) have a decentralized development and operations, the FCS operations cannot rely on the optimal delivery of resources. Each CS can provide a limited amount of resources that should be managed by the Constellation operation as a whole. For example, if a ground station has limited time of access to a specific spacecraft, in the FCS context, its operation should be maximized to exploit the limited access time, a.k.a the resource.

2.1.2. *Provisioning of Services*

It is the responsibility of the FCS to know and manage the services that can be provisioned by each constituent system or the sum of them. The entering of a new satellite or ground station into the Federated System is a new service provider with its shareable resources. It is the role of the FCS Operations to evaluate the impact of this addition and even so the reconfiguration of the whole system.

2.1.3. *Scalability of Demands*

Sharing resources on the ground or in space can be easily tackled when we deal with small numbers of satellites or ground stations. But a well-working system for a small constellation may collapse when the number of spacecraft is increased because the underlying architecture does not scale to large constellations [6]. Even so, the demands start increasing exponentially when for the number of constituent systems you have a close amount of stakeholders with their expectations.

2.2. *Modeling Method*

A FSS, and as a consequence FCS also, has its own goal, objectives, and its demands. In the context of a Distributed Satellite System, these goals, objectives, and demands are shared between the different CS. Even if they do not have the FSS goals as primary, so they share their resources as services to help the FSS to achieve its demands.

To better understand and approach the relationship between these three views (demands, resources, and services) we decided to use two concepts of modeling, one logical and the other structural.

2.2.1. *Structural Modeling*

Based on the CubeSat System Reference Model, CSRM [6], it is possible to define a structure profile that interprets the different aspects of the FCS. The general architecture for the FCS is represented in Figure 1. Where we can see distinguish between the different constituent systems and their properties.

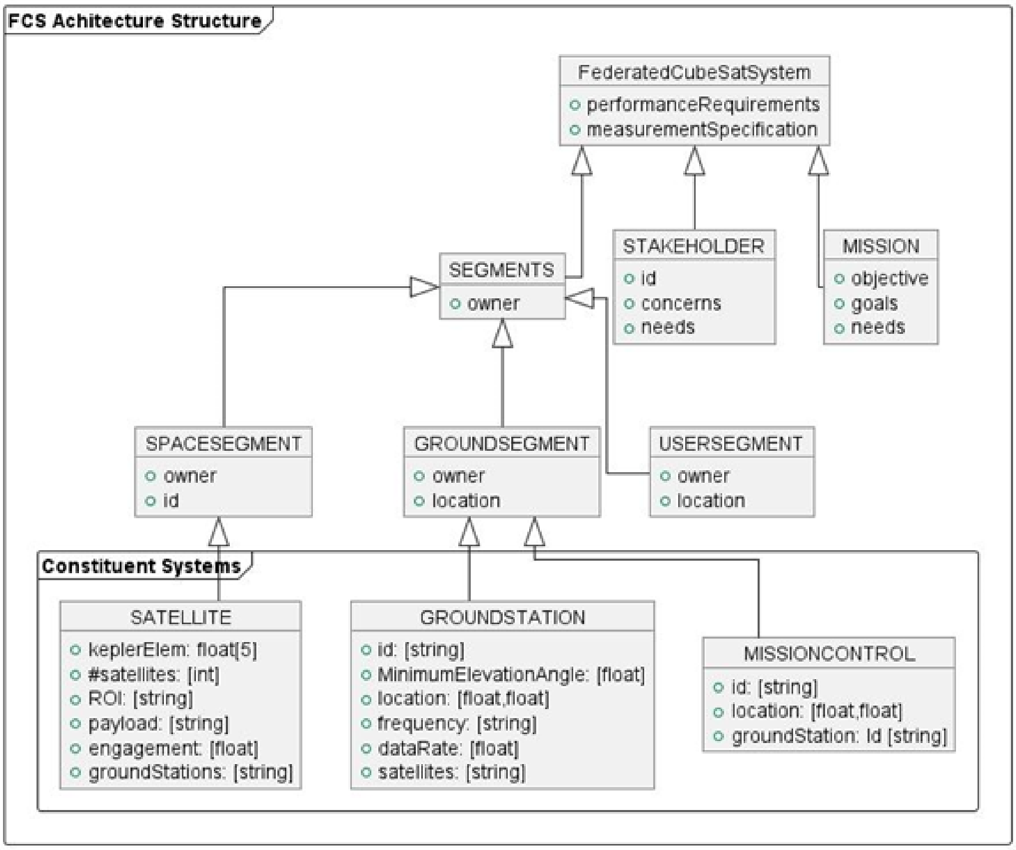

Figure 1: FCS Architecture Structure Profile, [6]

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Different measures can be derived and allocated from different entities in a CubeSat mission. These measurements are specific parameters/measures that support the quality assurance for a space mission [6]:

- Measures of Effectiveness (MoE) Captures Stakeholder descriptions of operational measures of success.
- Key Performance Parameters (KPP) Specifies a technical measure, constraints, and measurement activities.
- Measures of Performance (MoP) Descriptions of physical or functional attributes relating to system operation.
- Technical Performance Measures (TPM) Specifies attributes of a system/subsystem that determine how well the system element is satisfying or expected to satisfy the technical requirements.

From the mission perspective, we can define the Key Performance Parameters. They specify a technical measure, constraint, and measurement activities on how “good” a mission is being performed. From the Stakeholders’ perspective, and their concerns, we can define the Measures of Effectiveness, which capture descriptions of operational measures of success of the mission in terms of what are the stakeholders’ expectations. From each constituent system, we can characterize them with Technical Performance Measures, which specify attributes of a system that determine how well the system element is satisfying or expected to satisfy technical requirements. Even so, the so-called Measures of Performance, which represent physical or functional attributes relating to system operation, can be confirmed by the TPM of each constituent system or the sum of their available resources, see Figure 2.

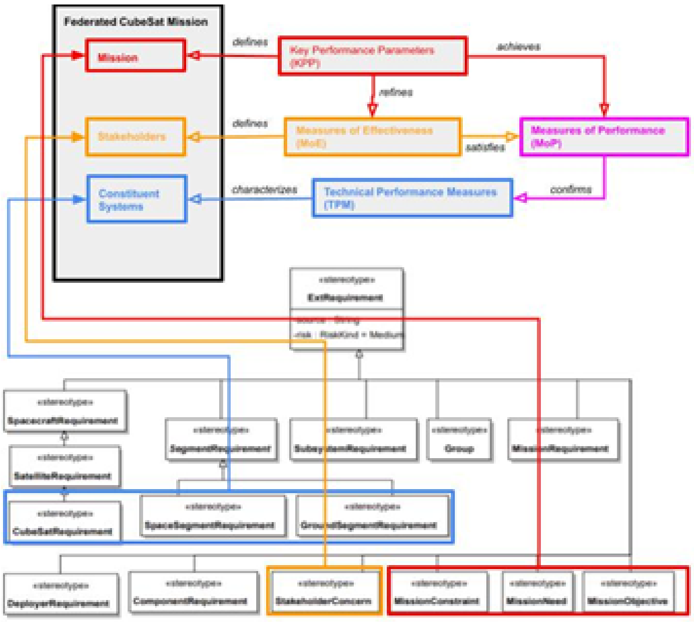

Figure 2: Relationship between Technical Measures and FCS Entities

2.2.2. Logical Modeling

The idea of logical modeling is to represent the logic-mathematical relationship between the aspects of the FCS. So, the demand, for example, can be expressed as a function of the decision variable which is used as a constraint in a constraint satisfaction model, which plays an important role in the simplification and description of multi-constraint problems.

On the whole, the constraint satisfaction model can design relevant demands according to the specific scenarios of the provisioning of services, these constraints are easy to describe, and have strong high extensibility.

Figure 3 exemplifies the relationship between the mission, with its demands, and the resources, with its own available services.

On each time fragment, T, the system domain (Eq. 1) has its own configuration, in terms of demands to fulfill, resources available, and services to share. So, for each time fragment, we gonna have a different set of demands (Eq. 2), resources (Eq. 3), and, of course, services, for the mission.

$$domain(T) = mission(m, T), resource(r, T), \forall\, m \in [1..1],\ r \in [1..R] \quad (1)$$
$$mission(m, T) = demand(d, m, T), \forall\, d \in [1..D] \quad (2)$$
$$resource(r, T) = service(s, r, T), \forall\, s \in [1..S] \quad (3)$$

The mission, m(T), has its demands, d(m, T), that can be derived from the stakeholders' expectations. In the same sense, each CS can be defined as a resource, r(T), with its services, s(r, T). These services should be shared to accomplish one specific mission demand. The accomplishment of each demand can be solved as a Constraint Satisfaction Problem, Σ.

