Architecting a decision support system for continuing supervision of commercial in-space servicing

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ABSTRACT

The rapid development of in-space servicing technology and other novel space capabilities requires robust and transparent governance frameworks to ensure long-term space sustainability and adherence to international regulations, notably Article VI of the Outer Space Treaty. Article VI requires that signatory states provide continuing supervision over non-governmental space activities, a mandate becoming increasingly more challenging to fulfill due to the accelerating pace of commercial space innovations. In previous work published by the authors, a Systems Architecture Framework analysis investigated the governance of in-space servicing in the U.S. and the corresponding Stakeholder Need misalignments with current authorization and supervision processes. The initial research provided insights into the apparent Need for a Decision Support System addressing the practical challenges faced in the operational supervision of in-space servicing activities. In response, this paper roadmaps the application of the Environment-Vulnerability-Decision-Technology (EVDT) framework into the realm of space sustainability challenges, such as for authorization and supervision of commercial in-space servicing. Originally conceived by the Space Enabled research group at MIT's Media Lab, the EVDT framework has demonstrated its effectiveness in facilitating sustainable development decision-making through analysis of complex socio-environmental-technical systems across various terrestrial applications. Historical uses of EVDT span across aiding flood resilience in Indonesia, promoting mangrove preservation in Brazil, managing invasive plant species in Benin, revitalizing cranberry wetlands in the U.S., analyzing environmental injustice in prison landscapes, and urban planning strategies during the pandemic. Most recently, the inaugural adaptation of the EVDT framework to the space domain shows potential to enhance collision avoidance operation decisions for a Stakeholder within NASA.

This paper proposes the expansion of the EVDT framework to broader space sustainability challenges, focusing on continuing supervision as the primary use-case, where this prototype's capability to model and analyze hypothetical commercial in-space satellite servicing missions under U.S. jurisdiction will demonstrate the potential of EVDT to enhance space situational awareness (SSA) and space domain awareness. These operations are critical for collision prediction and consequence, risk assessment, and the implementation of sustainable operational practices. We introduce the plan for developing the continuing supervision EVDT software prototype, using a MATLAB-based method characterized by a modular architecture, to facilitate integration and extension of functionality. The paper also introduces terminology, key concepts, objectives, and plans for using a Systems Architecture method to analyze EVDT software design options. The software design enables Stakeholders to custom-build and adapt their models to different space sustainability scenarios, improving code reuse, reducing development time, and simplifying interactions for external users and future space-based EVDT projects. The implementation of this Decision Support System has the potential to significantly influence the authorization and supervision of novel space missions and the evolution of supporting SSA technologies, ultimately contributing to the responsible and sustainable use of the space environment. It helps ensure compliance with international space laws and promotes sustainability by equipping Stakeholders with software toolsets capable of evaluating dynamic space operations. The paper also envisions the extensive application of the EVDT framework to an array of other space sustainability challenges, such as environmental sensitivity, debris mitigation, resource utilization, and planetary protections. Ultimately, the expansion of the EVDT framework into the domain of space sustainability will empower policymakers, commercial space operators, and other Stakeholders with an adaptive tool that not only conforms to the current space governance systems but also flexibly shapes to future space policies, paving the way for responsible stewardship over the space environment.

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1. INTRODUCTION

In recent years, the rapid advancement of In-space Servicing, Assembly, and Manufacturing (ISAM) technologies has exposed new opportunities and challenges within the realm of commercial space operations. These technologies encompass activities such as satellite repair, refueling, relocation, and debris removal, all of which have the potential to influence mission designs and lifetimes. Additionally, in-space servicing technologies offer promising advancements in satellite resiliency and flexibility, moving away from traditional satellite concepts of operations. In-space servicing enables orbital modifications, post launch upgrades, and potentially even complete satellite reconfiguration. Historically, in-space servicing concepts date back to the 1960s, with NASA's first successful demonstration in 1984 during the repair of the SolarMax satellite [1]. Other civil developments include NASA's maintenance missions for the Hubble Space Telescope and the International Space Station. Recent commercial successes, such as SpaceLogistics' Mission Extension Vehicles (MEV-1 and MEV-2) [2] and other international commercial ventures, demonstrate the operational potential of ISAM activities in the commercial sector. These include the End-of-Life Services by Astroscale demonstration/Multiple (ELSA-d/ELSA-M) and Astroscale's Life Extension In-orbit (LEXI), Axiom Space's independent commercial space station, Maxar's Space Infrastructure Dexterous Robot (SPIDER), SpaceLogistics' Mission Robotic Vehicle (MRV) and Mission Extension Pods (MEP), Orbit Fab's Tanker-001 fuel depot, and ClearSpace's debris removal missions [3–5]. Future government and commercial ISAM projects, such as NASA's OSAM missions partnered with Maxar (OSAM-1) and Redwire Space (OSAM-2) and the Defense Advanced Research Projects Agency's (DARPA) Robotic Servicing of GEO Satellites (RSGS), are expected to intensify through the current decade [3]. The integration of servicing into space operations could disrupt conventional mission planning and extend the operational life of space assets, as well as enhancing space safety and sustainability by mitigating debris risks. However, the commercial space servicing industry faces challenges, such as the need for a robust market to justify investment and regulatory certainties to support operations [3]. With these ongoing advancements and concerted efforts towards standards development, a resilient ecosystem of servicing satellites may emerge in the near future, improving the longevity and capability of both governmental and commercial space missions. However, as shown in previous work by the authors, the increasing prevalence of commercial in-space servicing activities necessitates thoughtfully designed governance frameworks to address the potential risks and ensure sustainable practices in outer space [6]. The inherent risks associated with servicing operations, such as close-proximity maneuvers and potential debris generation, indicates that clear regulatory policies and transparent oversight mechanisms are urgently needed.

The foundational legal principles for international space governance are given by the Outer Space Treaty (OST) of 1967 [7]. Article VI of the OST mandates that signatory states bear international responsibility for their national space activities, including those conducted by non-governmental entities, and for ensuring that these activities conform to the treaty through authorization and continuing supervision. However, the term "continuing supervision" within Article VI lacks a precise definition, leading to varied interpretations and implementation challenges among different nations [6]. In the context of an accelerating commercial space economy and emergence of novel mission paradigms, maintaining effective continuing supervision becomes increasingly challenging. The dynamic nature of ISAM operations, combined with the congested and rapidly evolving space environment, demands a clearer and more proactive approach to regulatory oversight. Therefore, the authors recommended in previous work a definition for continuing supervision as "no U.S. space activity transpires without the knowledge and cognizance of the U.S. Government" in order to ensure treaty compliance while addressing other Stakeholder Needs identified through a Systems Architecture Framework (SAF) analysis [6]. The research questions and original propositions for this ongoing study are given below. A later section of this paper will revisit the research questions and update these propositions based on findings from Stakeholder interviews.

