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

Carlos L. G. Batista* [a,b] **, Andras Foldvari**[c]**, Andras Pataricza**[c]**, Fatima Mattiello-Francisco**[a]

[a] *Department of Space Systems Engineering, Brazilian National Institute for Space Research, 1758 Av. dos Astroanutas, Sao Jose dos Campos, Brazil, 12227-010*, fatima.mattiello@inpe.br
[b] QA/AIT Engineering Department, Endurosat AD, 1A Flora Str., Sofia, Bulgaria, 1404, carlos.batista@ieee.org
[c] *Department of Measurement and Information Systems, Budapest University of Technology and Economics, 2 Magyar Tudósok str., Budapest, Hungary, 1117*, andras.foldvari@edu.bme.hu, pataricza.andras@vik.bme.hu
* Corresponding Author

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 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.

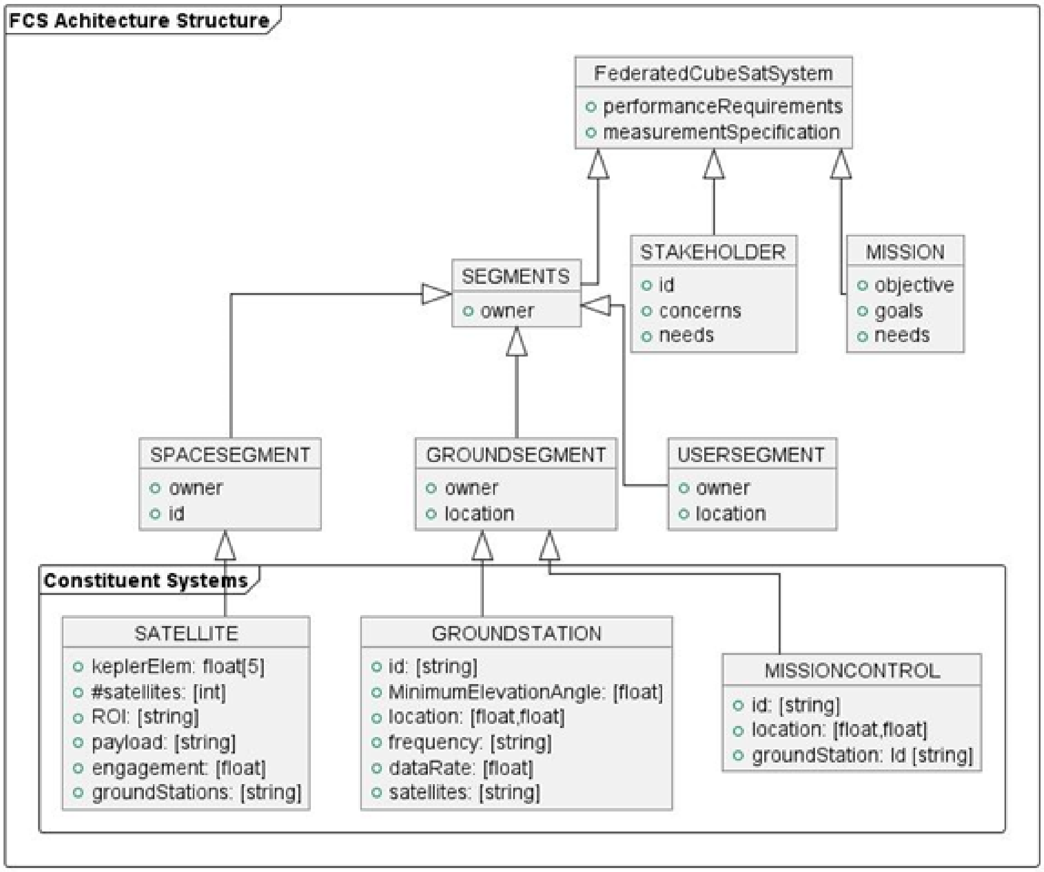


Figure 1: FCS Architecture Structure Profile, [6]

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.