The demand is independent of the service available. By any means, there is always a demand, and the system is trying to fulfill it within the resources at hand.

And the time fragment is discrete, the changes came from event modifications, an event-oriented approach.

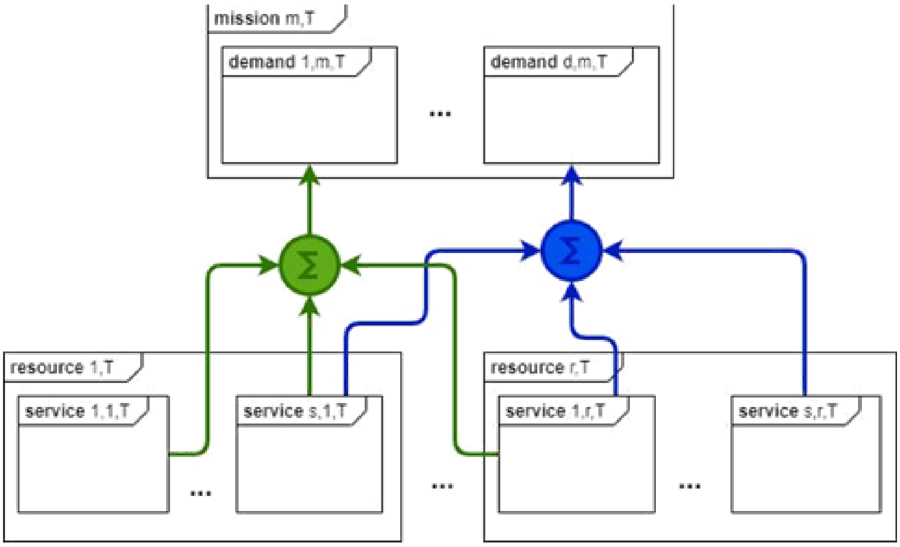

Figure 3: Concept of Mission, within its demands, and Resources, within its available services

2.2.3. *Integrated Modeling*

Getting together the two approaches, the Technical Measurements from the CSRM and Resources-Services sharing idea, we can exploit, in a concept of operation sense, where the TPM is related to each service, where each resource shared contributes to the MoP in order to satisfy specific KPP from specific demands. The fulfillment of these demands contributes to the MoE expected for each mission (Figure 4).

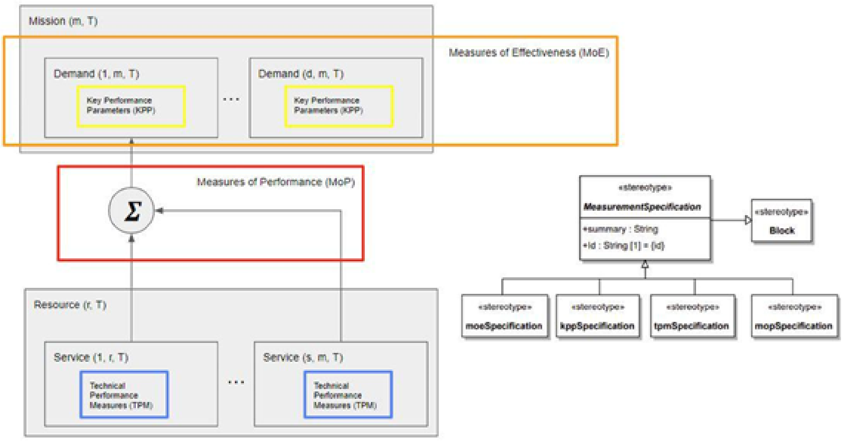

Figure 4: Relationship between the Technical Measures and the Constraint Satisfaction Model Elements

For example, given a system, S, evaluated in a time fragment, T, within a mission, m, with the space, ground, and user segments as shared resources.

$$S(T) = mission(m, T),\ resource(r, T),\ \forall r = [space,\ ground,\ user] \quad (4)$$

The mission has its own demands, d. Different regions of interest are to be covered, d_{roi}.

$$mission(m, T) = demand(d_{roi}, m, T)\ \forall\ d_{roi} > 0 \quad (5)$$

Each satellite can be defined as a CS, a service in an FSS, from the space resource available, r = space.

$$resource(space, T) = service(s_i, space, T),\ \forall\ i = 1..N \quad (6)$$

Where, N, is the number of satellites available to provide as-a-service.

Each ground station can also be defined as a CS, a service in an FSS, from the ground resource available, r = ground.

$$resource(ground, T) = service(s_j, ground, T),\ \forall j = 1..K \quad (7)$$

Where K is the number of ground stations available to provide as a service.

In a specific time fragment, T0, when evaluating the FCS, from a set of CS, r(T0) which have each service, s(r, T0), providing TPMs to achieve a demand, d(m, T0), T P M → f(s, d, T0).

The sum of these services becomes the MOPs of a given resource, r(T0), to fulfill the same demand, d(T0) now as SoS – MoP → f(r, d, T0).

The set of MOPs from each resource involved to fulfill the demand,d(T0), are compared to the KPPs, or the constraints of the mission – KPP → f(d, m, T0).

The sum of demands fulfilled by the FCS represents the MoEs of the FCS, moreover the Quality of Service provided by the FCS for that given mission in a given time – M oE → f(m, T0).

3. Global cOLlecting Data System -- GOLDS

As presented at the 2018 UN/Brazil Symposium on Basic Space Technologies, the Global Open cOLection Data System, a.k.a. GOLDS, the constellation is an international collaboration initiative [7]. It aims the creation of an international constellation cubesat-based, ground stations and data collection platforms working together to ensure quick access to environmental data [5]. GOLDS is a enhancement and an upgrade from the Brazilian Environmental Data Collection, started in the 1990s using two LEO satellites (SCD1 and SCD2), Data Col-lection Platforms spread over all Brazilian territory using ARGOS communication technology, and two ground stations located in Cuiaba (central region) and Alcantara (north region) [8].

Four points make GOLDS an excellent example of a Federated CubeSat System in this work [5]:

- For GOLDS, the satellite design is not a concern for the GOLDS operation;
- quality assurance about the system must be in the GOLDS requirements to achieve a satisfactory level of service;
- GOLDS is an open constellation, not restricted and defined to the number of members and their characteristics and;
- GOLDS still needs to be modeled in lower abstraction to level to reveal the challenges of sharing infrastructure between the missions.

Figure 5 shows GOLDS operational scenarios. Where the scientific community can access the data acquired by GOLDS through independent missions.

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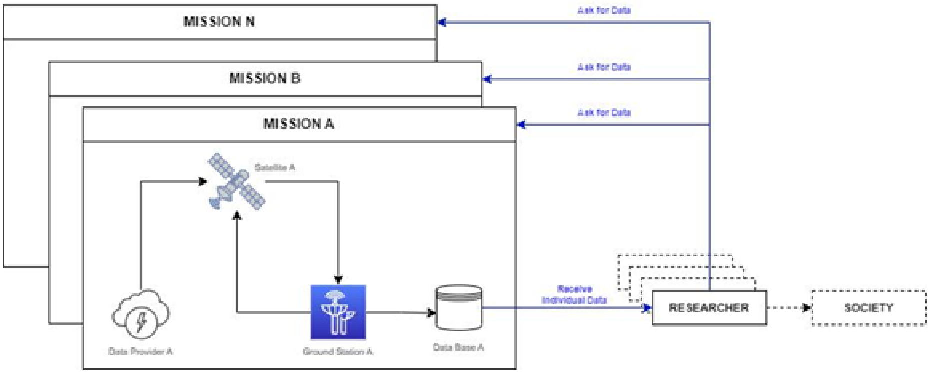


Figure 5: GOLDS operational scenarios, [5]