RQ1: Describe. How do U.S. Government Stakeholders describe their Contextual Constraints (regulatory, technical, economic, and security) associated with authorization and continuing supervision of commercial in-space servicing?

RQ1: Proposition. Ambiguity in the definition of continuing supervision leads to challenges in implementation, and the increasing complexity of commercial in-space servicing activities contributes to these challenges.

RQ2: Explain. What historical Constraints and Opportunities contributed to the development of the governance framework for the authorization and supervision of in-space servicing? How do current U.S. space laws and policies act as Constraints or Opportunities for achieving and maintaining continuing supervision?

RQ2: Proposition. Historical development of U.S. space law was influenced by international agreements, national security considerations, economic interests, and the nature of space technology over time.

RQ3: Evaluate. What misalignment exists between Stakeholders' Needs/Objectives and the current Forms/Functions of in-space servicing authorization and supervision? How might "continuing supervision" be more precisely defined and operationalized to address the misalignment?

RQ3: Proposition. Both strategic gaps, such as lack of agency-level funding and clear responsibilities, and operational gaps, such as limited data sharing and lack of exquisite space situational awareness resources, pose challenges to achieving effective continuing supervision in the U.S.; a more clearly defined and adaptable framework for continuing supervision can enhance U.S. compliance with Article VI of the Outer Space Treaty.

RQ4: Design. How can a Decision Support System be designed to meet U.S. Government Stakeholders' operational Needs for continuing supervision, and what new Forms/Functions are proposed to effectively aid in these activities?

RQ4: Proposition. Effective integration of DSSs in operational procedures can lead to better coordination, monitoring, and continuing supervision of commercial servicing activities; investigating how these systems can be tailored to aid in the USG's continuing supervision can inform the design of governance mechanisms in the future to protect the long-term sustainability of the space environment.

In the first research paper in this study, a SAF analysis was employed to evaluate the governance of commercial in-space servicing in the United States. When referring to specific systems engineering terms used within SAF, capitalization will be used (i.e. Stakeholder, Constraints, Needs, etc.). This systems engineering approach considered environmental, social, and technical factors that influence the regulatory landscape for commercial in-space servicing. The SAF analysis highlighted several misalignments between Stakeholder Needs and existing authorization and supervision processes. Key findings indicated that current Forms of continuing supervision were insufficient to meet the system Objectives of space safety and security. For example, Stakeholders expressed concerns about the lack of comprehensive oversight mechanisms, inadequate data sharing, and the need for clearer international harmonization of policies and practices. These findings point to a need for a Decision Support System (DSS) to assist U.S. Government (USG) Stakeholders in the effective authorization and supervision of commercial in-space servicing activity. Such a system would enhance regulatory performance, safety, and sustainability by offering tools for compliance verification, risk assessment and mitigation, data sharing, and/or policy analysis, for example.

According to Bonczek, Holsapple, and Whinston in *Foundations of Decision Support Systems* (1981), a DSS is "an information processing system that is embedded within a decision-making system," where a decision-making system is defined as a human-machine information processing system that yields decisions in the guise of information [8]. Originating from the management information systems field, the concept of "decision support" first appeared in the 1970s. In the 1980s, the rise of DSSs was spurred by advancements in the information age, characterized by significant progress in information processing technologies and the emergence of increasingly complex organizations. Bonczek et al. suggest that DSSs have three things in common: (1) incorporating models (defined as a plan for information processing that involves some transformation of information), including mathematical expressions, statements, or computer programs; (2) providing useful information for decision activities; and (3) furnishing system stakeholders with powerful yet simple to use tools for problem solving. They emphasize that many important decisions involve qualitative aspects that are not easily quantifiable and that the field of decision support is inherently interdisciplinary in nature [8]. More modern definitions of DSS include Turban et al. (2011) who define it as "a conceptual framework for a process of supporting managerial decision making, usually by modeling problems and employing quantitative models for solution analysis" [9] and Power (2002) who defines a DSS as "interactive computer-based systems intended to help decision makers use data, documents, knowledge and models to identify and solve problems and make decisions" [10]. Even with this evolution of the definition over time, the core principles of supporting human decision-making through data, models, and user interaction remain fundamental to the concept of a DSS. In the context of this research, A DSS is not designed to make decisions for people, but rather provides information to guide human decision-making. DSSs are essential in the government context because the challenges being faced by governments today could be considered complex sociotechnical systems, where people, technologies, organizations, and processes interact in ways that are often unpredictable and difficult to fully understand. These challenges cannot be addressed with straightforward solutions; instead, dynamic management is required to navigate the uncertainty, interdisciplinary nature, and complexity inherent in these issues [11].

This paper proposes leveraging the Environment-Vulnerability-Decision-Technology (EVDT) systems engineering framework, initially developed by the MIT Space Enabled Research Group. The EVDT framework has been successfully applied in various Earth-based contexts to facilitate sustainable development decision-making by integrating socio-environmental-technical information [12–23]. Recent applications in the space domain have demonstrated its potential in enhancing operational decision-making, specifically within NASA's collision avoidance operations for non-crewed spacecraft missions [24]. This paper explores the adaptation of the EVDT framework to address broader space sustainability challenges, particularly focusing on the continuing supervision of commercial servicing activities. By modeling and analyzing hypothetical scenarios, the EVDT DSS can contribute to improved space situational awareness (SSA) and space domain awareness (SDA), ensuring compliance with international space laws and promoting the responsible and sustainable use of the space environment.

2. METHODOLOGY

This section outlines the EVDT systems engineering framework and SAF in more detail, including the fundamental concepts and the processes for development. We also present previous use-cases for EVDT for both Earth-based and space-based applications. Finally, we introduce a novel version of EVDT called the Space Sustainability EVDT Framework which can be applied to a variety of complex sociotechnical systems in the space domain.

2.1 EVDT and Systems Architecture

The Environment-Vulnerability-Decision-Technology systems engineering framework is a process that allows for analyzing complex systems challenges, and it can be used to guide development of Decision Support Systems, often tailored to sustainable development applications. Central to the framework are five fundamental concepts:

- **Systems Architecture Framework and Stakeholder analysis:** SAF is employed to ensure that the DSS is contextually relevant and designed according to the Needs of the Stakeholders. This typically involves multiple iterations through SAF to capture the breadth of Stakeholder Needs and Desired Outcomes effectively [25].

- **Complex socio-environmental-technical system (SETS) conceptualization:** The framework views sustainable development as a complex system involving social, environmental, and technical dimensions. This conceptual approach allows the DSS design to incorporate various dimensions such as environmental states, human vulnerability, societal impacts, behavioral decision-making processes, and technology designs to ensures that the DSS can conduct detailed technical analyses while also informing and improving data collection systems [25].

- **Interactive DSS design:** The EVDT framework process facilitates the creation of an interactive DSS which can be implemented in various forms, including web-based platforms, standalone computer or mobile applications, or even as physical, tabletop exercises. Interactivity enhances Stakeholder engagement and ensures practical applicability [15–17, 25–27].