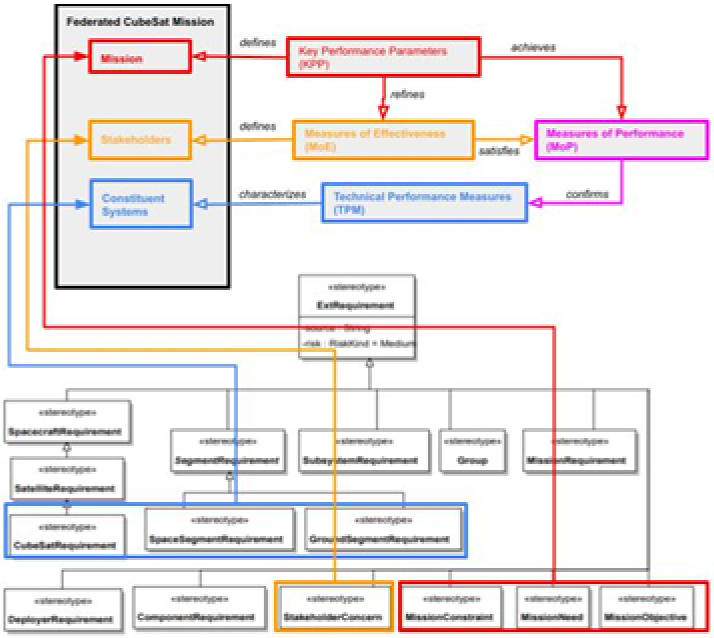


Figure 2: Relationship between Technical Measures and FCS Entities

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.

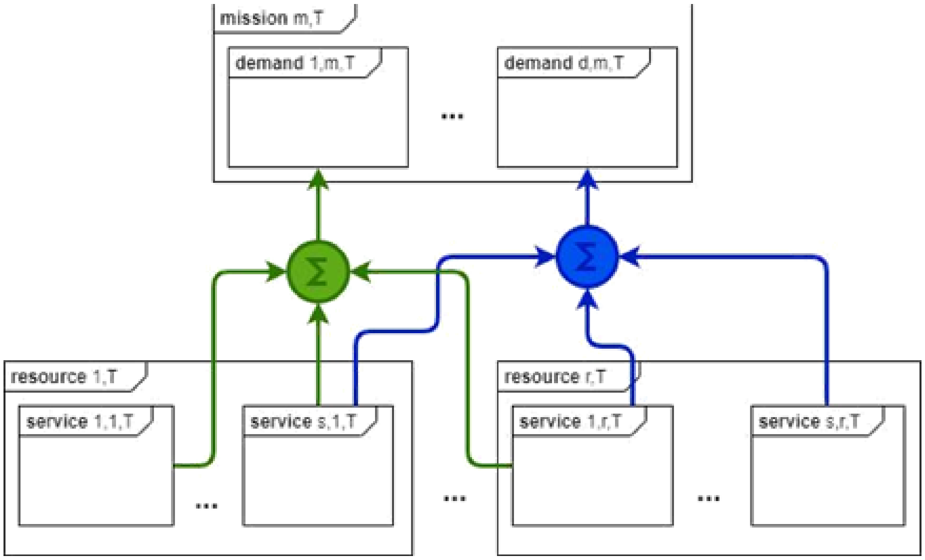


Figure 3: Concept of Mission, within its demands, and Resources, within its available services

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).

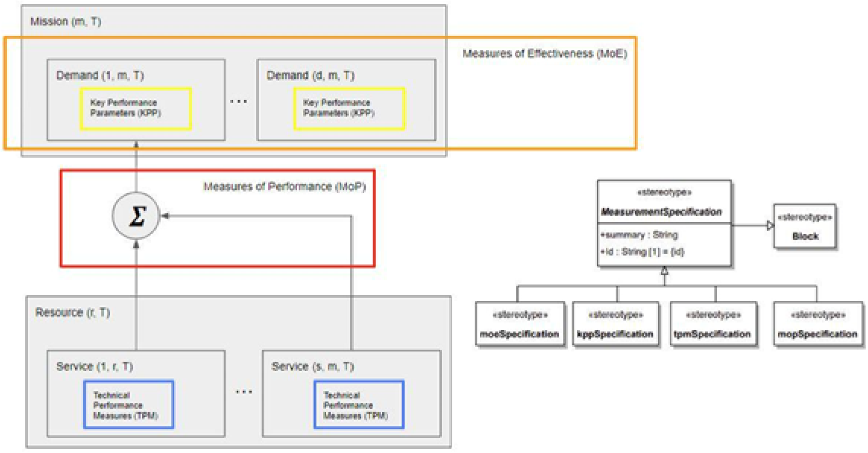


Figure 4: Relationship between the Technical Measures and the Constraint Satisfaction Model Elements

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.

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

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

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

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

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

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.

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

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.