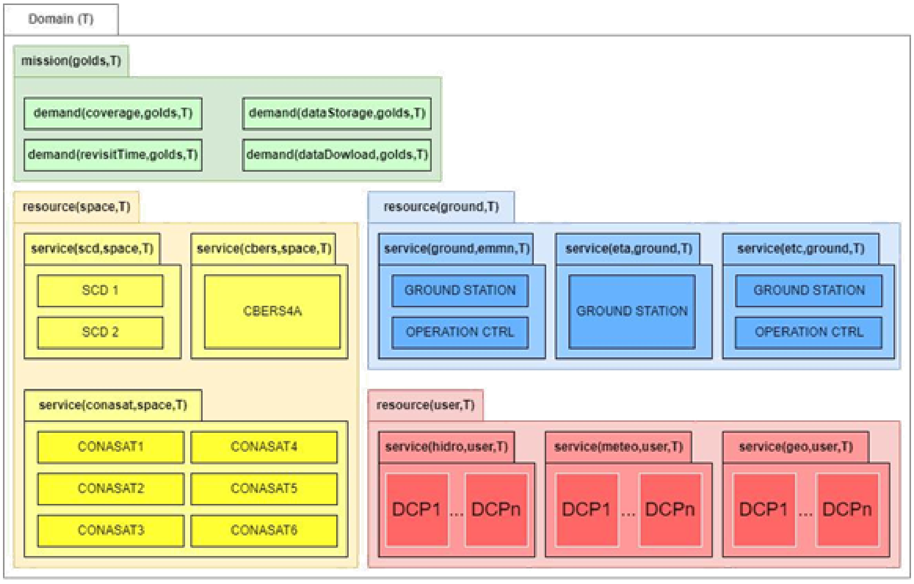


Figure 6: Domain space for the GOLDS ideal FCS

3.1. Modeling GOLDS

In order to model the GOLDS as an FCS, we first have to determine the Domain Space in a given time fragment for the system, Domain(T), see Figure 6.

Where:

- mission(golds,T) is the set of demands for the GOLDS mission, that assures the quality of service delivered for a given time fragment.
- resource(space,T) is the set of services, or spacecraft, available for the FCS in a given time fragment.
- resource(ground,T) is the set of services, ground segment, available for the FCS in a given time fragment.
- resource(user,T) is the set of services, user segment, available for the FCS in a given time fragment.

The time fragments, T, are defined as specific time fragments where the visibility between the entities does not change.

So, for the specific mission goals and stakeholder expectations that GOLDS has, we have different para-metric demands. These demands exemplify the MoEs for GOLDS mission, as many as they are fulfilled, we can assume a better quality of service provided.

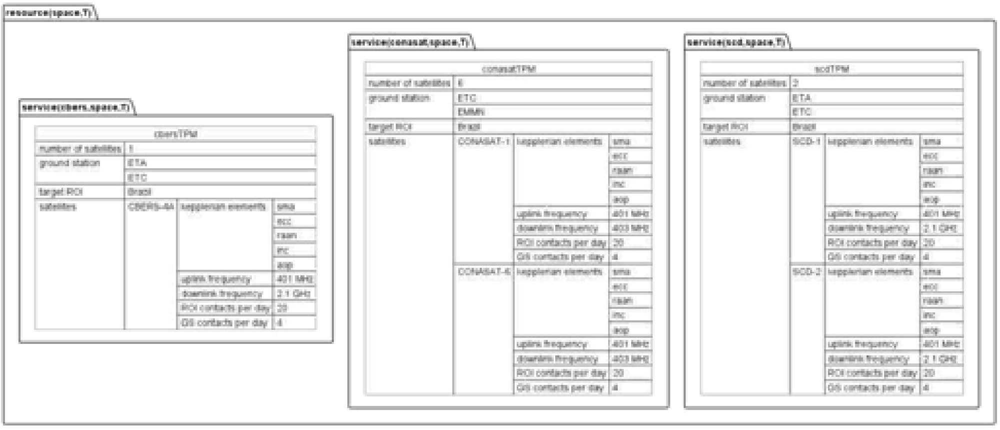
For the segments, or in this case, resources that we have available for the FCS, each of them has its available services.

Each service on the space segment, service ∈ resource(space, T), is a satellite, a family of satellites, or a constellation available on that given time fragment, T .

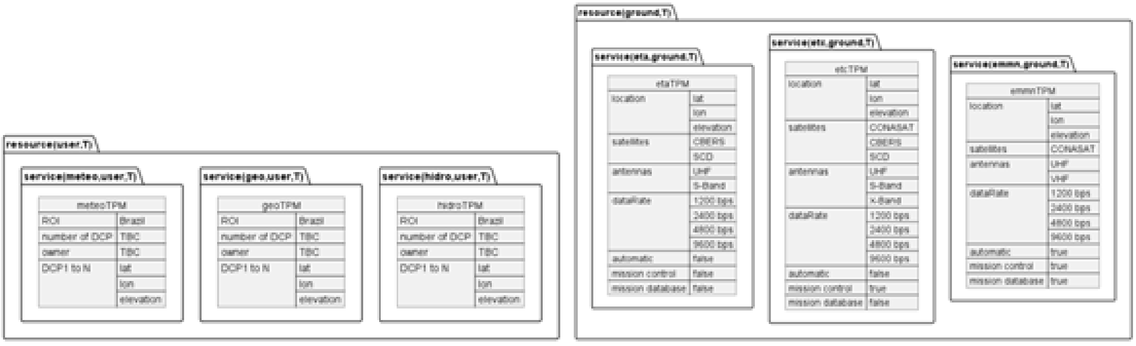
Each service on the ground segment, service $\in$ resource(ground, T), is an available ground station/operation control for the FCS on that given time fragment, T . It is a fact that each ground station is attached to a specific satellite or set of satellites being that a limitation inherent of this heterogeneous system.

Each service on the user segment, service $\in$ resource(user, T), is one Data Collection Platform network responsible for acquiring the environmental data (hydrological, meteorological, or geological) from a specific region and normally owned by a specific user, stakeholder, client on that given time fragment, T.

Figure 7 presents the parametric values for TPM of each GOLDS resource-related service.



(a) Space Resource



(b) User Resource (c) Ground Resource

Figure 7: TPM from resources-related services, a.k.a. shared commodities

4. Mission demand model

The evolving concept of the FCS as an extensible multi-satellite configuration requires a proper integration strategy of the new configuration elements to exploit the additional capabilities and capacities provided by the new members. Task reallocation is essential to such integration to balance the task and resource allocation.

Here the resource allocation after the extension of a configuration by new satellites can be prepared or even executed during mission design time before deploying the new member of the configuration. However, the mitigation of satellite faults by reconfiguration is a time-critical task to rapidly substitute resources and services originally provided by the faulty satellite and recover the original operational context. This necessitates the invocation of a fast reconfiguration estimator triggered by the detection of the dropout of an element in the configuration.

Technically, reallocation is a problem to be solved on the ground with no strict constraints on the use of computational resources. However, the long-term vision of large satellite configurations necessitates well-scalable algorithms.

Note that the peculiarities of cube/nanosatellites necessitate the operation-time design of such communication plans. The reliability of nanosatellites is significantly less than that of traditional ones [9]. This way, the ”disposable” nature of nanosatellites results in frequent faults, needing a redesign of the task allocation to the individual elements of a satellite configuration.

The following heavily simplified example illustrates the mapping of the core constraints and design objectives into a well-scalable mathematical model. For the sake of simplicity, the focus is only on the phases of acquiring information (i.e., taking pictures, receiving data) of the different regions of interest (RoIs) and downloading them to some ground stations. During the download phase, satellites can split the information into parts and download them in parts. Ground stations can receive this data from the corresponding satellites (See Figure 7c). Later, the ground stations can interchange information fragments using terrestrial communication.

To increase the download capacity, a satellite may send a data package to another one in the configuration which has access to another ground station or can prolong the time fragment available for data download due to access to a ground station in a period unavailable for the initiating satellite. This way, multi-hop downloads help to overcome the strict constraint of peer-to-peer satellite-ground station communication, thus increasing the time and/or bandwidth available for data download.

A simplifying assumption of the example is that any satellite over a RoI covers the entire region. Thus, for example, an image taken at an arbitrary time and sent to an arbitrary ground station fulfills the mission's objectives.