- **Modularity and re-use:** The EVDT process incorporates considerations of modularity and reusability, enabling the technical components of the DSS to be reused in future applications allowing for adaptability to evolve as new Needs, Opportunities, and Constraints arise [25].

- **Collaborative development:** Collaboration with Stakeholders in DSS development is a continuous process that extends beyond initial Stakeholder engagement. This collaborative effort enables continuous refinement and optimization of the DSS [25]. In this present study, it is important to note that we are engaging Stakeholders through interviews and considering the responsibilities of the U.S. government, but not directly collaborating with the government to develop a tool in response to any specific requests.

All these concepts that form the basis of the EVDT process span the entire life-cycle of an EVDT project. The elements are interconnected and are addressed in a relatively linear fashion following the steps seen in Fig. 1 [25]. It is important to note that typically the two SAF analyses are conducted at different levels of scale, where the first is for the overall problem area or project topics, and the second is to analyze a DSS as a potential intervention to support a specific decision-maker. The initial project idea and first iteration of the Systems Architecture Framework for this research project are presented in previous work by the authors [6]. This paper covers the EVDT framing and second SAF iteration. Future work will present the interactive DSS prototype.

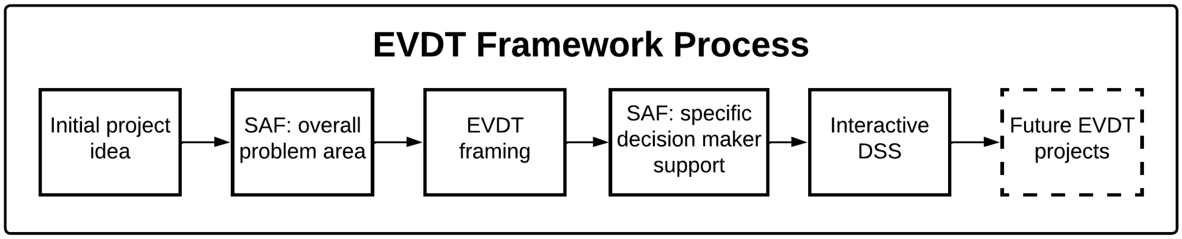


Fig. 1: The EVDT framework process, adapted from Reid [25].

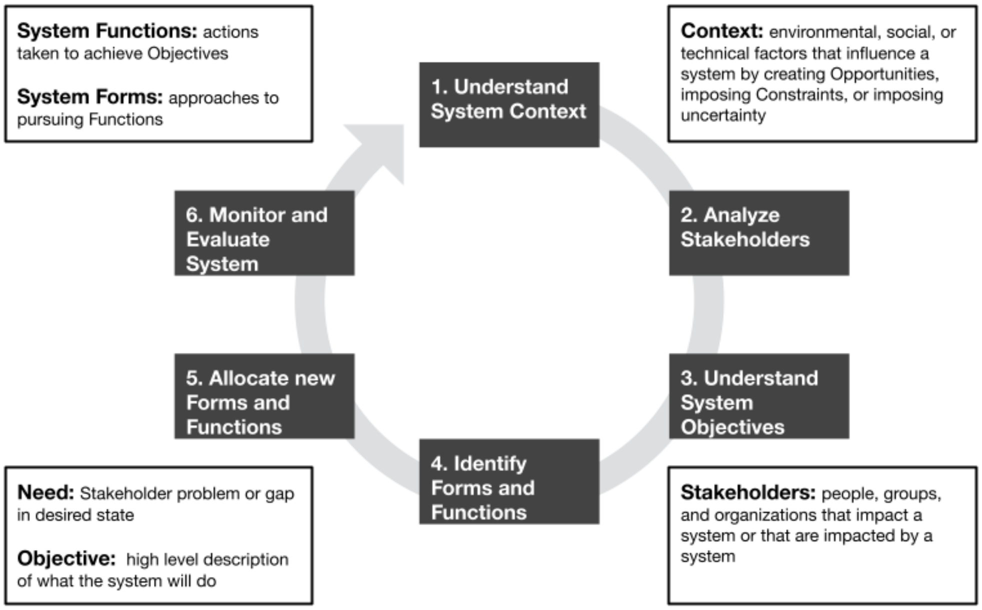


Fig. 2: The six steps of Systems Architecture Framework [6, 25, 28].

After an initial project idea is formed, SAF is the next step in the EVDT framework process, serving to understand the system Context, gather Stakeholder input, and determine the essential features of the DSS. It involves an iterative process of six steps rooted in systems engineering principles, shown in Fig. 2. SAF is a methodology used to analyze and interpret complex systems by understanding the relationships between the system's Forms, Functions, and Context. According to Crawley, Cameron, and Selva, system architecture is defined as "the embodiment of concept, the allocation of physical/informational function to the elements of form, and the definition of relationships among the elements and with the surrounding context" [29]. This approach emphasizes the principles of Form–Function relationships and Emergence, where different entities within the system adopt Forms to fulfill specific Functions aimed at meeting Stakeholder Desired Outcomes. These functions can be met through various Forms, whether by intentional design or unintentional evolution [29]. In SAF, Stakeholders are categorized into primary, secondary, and tertiary groups based on their influence on the system and what they receive from it. Primary and secondary Stakeholders directly (primary) or indirectly (secondary) influence the system through their decisions and outputs, while tertiary Stakeholders, also known as beneficiaries, are those whose Needs are met by the system's outputs [29]. Understanding the Context in which the system operates is also essential to SAF. Context is evaluated at different levels and interpreting Context helps define the boundaries of the system, ensuring that all relevant factors are considered. By applying SAF, systems are analyzed through six stages that involve understanding Context, analyzing Stakeholders, identifying system Objectives, identifying Forms and Functions, allocating new Forms and Functions, and finally monitoring and evaluating the system [29–32]. The SAF process is discussed in more detail in previous work by the authors [6], and the results of the first iteration of SAF are presented in Fig. 3. This graphic provides a depiction of U.S. governance of in-space servicing, drawing from data collected through Stakeholder interviews, literature review, and the authors' field observations. It serves as a conceptual illustration of how various inputs, categorized as Constraints or Opportunities, shape the U.S. space servicing governance system and leads to outputs in the form of Emergence. The figure also highlights the connections between the system's Stakeholders, system Objectives, Functions, and Forms, as identified through the SAF analysis.