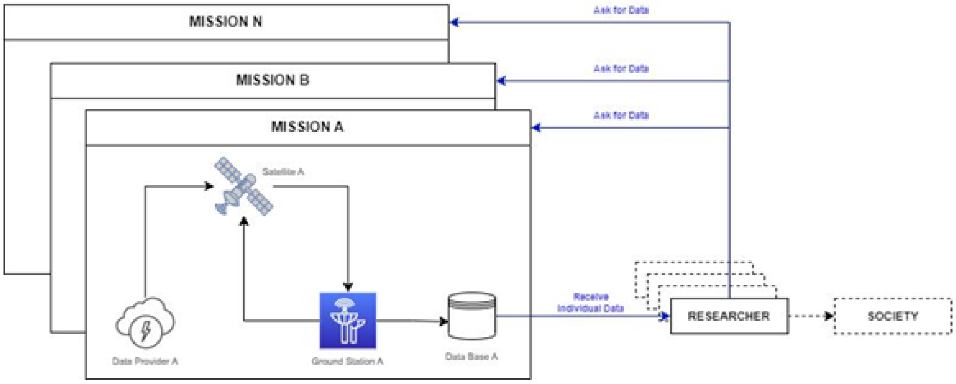


Figure 5: GOLDS operational scenarios, [5]

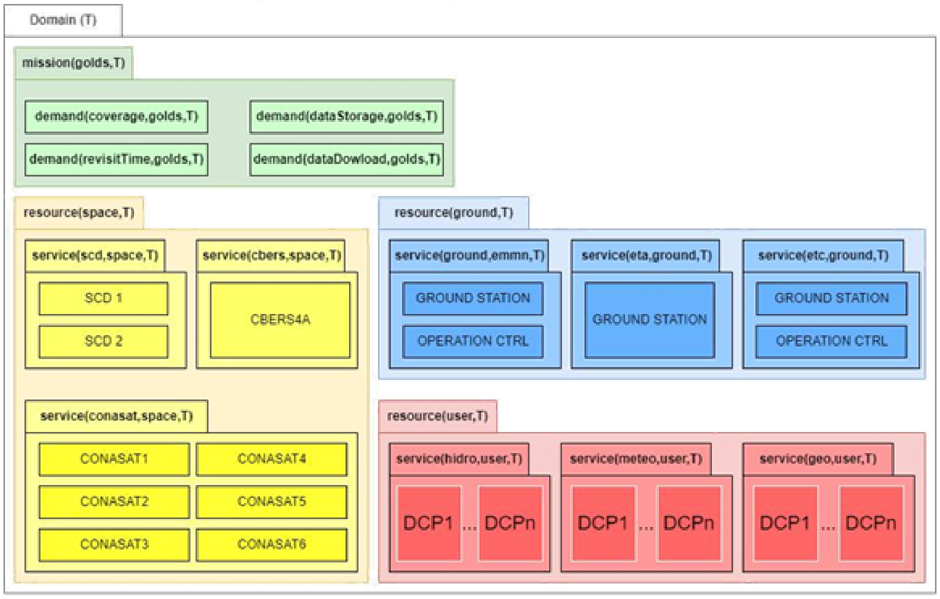


Figure 6: Domain space for the GOLDS ideal FCS

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.

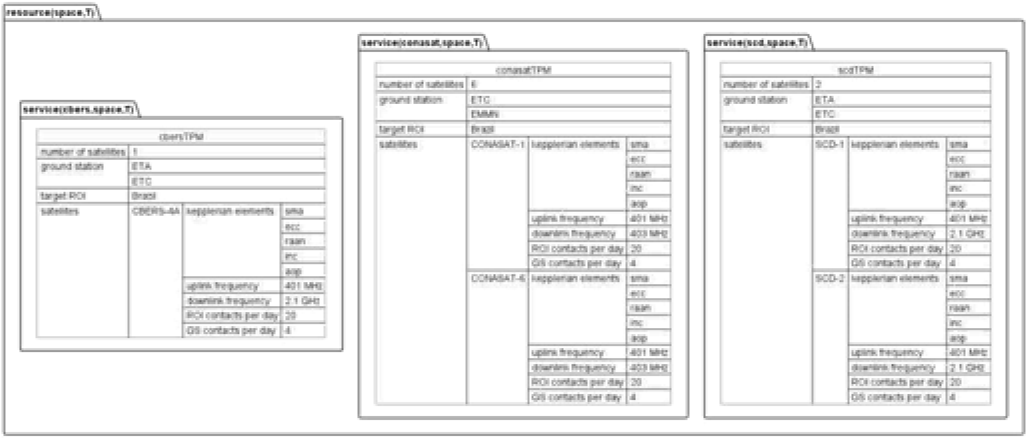
For the segments, or in this case, resources that we have available for the FCS, each of them has its available services.