The quality assurance measures for space missions can be interpreted in the context of the example as follows:

- MoE: In this example, the amount of available data represents the effectiveness of the mission. The stakeholders demand that the FCS be capable of distributing all the data acquired in the RoI. The stakeholder being able to receive the data is the effectiveness of the system.
- KPP: From the MoE we define the key parameters to ensure the effectiveness of the mission. The KPP in this example model only includes the communication (coverage, revisit, and data management) aspect of the system. It allows the definition of the mission constraints based on the mission objectives and needs.
- MoP: Utilization, which determines how much of the theoretical capacity limit of the particular resource is used by the system. That is, for example, how much of the maximum available download volume is actually used.
- TPM: This model includes communication parameters (e.g., bandwidth) of the satellites and the ground stations. This way, we can measure the generated data (e.g., by taking pictures) and the amount of downloaded data. The specific value determines how much of the system's capacity is used according to a given schedule.

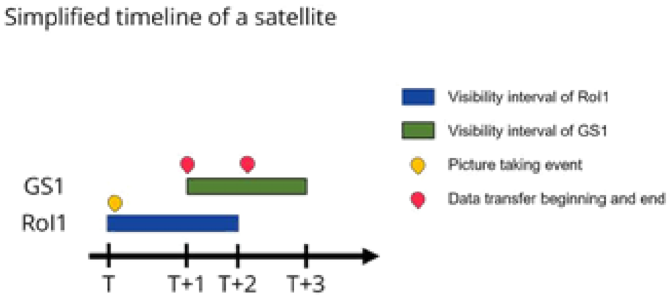


Figure 8: Simplified timeline of a satellite

The time fragments in the example are modeled similarly to in event-oriented simulation (Figure 8). Each time instance in which the system changes qualitatively, its state is taken on a timeline. The different timelines that correspond to event types merge into a single mission descriptor timeline. The simplified model contains the following events:

- entering and exiting the visibility range of a RoI;
- establishing and losing connection to a ground station (data transmission);
- beginning and end of an inter-satellite transmission;
- loss of a satellite due to a fault;
- acquiring information of a RoI.

Simulation establishes the system state in the individual time instances corresponding to the events at the merged timeline[1].

The design space can be defined by setting mission demand requirements as constraints. We currently consider only four mission demands on a simplified system model without loss of generality. Although simplification is

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[1] Note we assume that all faults are fatal in the running example. Thus we neglect repair actions like the potential recharge of the energy storage after its exhaustion.

achieved in the system, this model can be easily extended with additional parameters, constraints, and optimization criteria. Introducing more constraints leads to more efficient cuts in the search space, thus facilitating a reduced choice of possible parameters.

In the model, $s_i \in$ resource(space, T) is the i-th space resources for the given time fragment, and $g_j \in$ resource(ground, T) is the j-th ground resource (ground stations (g_{sj}), RoIs (roi_j)) for the given time fragment. The duration of a time fragment, i.e., the length of the corresponding time interval τ ($\tau \in$ T) is denoted by τ_T . Between a space (s_i) and ground (g_j) resource for a given time fragment T , the visibility is denoted by the binary variable v_{ij}(T), and the active connection is denoted by c_{ij}(T). Accordingly, a connection between si and gj corresponds to v_{ij}(T) = 1 and c_{ij}(T) = 1.

In the simplified model, the following general assumptions were made:

- A ground resource (g_j) can connect to a maximum of one space resource (s_i):

$$\sum_{i=1}^{|resource(space,T)|} c_{ij}(T) \leq 1 \tag{8}$$

- A space resource(si) can connect to a maximum of one ground resource (gj):

$$\sum_{j=1}^{|resource(ground,T)|} c_{ij}(T) \leq 1 \tag{9}$$

- Only there can be an active connection between the space (si) and ground resources (gj) if there is visibility between them:

$$c_{ij}(T) \leq v_{ij}(T) \tag{10}$$

This kind of connections can describe both taking pictures of RoIs (roi_j) and transferring it to the ground station (gs_j).

The four examined mission demands are the following:

1. Data download: One of the most important requirements is that data generated from space resources can be transferred to the ground. This is possible when there is an active connection between a space and ground resource. We assume that the ground station can receive the transfer from any satellite (it has at least such a bandwidth as any satellite). If we assume for simplicity that there is the same data rate between all resources then we can calculate by using the number of connections without explicitly transforming it to the actual download bandwidth. The following constraints can be formulated:

The goal is to maximize the number of active connections (c_{ij}(T)) between the space (s_i) and ground resources (g_j) for all time fragments (T ∈ T). The result gives an upper estimate of the global active connections:

$$\forall T \in \mathcal{T} : max \sum_i \sum_j c_{ij}(T) \tag{11}$$

The optimization criteria can be easily extended with the duration of the time fragment, which gives an upper estimate of the available time for the information exchange (which is proportional to the amount of data downloaded under the simplifying assumption of identical communication speed between all elements).

$$\forall T \in \mathcal{T} : max \sum_i \sum_j \tau_T * c_{ij}(T) \tag{12}$$

Note that the model is quite flexible to include different model parameterizations. For instance, if we relax the identity of data rates between all devices thus there is a different data rate between the resources, the model can be extended to include the data rate between two resources ($datarate_{ij}$). In this case, the objective function determines the maximum possible transfer rate in a given time fragment.

$$\forall T \in \mathcal{T} : max \sum_i \sum_j \tau_T * datarate_{ij} * c_{ij}(T) \tag{13}$$

Besides the current objective function, which is based on time, it can easily be supplemented with other metrics such as energy consumption, less channel switching, and more efficient satellite intercom.

2. Data storage: The satellites ($\{s_i\}$) store the pictures of RoIs ($\{roi_j\}$) in their internal storage memory (m_{si} (T), which varies along the time due to new pictures taken and the download process). The information can be downloaded to ground stations ($\{gs_j\}$) in chunks, and the already downloaded data chunks can be deleted. The current memory for all time fragments can be calculated by (memory size in the previous time fragment - downloaded data in the current time fragment if there is a connection between a satellite and ground station or memory size in the previous time fragment + size of the collected information from RoI):

$$m_{s_i}(T) = \begin{cases} m_{s_i}(T-1) - c_{ij}(T) * datarate_{ij} * \tau_T & \text{if the connections is between } s_i \text{ and } gs_j \\ m_{s_i}(T-1) + c_{ij}(T) * informationsize & \text{if the connections is between } s_i \text{ and } roi_j \end{cases} \tag{14}$$

For all time fragment, the used memory (m_{si} (T)) should be less or equal to the storage capacity (sc_i) of satellite (s_i) for all time fragments (T ∈ T).

$$\forall T \in \mathcal{T}, \forall s_i \in S : m_{s_i}(T) \leq sc_i \tag{15}$$

3. Revisit time: Revisit time (Δ_j (T)) gives the time elapsed since the last visit to RoI (roi_j) at the time fragment T .

$$\Delta_j\ (T) = (1 - c_{ij}(T))(\Delta_j\ (T-1) + \tau_T), \tag{16}$$

Elapsed time between two consecutive contacts between any RoI (roi_j) and a satellite (s_i) should not exceed a time limit (tl) predefined by the stakeholders.

The Revisit Time constraint ensures that the stakeholder, or any other entity interested in the generated data by the FCS, may have access to data that is a maximum 1-hour-old from the time that it was acquired. Reducing the time interval between consecutive data acquisitions from the same RoI enables the construction of better representative time series. Such more detailed time series may create better models to foresee and help the decision-making actions, for example in the case of accidents, deforestation, natural disasters, etc.

$$\forall roi_j, \forall T \in \mathcal{T} : \Delta_j\ (T) \leq tl \tag{17}$$

4. Coverage: cov_j represents the coverage ratio for an RoI, roi_j. If the RoI (roi_j) is visible from any satellite then v_j(T) = i(v_{ij}(T)) = 1 .

$$cov_j = \frac{\sum_t \tau_T v_j(T)}{\sum_t \tau_T} \tag{18}$$

The goal is to maximize the coverage for all the regions:

$$\forall g_j : max\ cov_j \tag{19}$$

Even with low values of revisit time on one specific RoI, we cannot assure that we do not have gaps where there is no contact between the spacecraft and the RoI. In this sense, the percentage of coverage may help in understanding, at least on average, how much time we have with this RoI being monitored. Maximizing the coverage means closer to real-time data access.