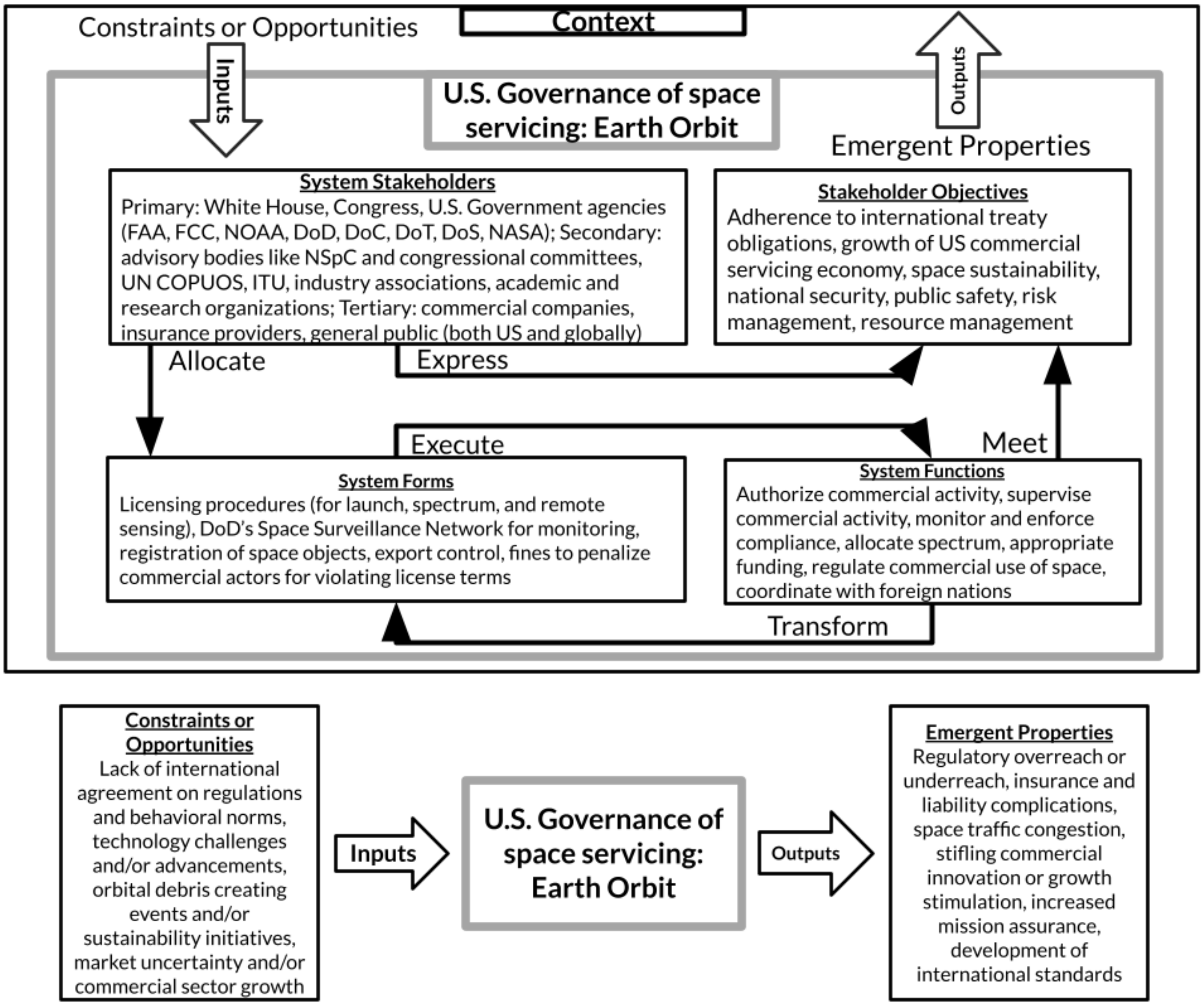


Fig. 3: Results of first iteration of SAF for the system being studied [6].

Figure 4 shows the generic form of an EVDT DSS for a traditional terrestrial use-case. Each box represents a submodel function within the EVDT framework, where inputs are processed and converted into outputs. These functions can be based on observations from sensors, estimates generated by models, or a combination of both, where the information could be either qualitative or quantitative. EVDT can operate as a self-contained, software-based environment or interact with humans who provide inputs such as decisions or preferences. The four submodels shown in the graphic aim to answer these fundamental questions [25]:

- **Environment:** What is happening in the natural environment?
- **Vulnerability:** How will humans be impacted by what is happening in the natural environment?
- **Decision-making:** What decisions are humans making in response to environmental factors and why?
- **Technology:** What technology system can be designed to provide high quality information that supports human decision making?

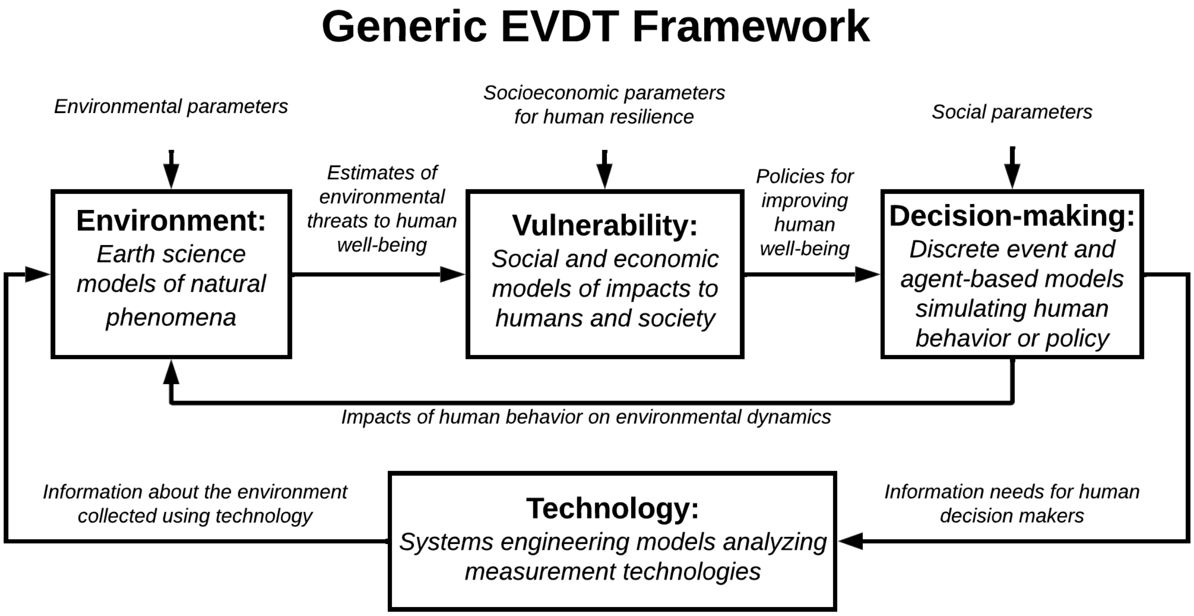


Fig. 4: Generic form of the EVDT framework for terrestrial sustainable development applications [25].

For some use-cases, it may be necessary to add or adjust the submodel components in the EVDT DSS depending on what questions the tool aims to address and what is revealed through the SAF analysis [25]. Table 1 shows the variety of use-cases demonstrated for EVDT for Earth-based sustainable development applications, showcasing a large diversity in location and purpose. Reviewing these examples of EVDT for Earth-based complex systems reveals that it can be effectively applied across a diverse range of contexts and topics, particularly in addressing public sector challenges like those related to the Sustainable Development Goals [33] and government responsibilities. A recurring theme in these examples is the trade-off between environmental well-being, human economic progress, and human physical health. The EVDT framework seeks to aid the design of solutions that balance and foster all three areas. These concerns are not only prevalent in complex engineering systems on Earth, but also resonate with the challenges faced in space-based problems as well.