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

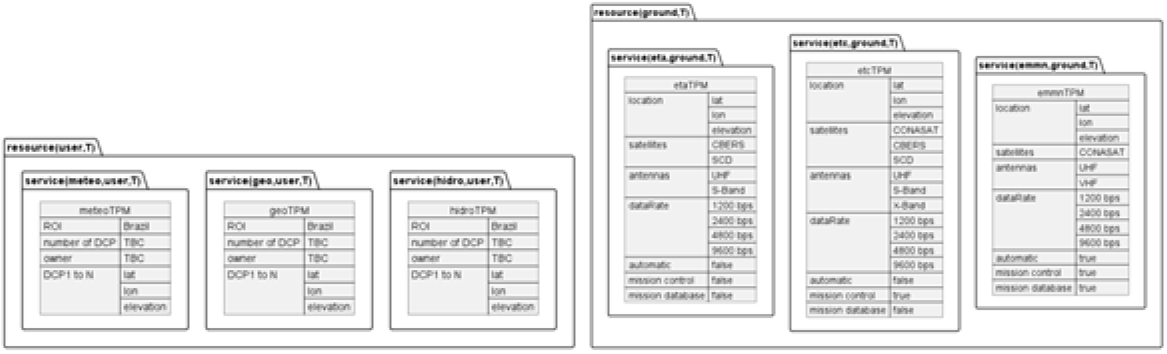
Each service on the ground segment, service ∈ resource(ground, T), is an available ground station/operation control for the FCS on that given time fragment, T . It is a fact that each ground station is attached to a specific satellite or set of satellites being that a limitation inherent of this heterogeneous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

Each service on the user segment, service ∈ 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.

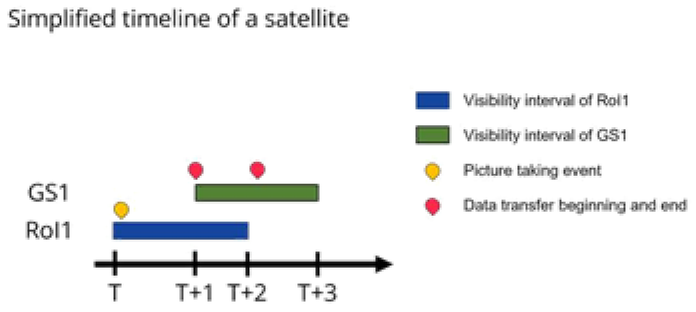


Figure 8: Simplified timeline of a satellite

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 ($T \in T$). 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:

- 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.

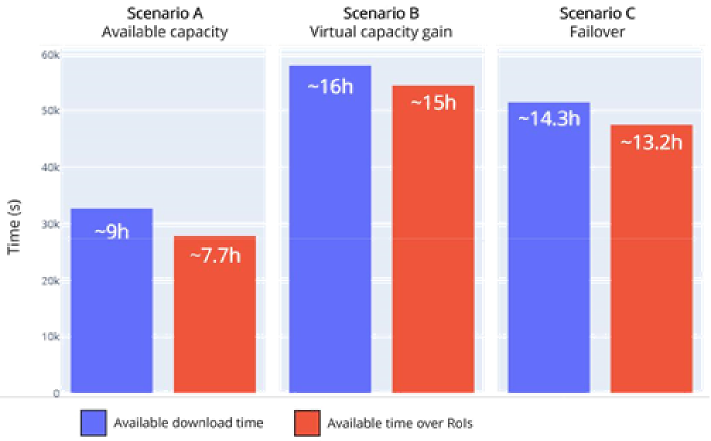
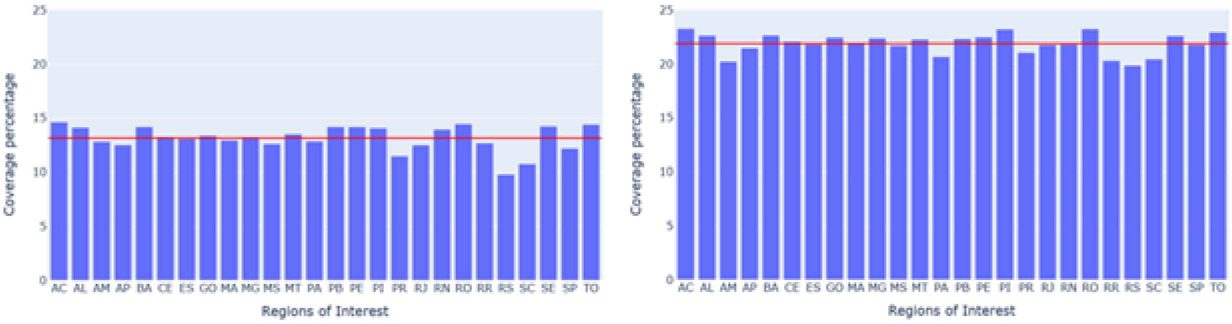


Figure 9: Available download time and over RoI time for the evaluated scenarios



(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.

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