Naturally, the constraint logic description of the system can be extended by several resources together with their associated requirements, usage constraints, and preferences. In the case of the objective function, there are several ways to reflect multi-aspect objectives:

1. One solution could be the exploration design space by calculating the particular solutions by taking into account only the individual aspects (e.g., the solution requiring the minimum number of satellites involved) and neglecting the distribution of the utilization of the individual resources of the elements in the configuration. Out of these marginal solutions, the design space is well-defined and can serve as a tradeoff.
2. On the other hand, combining the different objectives by introducing penalty and benefits functions to the exploitation of the resources allows a global optimization by introducing weights by the individual sub-objectives.

4.1. Mission demand evaluation

The evaluation of the mission demands and the constraints was performed on simulation data from actual orbital satellite data, i.e., SCD-1, SCD-2, and CBERS4A TLEs. And from an idealized, still under design, new satellite orbital parameters, the project is called CONASAT [10]. It envisions the update of the BEDCS with the use of a CubeSat Constellation, for our simulation purposes 6 satellites, Polar LEO, with 60 degrees of phase difference. It was also used as input for the simulation of the location and pointing characteristics from the Brazilian Ground Stations, located in Cuiaba (ETC), Alcantara (ETA), and Natal (EMMN). For the RoI, it was assumed that each of the Brazilian states was one DCP, a simplification to reduce to 27 RoI instead of dealing with more than one thousand of DCPs in the real scenario.

The simulation is based on the GOLDS constellation, running over the GMAT/NASAv. It covers two complete days, during which the mutual visibility of satellites and ground resources (ground stations, RoIs) was monitored.

The goal of the evaluation is to verify if the different configurations for the GOLDS as an FCS is capable of assuring the Quality of Service expected by the stakeholders (e.g., over 20% RoI coverage). In this sense, we were able to run at least two different configurations, i.e. as-is and to-be, feeding the simulation with different orbital parameters for the new income satellites, i.e. CONASAT Constellation. This simulation data allowed us to evaluate services that are not yet active. This way allows a comparison between the resources of the existing and the planned services. Note this example focuses on the download capacity and the coverage of the RoIs. The revisit time and data storage constraints are neglected in this simplified demo model.

4.1.1. Workflow

In our approach, the evaluation is presented in Jupyter Notebooks as they are reusable with different parametrization and provide an easy-to-follow structure (including both the code and the textual documentation/findings of the results). The steps of the evaluation are the following:

1. Definition of the time fragments: In order to define the time fragment from the simulation data, we have considered that in a fragment, the visibility between ground stations / RoIs and satellites does not change. This way, each time fragment includes the possible pairing of the space and ground resources.
2. Definition the constraints: The constraints include the limitations for the possible connections between the space and ground resources (e.g., Constraint 8-10). Moreover, this is where the various cost metrics are defined. These cost metrics may include the data rate between space and ground resources. Specifying the loss of satellites due to a fault is also possible. This can be used to evaluate how the QoS changes in case of failures, i.e., how the performing satellites can take over the task of the failed ones.

3. Definition of the mission objectives: Mission objectives are defined by optimization criteria. For example, maximizing the download capacity and coverage and minimizing the revisit time.
4. Evaluation: The evaluation of the results includes the visualization of the findings and the domain expert feedback.

4.1.2. Example Evaluation

One of the mission goals of this example is to access as much download time as possible. In addition to the maximum available download time, the evaluation examined the time available for monitoring RoIs. Three scenarios were considered:

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- Available capacity: In Scenario A, the already-in-service satellites were used from the simulation data. It shows the current capacity of the available resources.
- Virtual capacity gain: Scenario B considered the new incoming satellite constellation, CONASAT, and compared the capacity with the current one. It shows the capacity gain by increasing the number of resources.
- Failover: Scenario C introduces the failover behavior. Failing satellites can cause the system will not to fulfill the QoS requirements. The evaluation environment supports the analysis of cases where satellites fail at a given time fragment and can not operate anymore. This way, a ”what-if” type analysis can be carried out.

Available capacity and virtual capacity gain In Figure 9, the blue bars indicate how much time (in seconds) is available for satellites to exchange information with the ground stations in each scenario. This available time can be used to exchange mission data between the satellite and the ground station or to download operational data (telemetry). This example gives an upper estimate of the time available as it does not consider cases where a task with a higher priority opposes the connection. Between Scenario A and Scenario B, both metrics nearly doubled by adding the 6 new CONASAT satellites.

The red bars show the available time (in seconds) over the RoIs. It can be observed that since the first priority is to download as much data as possible, the time spent on RoIs is less. However, a shorter time is also sufficient to collect a sufficient amount.

In addition to the download time, we examined the potential percentage gain in coverage by introducing the CONASAT constellation. Figure 10a shows the coverage of each region without the CONASAT constellation. It shows that the coverage of the regions by the satellites is almost uniform, with an average of 13%. Figure 10b shows the coverage with the CONASAT constellation, which reaches an average of 21% RoI coverage. It can be observed that in the second case, although 9 satellites are available instead of 3, the coverage percentage did not change linearly. So, in this case, a proper orbit configuration is also needed to satisfy QoS requirements.

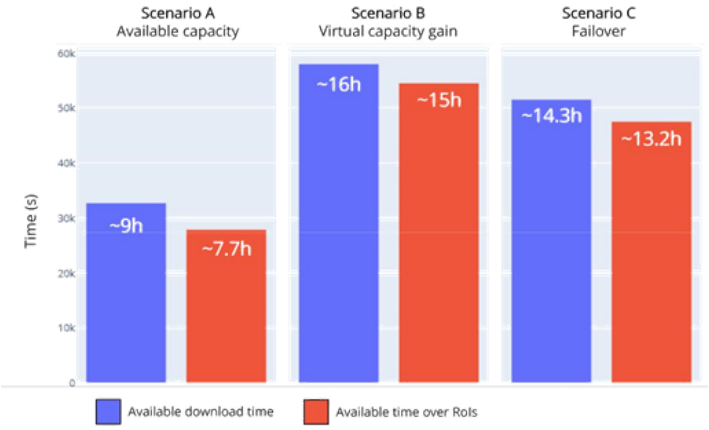
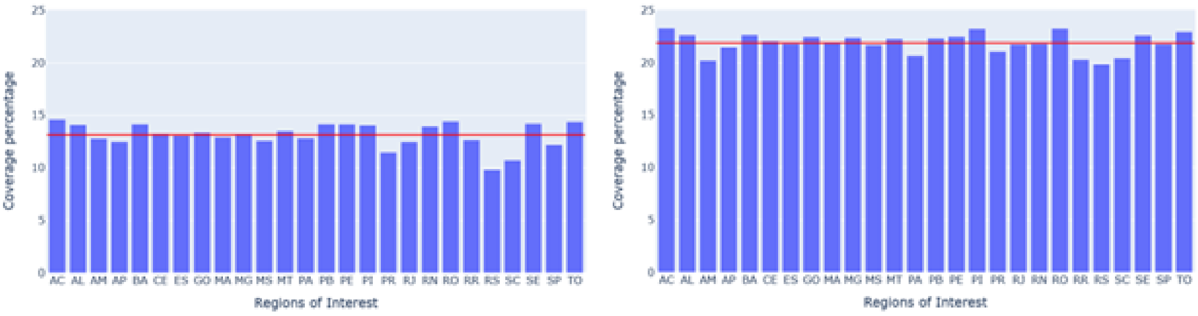


Figure 9: Available download time and over RoI time for the evaluated scenarios



(a) without conasat

(b) with conasat

Figure 10: Coverage percentage evaluation

Failover In the general case, a failover necessitates the transfer of the data to the backup resource and, afterward, triggering its operation. The time needed for the failover depends on the type of backup strategy used. (1) In the case of a cold backup, the resource substituting the failed one has to be initiated. For example, data to be transferred to the ground station has to be submitted to this satellite (and afterward starting the operation). (2) In time-critical cases, the synchronization of the candidate backup resource is continuous, and thus, nearly immediately after activating it, it can start functioning and substituting the failed one. Note that this later strategy continuously needs resources to ensure synchronization. For the sake of simplicity, we present the impact of the second case by neglecting the synchronization overhead.