Table 1: Previous uses for EVDT in Earth-based sustainability.

Location	Purpose	Description
United States	Environmental justice in carceral populations	Evaluates how satellite data has been used to identify and address environmental justice disparities in the U.S. [34]; Explores the perceptions of organizers working at the intersection of prison and environmental issues, revealing their use of and challenges with geospatial data and technology, and highlighting the need for improved tools to support prison ecology activism [13].
Mexico	Urban expansion decisions	Uses labeled multispectral satellite images and convolutional neural networks to assess human settlement sprawl and introduces a new information-based metric for evaluation [14].
Indonesia	Coastal flood mitigation	Improving understanding of historical trends and policy impacts for flood management among pilot study participants, suggesting potential benefits for decision makers [15]; Utilizes satellite remote sensing data to help local leaders in Pekalongan City address complex coastal flooding and land subsidence challenges and their socioeconomic impacts [16].
California, U.S.	Indigenous tribe forest management	Uses freely available satellite data with intentional Stakeholder engagement for aiding forest management for carbon sequestration and detecting environmental issues for the Yurok Tribe [17].
West Africa	Decentralized solar power for electricity access	Develops a soiling estimation model for photovoltaic systems, significantly reducing error in power loss estimates and informing design of solar power systems [18].
Massachusetts, U.S.	Cranberry bog land restoration	Analyzes the environmental and economic impacts of land use decisions in the cranberry industry, using ecosystem service modeling and geospatial data to inform sustainable practices and support Stakeholders in making decisions for climate resilience [19].
Benin	Invasive plant species mitigation	Uses combined space-based and ground-based data collection for managing invasive vegetation on Lake Nokoué, addressing historical power imbalances and promoting inclusivity in climate data systems [20, 21].
Brazil	Mangrove forest and community health	Translates Earth observation data into actionable metrics, demonstrated through a case study of mangrove forests and associated impacts to community health in the Guaratiba area of Rio de Janeiro [22].

In 2024, Es haghi et al. published the first use-case of the EVDT framework applied to a space-based application. They developed a Decision Support System for collision avoidance (COLA) operations in space, modeling NASA's conjunction assessment processes to highlight the impact of various risk mitigation strategies [24, 35]. The COLA-EVDT use-case demonstrated major findings including its ability to dynamically simulate conjunction events and their potential socioeconomic impacts. COLA-EVDT is an operational tool built in MATLAB that models the trajectories of NASA non-crewed science satellites along with any satellites that could potentially collide with them. This helps answer policy questions such as determining the overall operational impact of setting various thresholds on probability of collision for maneuvering. The framework efficiently processes conjunction data messages (CDMs), assesses conjunction risks, and suggests risk-mitigation actions, thereby providing a DSS for managing collision avoidance. Additionally, simulations demonstrated that the choice of SSA data provider influences operational costs and the workload on collision avoidance operators, highlighting a trade-off between government and commercial data sources in terms of accuracy and economic efficiency. Figure 5 shows the EVDT framework diagram for the novel space-based use-case for collision avoidance. The Environment function models conjunction events between NASA science satellites and other space objects and generates simulated CDMs for the collision assessment process. The Vulnerability model evaluates the socioeconomic consequences of each conjunction event based on an estimated value of the objects involved (which considers information value, costs associated with development and launch, object mass, object type, orbital characteristics, etc.) and the collision consequence as measured by resulting number of debris estimated from a collision. The Decision component within COLA-EVDT uses the simulated CDMs along with the estimated value of the conjunction to determine the appropriate course of action for risk mitigation using a decision tree. Finally, the Technology submodel generates simulated SSA data from government and commercial providers to feed back into the overall COLA-EVDT process. Further work on COLA-EVDT was accomplished by Wei who expanded the COLA-EVDT software capabilities to be able to ingest real CDMs rather than relying solely on simulated CDMs for analysis [36]. Wei's research addresses the gap in quantitative studies on the impact of potential space policies, particularly those related to collision avoidance maneuvers. The research implemented improvements to the COLA-EVDT system to simulate and analyze scenarios where space policies use probability of collision and maneuver time thresholds for spacecraft operators. The study also introduces an improved Vulnerability model that ranks space objects based on their hardware value and socioeconomic impact, and examines how these rankings affect the frequency of collision avoidance maneuvers and sensitivity to various parameters [36]. In both projects, COLA-EVDT informs policies and strategies to reduce collision risks while considering broader socioeconomic factors.

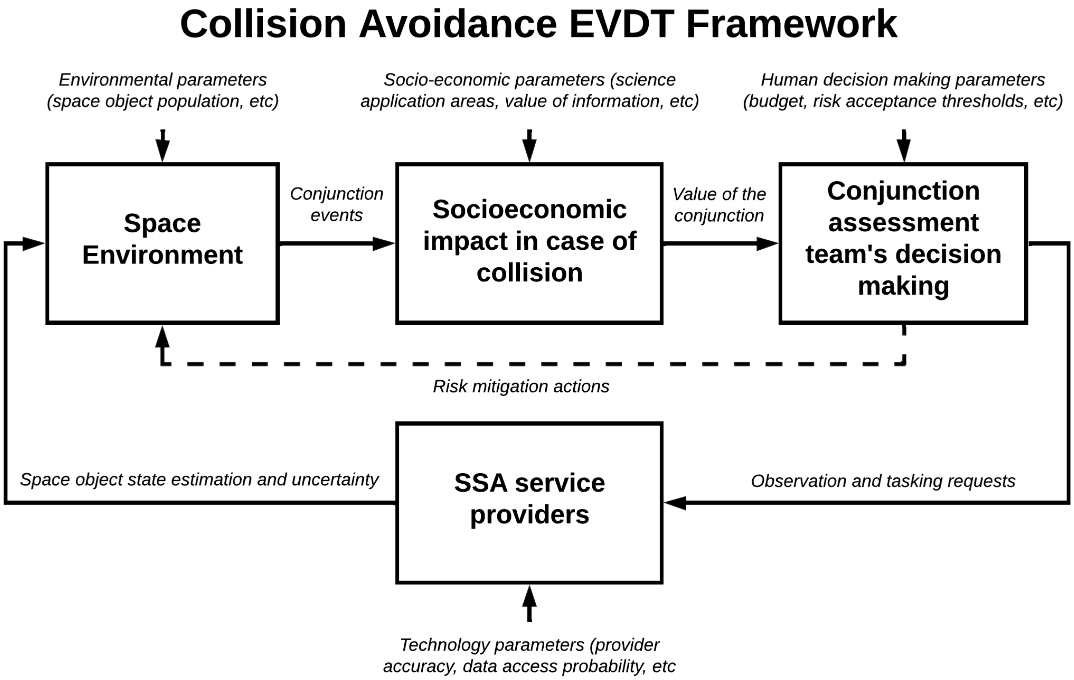


Fig. 5: EVDT schematic for space collision avoidance operations [24].