Figure 9 shows the comparison between Scenario B, where all satellites operated as intended, and Scenario C, where the CONASAT5 satellite went down at the 500th time fragment and CONASAT6 at the 600th time fragment. Table 1 shows that at the 3443rd time fragment, the CONASAT6 was assigned to the ETC ground station, and the SCD2 was monitoring the GO RoI. As in Scenario C, CONASAT6 is not operating in the time fragment, and the optimization criterion is to maximize the download capacity; SCD2 uses the time frame to communicate with the ETC ground station.

Time fragment ID	**Scenario B**		**Scenario C**	
3443	CONASA6	ETC	-	-
	SCD2	GO	SCD2	ETC

Table 1: Failover example

5. Conclusions and Future Work

The concept of FCS still stands as a feasible solution to deal with distributed and heterogeneous systems. But it also still lacks modeling and foreseeing the resource sharing to achieve the common goal. In this work we aimed to respond to this problem in the operational context, creating a workflow to evaluate the capabilities of an idealized FCS, the GOLDS constellation, from a real-world FSS, the BEDCS.

In the sense that the operation aims to fulfill the stakeholder expectations, we were able to define what are the main constraints and with the help of satisfaction and optimization logic, achieve results that can help the decision-making actions on the FCS. This decision-making action goes from the deployment of new members at the FCS, which does not always means better QoS, until the reorganization of the operations in the case of a failure within one of the constituent systems.

The QoS service of a space system of systems is not directly correlated with the number of constituent systems available. Adding members to the FCS can increase individual capabilities, such as data storage limits, but also increases its complexity in terms of operation once we may have concomitant overpasses which demand the creation of priority criteria among the spacecraft and ground stations. Also, the addition of new satellites is not linearly related to the improvement of certain performances, e.g. coverage. This means that a possible proponent to be part of the FCS should be carefully studied in order to assure that its integration into the system will bring real improvement to the QoS versus the number of resources it will be consumed for its operation.

The mathematical approach using constraint logic problem satisfaction helped us to better elaborate and define our domain and solution space, model the problem within useful information, and upscale the demands as more complexity is added to it. Limiting our domain, given boundaries to what can be mathematically modeled, and what not, allows us to focus on the QoS in terms of validating the system not bothering with individual design problems, such as orbit optimization. Defining the technical measures profiles that are relevant to our study case increases our chances of correctly defining the demands/resources/services that we have available as entities of the FCS and how they are related. The generalization of the mathematical model also helps us to quickly upscale the demands in terms of complexity of the constraints satisfaction, fault tolerance, and optimization of the resources. Verifying the limitations of the modeling in terms of capabilities and how much complexity it can afford is one of the next steps in validating this approach.

Acknowledgments

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ANNEX B - PAPER ACCEPTED AND PRESENTED AT THE 5TH BRICS SCITECH FORUM 2023, MOSCOW, RUSSIA

SciTech-2023-72

TOWARDS STUDIES ON THE CONCEPT OF OPERATION OF SATELLITE CONSTELLATIONS

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The analysis of the concept of operation of a satellite constellation is a necessary step to understand the interoperability of the entire system and to ensure it fulfills the users' needs, allowing for iteration into better designs. Commercial simulators supporting such studies are usually too costly or time-consuming for concept studies, especially for entry-level developers like startups or universities, and for academic purposes. This paper introduces COSCAT (ConOps Satellite Constellation Analysis Tool), a simulator that addresses these challenges. The analysis of an idealized GOLDS constellation demonstrates the use of the simulator to acquire revisit statistics for ground elements and to estimate ground station availability. Moreover, COSCAT supports the simulation of the consumption of each satellite's resources, expressing the balance of battery and memory budgets of the entire system. A visualization tool makes for an intuitive overview of the constellation operation and simulation results. The application examples demonstrate how this analysis can be used in tradeoff studies and failure scenarios.

INTRODUCTION

During the concept phase of a large engineering project, although it utilizes only a fraction of the budget, about 75% of the project life cycle costs are committed.[1] This happens because, after the trade studies and establishing the concept, substantial modifications on the project would require retroceding to the concurrent engineering steps, making this a vital step to reducing future project costs and reworks.

In satellite systems, concurrent engineering centers conduct the concept phase, employing simulations and analysis tools for verification and validation of the design, feasibility analysis, and tradeoff studies.[2,3] The concurrent engineering center is a dynamic design environment, with many disciplines working together to explore the design spaces. The team usually explores many concepts constantly being iterated upon, and a quick means of analysis is required to follow the study pace.[4] In constellations with discontinuous coverage, the typical observed parameter in the trade studies is the revisit time.[5] Other parameters can influence the system performance, like region of interest (ROI) visibility percentage, ground station availability with the increasing number of satellites, and the spacecraft's memory and power budgets to fulfill the mission.

While some authors have developed spacecraft simulators for concept studies, almost no tool focused on simulations of the entire mission concept or constellations.[3] In the case of satellite constellations, the mission concept analysis is usually supported by commercial simulators, due to the

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abstraction necessary to model the composition of the constituent spacecraft, to the best of the authors' knowledge. These simulators, having a complete operational and functional analysis in mind, have a high cost for simulation setup and analysis time, making them impractical for those time-constrained projects.

This paper presents a simulator, called COSCAT (ConOps Satellite Constellation Analysis Tool), addressing the quick simulation of constellations Concept of Operations (ConOps) in mission analysis phase. The ease of setup and iteration of parameters, intuitive relation to the constellation ConOps, and main relevant parameters readily available make for a quick and cheap tool to use in concurrent engineer centers. Furthermore, the simulator can be easily configured with extra functions to modify the simulation and analysis behavior for unusual studies, and the XLSX output is ready for post-processing of the data directly from a spreadsheet.

The simulation parameters, derivation of trade and failure studies, and understanding of the results require characterization of part of the constellation's ConOps. The concept of operation expresses how the mission will operate to fulfill user needs, including dependencies between elements, budgets, and operation scenarios.[6] Therefore, before the simulation steps, the relevant aspects of the project's ConOps are defined and introduced.

COSCAT has been applied to the mission concept analysis of the GOLDS (Global Open coLlecting Data System)[7] constellation, which extends, for educational purposes, the existing INPE operational constellation responsible for the collection of environmental data. The ultimate goal is to create a collaborative network for world institutions to join the effort, deploying their satellites and ground data collection platforms (PCD, in Portuguese) and improving the system's capabilities and performance. The INPE constellation currently comprises three satellites collecting Brazilian environmental data, with plans to deploy a new CubeSat constellation called CONASAT. The study of an idealized GOLDS constellation, including six CONASAT satellites, demonstrates the use of the simulator to analyze the concept performance, which can be used in trade studies, and failure scenarios, to study the system's robustness.

The "Problem Concept" section addresses the concept of dealing with Constellations in terms of using legacy and newly designed systems and the implications for them to work together to fulfill the mission demands, needs, and goals. The "Methodology" section defines the relevant aspects of the mission ConOps, the simulation scenarios, and insight into the analysis of the results. The "Results and Discussion" section presents the simulation results and the analysis of its impact on the example mission. The "Conclusion" section closes the paper with further discussion on the implications of the simulator, obtained results, and next steps.

PROBLEM CONCEPT

As stated before, this work focuses on the mission concept analysis for the GOLDS mission. GOLDS is an extension and update of the Brazilian Environmental Data Collection (BEDCS), developed in 1980 and functional since the beginning of 1990 with the launch of the first Data Collection Satellite, SCD-1.[8]

In terms of taxonomy, the GOLDS mission can be classified as a Distributed Space Mission (DSM).[9] Its constituent segments (Space, Ground, and User) are orbital and geographically spread.

As-is, the actual space segment is composed of three LEO satellites, SCD-1 and 2, fully dedicated to the BEDCS, and the CBERS-4A, a Chinese-Brazilian Earth Observation satellite that holds a Data Collection Transponder for the BEDCS. In this case, the CBERS-4A is not committed 100% of the time with the BEDCS. About the ground segment, INPE operates these three spacecraft from the Mission Operations Center with the help of two Ground Stations, for download of payload data, located in the north and central regions of Brazil. Also, the user segment is composed of more than 1000 PCDs spread along the Brazilian territory, with different configurations, instruments, and owners. The platforms contain their specific sensors to collect the required environmental required by each user. Most of the PCDs are in remote regions of the country, where data cannot be transmitted by cellular networks, requiring a satellite for data relay.

In this configuration, the BEDCS already presents itself as a Heterogeneous Cooperative DSM.[10] The attempt with GOLDS to improve the BEDCS with the CubeSat and Ground Network technologies demands from the mission operations concept an even more detailed analysis.

We can say so due to the heterogeneity derived from adding new technologies to the legacy system. The principle behind the GOLDS is that any satellite with the EDC (Environmental Data Collector) payload on board can be part of the GOLDS solution once they start acquiring data from the PCDs. Even any ground station that wants to be part of it is also allowed and new PCDs in any part of the world can join as long as they comply with the GOLDS interface for ground-to-space communication.[7]

In this new configuration, the GOLDS presents itself also as a Heterogeneous Cooperative DSM, or a Federated Satellite System,[11,12] with an ad hoc relationship, reconfigurable, with predetermined orbits and phased deployment of new constituent systems to accomplish a common goal in a collaborative functional configuration sharing services available on each resource.[13]

Different scenarios can be evaluated to determine the effects of a new income/outcome constituent system and the general quality of service of the GOLDS mission. How much resources can be shared to fulfill the mission goals? How many constituent systems are available in each scenario? In the case of a failure or unavailability of a spacecraft or ground station, how is the quality of the constellation system affected?

METHODOLOGY

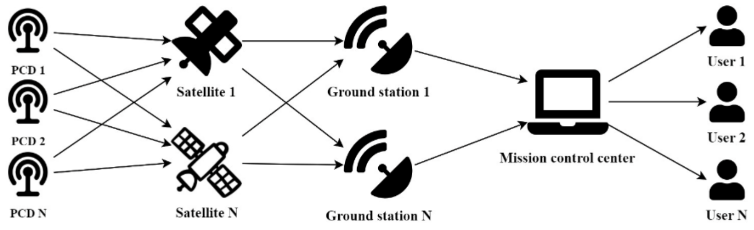

Figure 1. GOLDS ConOps illustration (Based on Reference 7)

Figure 1 illustrates the general ConOps of the GOLDS mission where, in general, every PCD transmits data to every satellite, and ground stations are all available for downlink. As other constituent systems join the constellation, this might change depending on each satellite and ground station's available resources and the commitment to the collaboration effort. The BEDCS currently counts on the three mentioned satellites, already in orbit and controlled by INPE. CONASAT satellites are planned to join the constellation in the future and are the object of this paper's case study. Employing COSCAT for the analysis, we study the contribution of the addition of six such satellites to the effort and the effects of failure scenarios on the constellation behavior. An additional ground station on Alcantra was added to support the operation of more satellites.

The main output parameter defined for the analysis of this example constellation is the revisit time, which is the design driver for the project. Other parameters included in the study can affect the project viability or the main parameter. Ground station availability assessment ensures that the ground stations planned for the mission are enough to satisfy the requirements. For this, the satellite's total connection time to ground stations when in operation within the constellation is compared to the same parameter if it was operating solo, to check for conflict rates. The reduction in connection time when with the constellation corresponds to the connection conflicted time. Internal memory and battery levels for the new planned satellites are also tracked in the simulation to confirm that the preliminary architecture satisfies the operational needs.

The definition of the internal components for the CONASAT satellite is based partly on some of the concepts developed for the ongoing project and on similar-sized missions, with some freedom for this example case study. Six essential operation equipment (or subsystems) were defined to consume energy from the batteries and either acquire or downlink data, like the onboard computer (OBC), antennas, and torque generation subsystem. An EDC instrument, as defined by the specifications document[*], is the spacecraft payload responsible for collecting the data acquired by the platforms and transmitting it to the OBC for further downlink.

Although Figure 1 illustrates the GOLDS mission ConOps, a more detailed description of the mission topology and the connections between the elements, the instruments' operation rules, and the operation scenarios are required to configure the simulation and define the analysis elements.

In this regard, all satellites can connect to the ground stations and PCDs. While the CONASAT satellites are considered to have internal storage for mission data, the three initial satellites only have a transponder to relay the information, making platform connections only possible with a simultaneous ground station connection. The instruments' operation rules are also chosen based on other missions and reasonable values that can maintain the satellite operational, like an always-on OBC and electric power subsystem, and intermittent torque generator. The EDC is turned on only in the visibility of the Brazilian territory to save battery since the system does not currently comprise other countries.

It is also relevant to mention that even if there are currently hundreds of PCDs, the simulation only considers one platform per Brazilian state. This setup is sufficient to capture the revisit times in every Brazilian region, with reduced setup and simulation times.

The first scenario comprises only the three initial satellites, making the results a basis to verify the effect of adding new satellites to the effort. The second scenario is the regular operation of all proposed satellites, allowing the analysis of the new operation parameters.

The subsequent scenarios consist of failure scenarios, illustrating their effects on the constellation performance and the means to analyze the results in the context of the constellation concept studies. Initially, The ETC ground station (in the central region of Brazil) was considered faulty and removed from the simulation. Next, we consider the satellite not successfully deployed and study the constellation in its absence. Finally, a solar panel of a CONASAT was considered faulty, and the EDC operation was reduced to half the passes to save battery, an availability constraint.

Note that in terms of the GOLDS operation, these failures represent the unavailability of a specific constituent system. The reason for the unavailability is not relevant for the simulation purposes, and the required simulation scenarios will be defined by the concurrent engineering team based on risk analysis. It can be a real failure on a spacecraft that will not serve the constellation anymore or just that the specific satellite, whose main goal is not related to GOLDS, is not available

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[*] https://www.gov.br/inpe/pt-br/area-conhecimento/unidade-nordeste/environmental-data-collector-edc. Retrieved November 22, 2023.

to support the constellation during a particular period. From GOLDS' perspective, these two scenarios are the same.

The simulations were ultimately executed by studying a ten-day operation frame to better capture the maximum revisit times and a representative average revisit time. The maximum revisit times could theoretically always increase with more simulation time because of the heterogeneous orbits for the initial satellites. Increasing simulation times were used before concluding that ten days were a good convergence, where the parameter had only marginal changes.

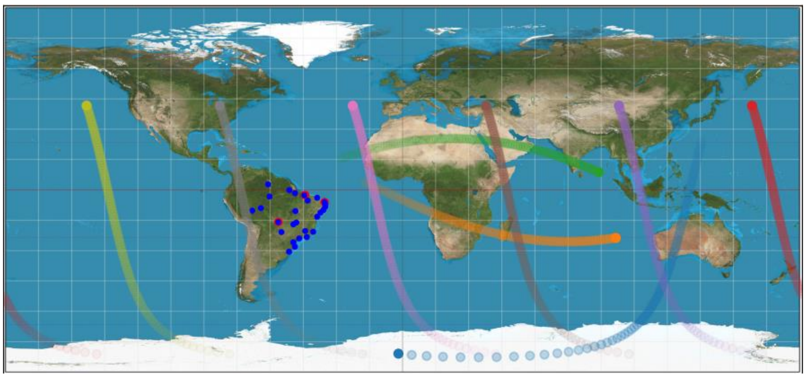


Figure 2. Visualization of the simulation results (orbits and connections).

For the results analysis, the first step after the simulation is to use the results visualization tool, giving an overview of the system's behavior over the simulation time. The tool provides plots for battery and memory levels for each satellite, visualization (Figure 2) of the orbits and connections to ground stations and PCDs, some general information on the simulation, and statistics on revisit times. In the image, the blue dots represent the PCDs, the red dots represent the ground stations, and the trailed dots, each satellite with its path in a simulation step. This tool directly provides most of the required information without data post-processing, and even if the user wishes to use the raw data, it still delivers valuable insight into whether the setup was correct and the orbits and connections are behaving as expected.

The tool also outputs an XLSX file with the detailed simulation results for every time step, and relevant statistics like revisit times and ground station availability. The readability of the output allows for easy data post-processing directly in Excel or using a programming language.

PCD's mean and maximum revisit times are the main constellation performance parameters, making its analysis crucial in every scenario. Ground station availability is verified in the first two scenarios to check for the conflict between satellites trying to connect to the same ground stations. The investigation of CONASAT power and memory budgets in each scenario confirms that the developed concept handles the operational needs.