Building on the foundational work of Maier [30] and Crawley [29], Space Enabled researchers have been advancing the SAF and EVDT frameworks to address the challenges of increasing complexity in socio-technical and socio-environmental systems and the historical pitfalls of other systems engineering techniques [37]. These frameworks facilitate a multidisciplinary and Stakeholder-centered approach to system design and development by focusing on understanding Stakeholder Needs, integrating them into system architectures, and supporting sustainable development through informed decision-making [37].

2.2 Space sustainability EVDT

In this research, we define "space sustainability" using the definition established by the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) which has been expanded upon by Wilson and Vasile: "The long-term sustainability of outer space activities (on-ground and in-orbit) is defined as the ability to maintain and improve the conduct of space activities indefinitely into the future in a manner that ensures continued access to the benefits of the exploration and use of space for peaceful purposes, in order to meet the needs of the present generations while preserving both the Earth and the outer space environment for future generations. Space sustainability also requires promoting the use and environmental benefits of space data and recognising the need for the launch and in-orbit activities to be carried out in an increasingly responsible and sustainable manner" [38]. Figure 6 outlines a generalized EVDT framework tailored for space sustainability applications, intended to serve as a basis for specific space-based use-cases, such as the aforementioned collision avoidance application. By maintaining a unified structure for space sustainability related EVDT applications and standardizing inputs and outputs for each submodel, components can be shared via a common code repository, enabling sharing between various space policy and development challenges. The vision for this framework is to create a family of DSSs that can generate estimates of behavior of space objects in orbit, assess the socioeconomic implications of these behaviors, and explore potential policy actions and technologies for monitoring space objects based on modeling, simulation, and observational data. The framework is focused on developing software-based simulation tools and tools that leverage observational data to provide insights for various space sustainability challenges. While Fig. 6 shows generic ideas for the submodels and inputs/outputs, the authors envision a future state for the Space Sustainability EVDT Framework where the data and components could take on a variety of forms:

Environment: *Models of the space domain with future state predictions.* Within the Environment submodel, space object catalogs complete with position and velocity estimates can be modeled via TLE propagation, high fidelity orbit propagation, numerical propagation, or analytical propagation, or the submodel may take the form of statistical models, population evolutionary models, space environment simulation software, or others. Environmental parameter inputs to the Environment submodel may include zonal harmonics, third-body effects, atmospheric drag, solar radiation pressure, space weather, launch profiles for future predictions, etc. Some specific examples of tools that could be used in this submodel are space-track.org [39], Traffic Coordination System for Space (TraCSS) [40], MIT Orbital Capacity Analysis Tool (MOCAT) [41], NASA's Orbital Debris Engineering Model (ORDEM) and LEO-to-GEO Environment Debris model (LEGEND) [42], ESA's Meteoroid And Space debris Terrestrial Environment Reference (MASTER) [43], Space Cockpit [44], and Systems Tool Kit (STK) [45].

Vulnerability: *Models of socioeconomic consequences impacting humans.* Depending on the use-case, the Vulnerability submodel may utilize space debris creation models, orbital capacity estimations, collision consequence models, estimation of spacecraft economic value, valuation of spacecraft mission benefit, or even threat assessments. Socioeconomic parameter inputs to the Vulnerability model could include data about spacecraft parameters, launch costs, replacement value, revenue, and value of scientific data provided. Some specific examples of tools that could be used in this submodel are ESA's Database and Information System Characterizing Objects in Space (DISCOS) [46], Track the Health of the Environment and Missions in Space (THEMIS) [47], Space Sustainability Rating [48], NASA Standard Break-up Model [49], and Aerospace Corporation's IMPACT fragmentation model [50].

Decision: *Space policy and process decisions made by humans.* The human Decision-making submodel for Space Sustainability EVDT could be used to examine space policy decisions such as mission authorization and licensing decisions, compliance verification processes, space traffic management or coordination processes, and could utilize agent-based models, game theoretic models, decision trees, or system dynamics models for example. As inputs to this submodel, the social, political, and national security parameters may include international and domestic space policies, political leadership and priorities, interagency coordination, treaties and agreements, geopolitical tensions, diplomatic relations, military capabilities, counterintelligence, cultural values, behavioral norms, and liability.

Technology: *Models of space technologies monitoring the space environment and informing decision-making.* Simulated in the Technology submodel can be data from ground-based SSA, commercial SSA, government SSA, space-based SSA, telemetry data, owner/operator ephemeris, or communications and navigation technologies. Technology parameter inputs to the submodel may include provider accuracy and precision, observation update frequency, data accessibility, data processing and fusion capabilities, and more.

While the Space Sustainability EVDT Framework seeks to answer the same fundamental questions as the Earth-based EVDT Framework, the information shared between submodels is tailored to the space domain. For example, the Environment model in Space Sustainability EVDT is focused on the space environment rather than Earth-science models. The Vulnerability submodel still makes estimates of the socioeconomic impacts to humans, and the Decision-making submodel still models human behavior and policies. In Space Sustainability EVDT, the Technology component is focused on modeling technologies that monitor the space environment such as space situational awareness capabilities. For both Space Sustainability EVDT and Earth-based EVDT, the frameworks aim to model and simulate information about the environment that human decision-makers need to understand the impacts to society based on environmental, socioeconomic, and technical parameters.

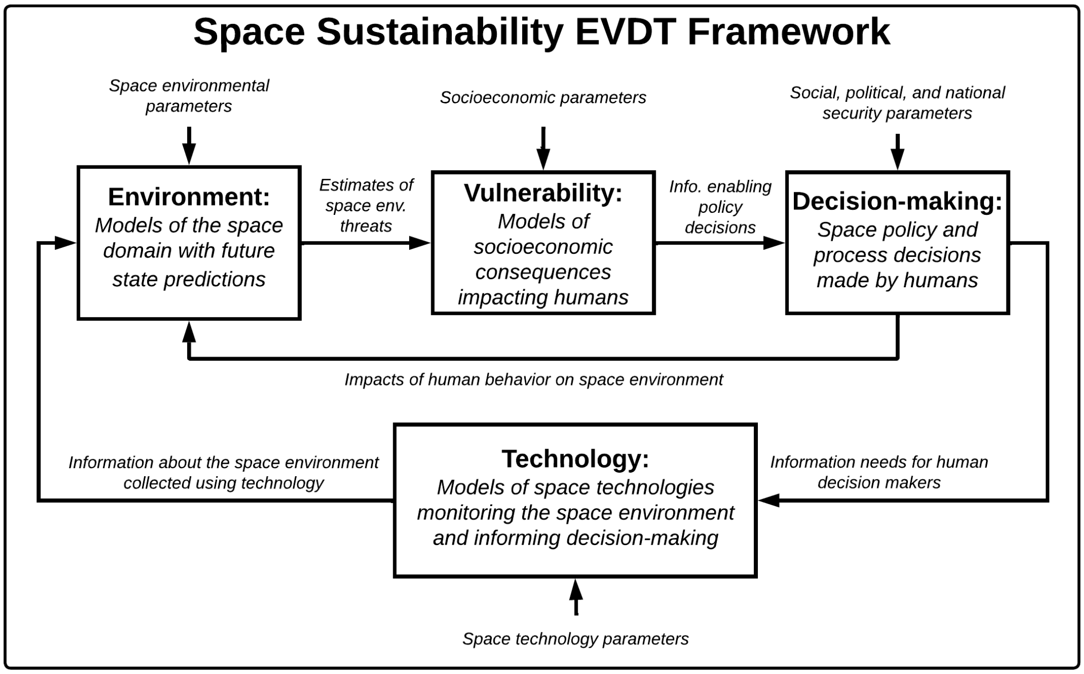


Fig. 6: Generic EVDT framework for space sustainable development applications.

3. USE-CASE FOR CONTINUING SUPERVISION

This multi-year research undertaking will develop a prototype application of the Space Sustainability EVDT Framework used to analyze outcomes for hypothetical in-space satellite servicing missions under U.S. jurisdiction in the context of the need for continuing supervision as outlined in the Outer Space Treaty. This section will discuss the process for developing the proposed continuing supervision EVDT model and the work completed so far. To develop a robust prototype for the EVDT driven Decision Support System in this context, certain features and capabilities must be present based on the framework's principles and the specific requirements of continuing supervision. First, Stakeholder input and analysis must be prioritized and integrated iteratively, as discussed in more detail in previous work by the authors for this use-case [6]. Second, the DSS should offer an interactive, modular design, featuring a user-friendly dashboard that is easily accessible. This enables the addition of new functionalities as technologies and policies evolve. The DSS should aim to incorporate simulated data from sources such as space situational awareness systems and potentially even satellite owner/operator shared data sources. For assessing space environmental impact, both short term collision risk and consequences as well as long-term evolutionary population propagation models may be necessary. However, the initial focus of the prototype will be for short-term implications of government supervision of commercial servicing with the U.S. as the primary example. Ultimately, the prototype aims to assess the socio-economic impacts of potential commercial space policies, enabling policymakers to make informed, data-driven decisions regarding space governance for in-space servicing missions. Figure 7 shows the proposed framework for the continuing supervision of in-space servicing EVDT application. The graphic shows a high-level interpretation of how inputs and outputs will flow through the software tool and what is modeled within each of the EVDT components. This application is a use-case for the generic Space Sustainability EVDT Framework presented earlier, for which the authors envision making multiple other capabilities in the future.

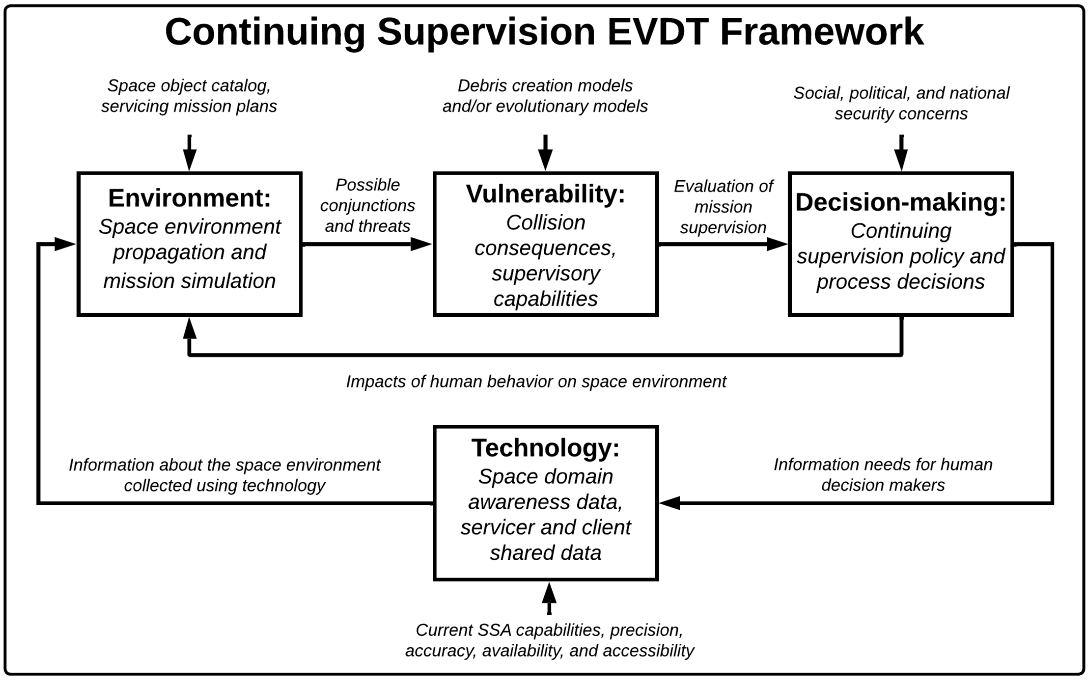


Fig. 7: EVDT framework for continuing supervision of in-space servicing application.

3.1 Systems Architecture Framework analysis

In previous work published by the authors, a SAF analysis was completed focusing on Needs and Desired Outcomes of USG Stakeholders involved in policy and regulation of commercial in-space servicing [6] based on interviews with knowledgeable Stakeholders. For this paper, a more focused SAF analysis was conducted, viewing the EVDT developers as the primary Stakeholder, the USG regulators as secondary Stakeholders, and the broader commercial space community including both in-space servicing clients and providers as tertiary Stakeholders. An additional seven interviews were conducted, adding to the fourteen previously conducted for the first research paper in this series. Virtual or in-person interviews were conducted for 30-60 minutes, recorded for participants who consented through signed informed consent documents, and all recordings are stored securely with password protection. The interview plan, informed consent letter, and data storage strategy adhered to guidelines from the MIT Institutional Review Board called the Committee on the Use of Human Subjects as Experimental Subjects (COUHES). These extra seven interviews were focused more on the Department of Commerce (DoC) Office of Space Commerce (OSC). These experts were chosen for the study based on the National Space Council (NSpC) draft legislation currently under consideration titled “Authorization and Supervision of Novel Private Sector Space Activities Act” which would place the authority for authorization and supervision of commercial in-space servicing activity into the DoC [51, 52]. Figure 8 shows the results of this iteration of SAF. The results of this SAF are used to inform the Functions and Forms for the EVDT prototype. Additionally, Fig. 9 shows the specific system Objectives for the EVDT model based on Stakeholder Needs and Desired Outcomes.