RESULTS AND DISCUSSION

The simulation of the system's current state gives insight into the initial capabilities. Despite only three satellites collecting data, the average over all the PCDs' mean revisit times of 1.31 hours is enough to collect updated data from the platforms most of the time. However, the maximum revisit times, with an average of 3.4 and a maximum of up to 5.4 hours, are more concerning when users require recent data and no satellite has a coinciding orbit with the platforms.

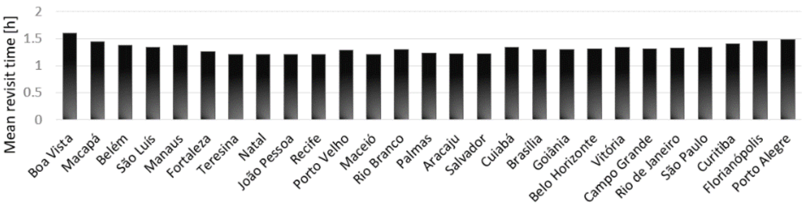


Figure 3. Mean revisit times in the first simulation scenario.

The revisit times for each Brazilian state capital, ordered by latitude, are depicted in Figure 3, where the results are mostly uniform, with slightly worse revisit times near the equator and at high latitudes.

Furthermore, the ground station availability in this scenario resulted in nearly 5% connection time conflict, which is small compared to the contribution of a new satellite to the system. If the satellites are capable of downloading all mission data, no additional ground stations are necessary.

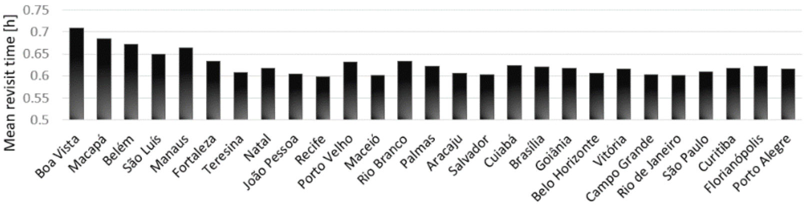


Figure 4. Mean revisit times in the second simulation scenario.

The second scenario shows an improvement of the mean revisit times (Figure 4) to only 0.63 hours and the average of the maximum revisit times to 2.18 hours, with the highest value of 3.1 hours, an almost two-fold improvement over the previous scenario. It is important to note that this is not a linear system where the reduction of revisit times and general constellation performance is not proportional to the number of satellites.

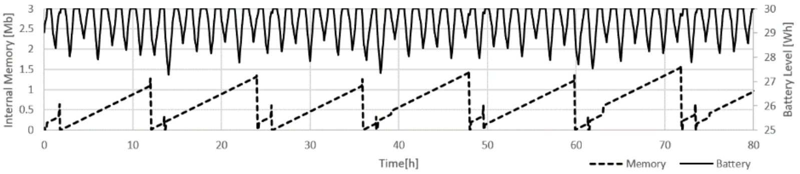


Figure 5. Memory and Battery of a CONASAT in the second scenario.

The connection conflict to ground stations increased only by 0.6% since the CONASAT satellites have orbits with regular spacing and never conflict over any regions with each other. Furthermore, the internal memory and battery levels of a CONASAT, presented in Figure 5, remain stable over time, and the equipment handles the nominal operation scenario. The margin in the battery charging and data downloading also shows spare resources on the satellite, which can be used to collect data from other countries when the GOLDS effort expands.

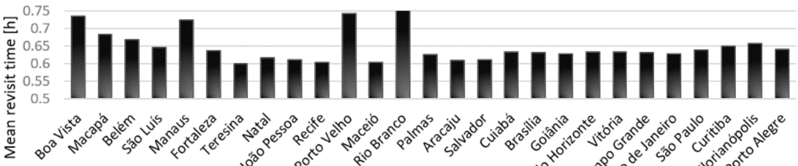


Figure 6. Mean revisit times in the third simulation scenario.

In the third scenario, the absence of a ground station caused a small increase in mean revisit times to 0.65 hours because of the incapability of the initial satellites to collect data without a ground station connection. It is relevant to note the special effect in PCDs from Porto Velho, Rio Branco, and Manaus from Figure 6, which are the westernmost platforms, while both remaining ground stations are further away in the northeastern region of Brazil. The effect on the remaining platforms is minimal.

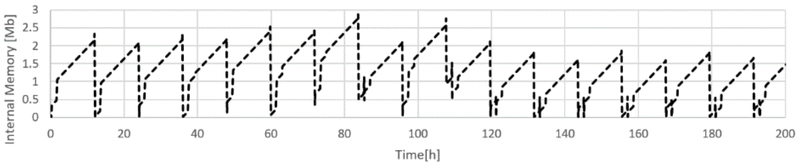
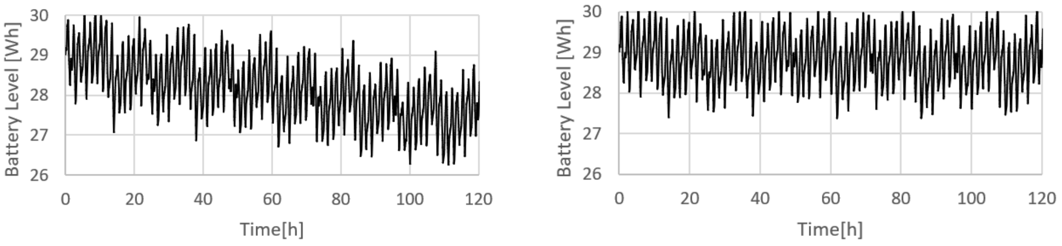


Figure 7. Memory balance of a CONASAT in the third scenario.

The evaluation of the memory balance of CONASAT satellites, necessary because of the decreased download time, resulted in a condition where the downlink capability nearly equals the data generation capability, as depicted in Figure 7. Despite leaving the CONASAT memory balance on the edge of unsustainability, this scenario would not hinder the data collection capability of the system.

The fourth scenario resulted in a further mean revisit time increase to 0.69 and an average of maximum times to 2.34, proving that the absence of a single satellite would also not have a large impact on the data collection.



a. With regular operation. **b. With intermittent operation of EDC.**

Figure 8. Battery levels of a CONASAT in solar panel failure scenario

The fifth scenario demonstrated the capability of the simulator to deal with a more intricate scenario. A supposed malfunction of the solar panel of a CONASAT reduced the power generation of the satellite. The battery levels in Figure 8a demonstrated that the satellite would not support continuous nominal operation, because of the trend leading to battery depletion. The example decision to limit the EDC operation to only half the passes was enough to keep the battery levels constant (Figure 8b). As expected, this had an even lower effect on revisit times than the missing satellite.

Table 1. Average of PCDs revisit times for each scenario.

Scenario	Maximum revisit times (h)	Mean revisit times (h)
1	3.40	1.31
2	2.18	0.63
3	2.31	0.65
4	2.34	0.69
5	2.25	0.65

The summary of the results in Table 1 shows how adding the new satellites improved the system, even under failure scenarios. These steps are important in the design process for a better understanding of the capability of the studied concept to fulfill requirements and robustness to expected failure scenarios. The analysis results are valuable information for trade-off studies searching for the best solution. Furthermore, it allows for validation of optimization tool results and design iteration, improving the found shortcomings.

CONCLUSION

The COSCAT simulator was capable of successfully analyzing every proposed operation scenario of the GOLDS constellation, providing valuable insight into the capabilities of the mission concept and the effect of failure scenarios. The ease of setup resulted in only a few hours to simulate all the operation scenarios and proved suitable for use in dynamic concurrent engineering environments.

The flexibility of the simulator, allowing for the inclusion of functions to modify the standard operation, proved necessary for the simulation of the satellites only connecting to PCDs when in ground station visibility and also for creating operation rules for the faulty satellite. Finally, the visualization tool accompanying the simulator provides a means for quick analysis of the results, with the main constellation parameters readily available for use without further post-processing.

Future work on the simulator will focus on implementing new features allowing for better analysis, like functions to introduce failures on the system mid-simulation and the use of stochastic models for failure injection, and also improving the user experience and ease of setup. COSCAT is also planned to be made available open source in the future so that small companies can use the tool to start their projects on a limited budget.

Furthermore, work on a modeling procedure for developing constellation ConOps and a plugin to transform model elements into the simulation configuration is being conducted. It will further improve the ease of designing new constellation concepts and simulating its scenarios.

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