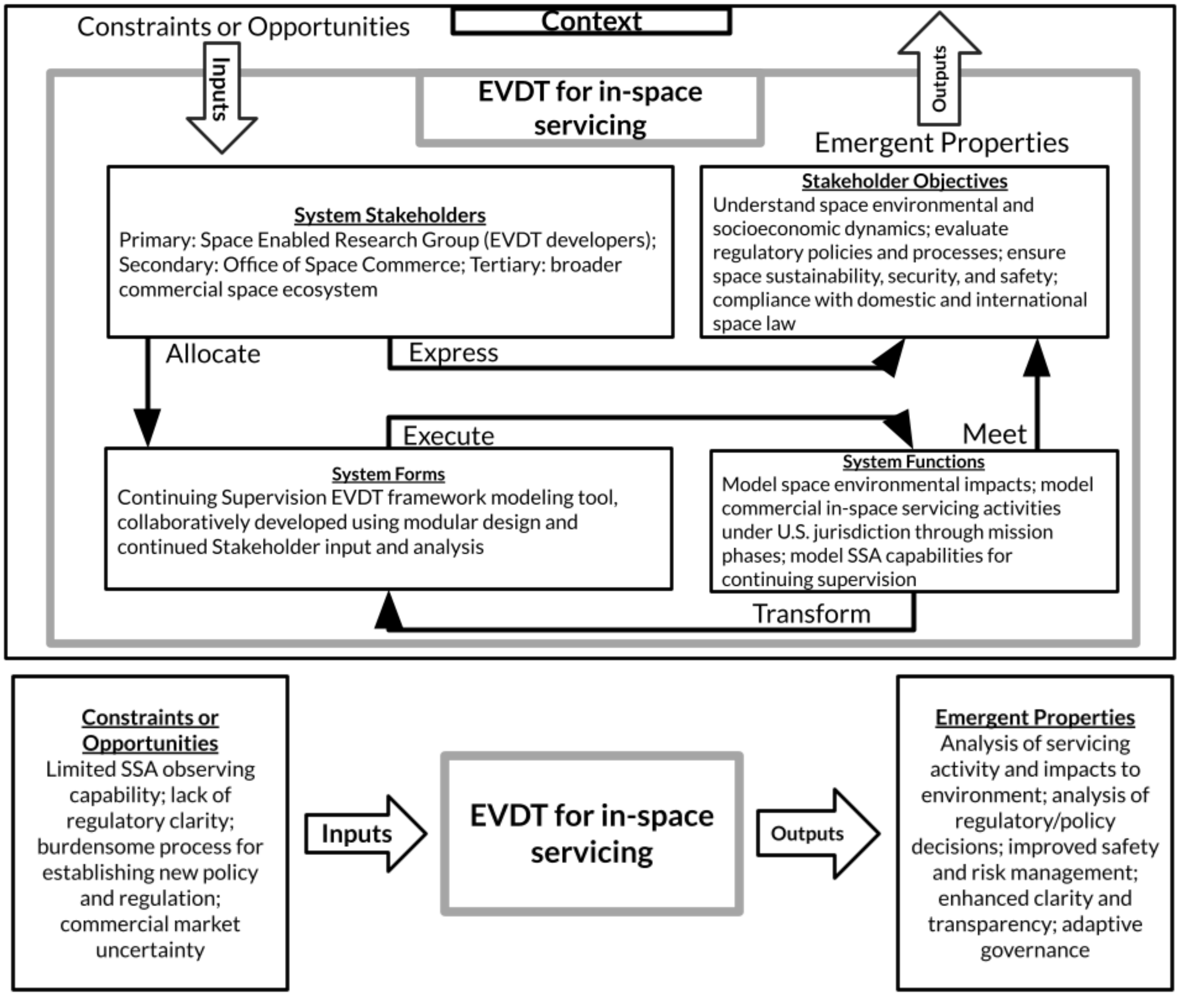
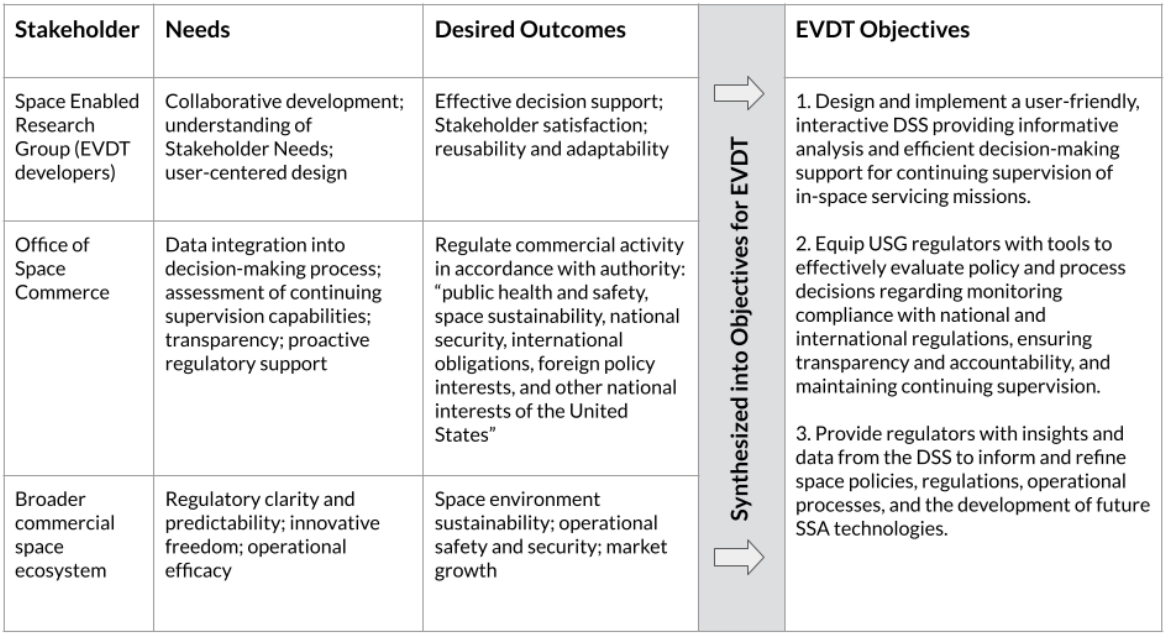


Fig. 8: Results of second iteration of SAF for the system being studied, viewing EVDT developers as the primary Stakeholder.

Insights from the second iteration of SAF based on the new interviews are gathered and synthesized as answers to the research questions and updates to the research propositions, given below.

RQ1: Describe. How do U.S. Government Stakeholders describe their Contextual Constraints (regulatory, technical, economic, and security) associated with authorization and continuing supervision of commercial in-space servicing?

- **Regulatory Constraints:** According to interviewees, there exists a lack of clarity and standardization in "continuing supervision," an absence of specific legislative authority, challenges in understanding jurisdictional boundaries, and regulatory inefficiencies and delays.
- **Technical Constraints:** Technical constraints identified include inadequacies in current SSA systems, significant engineering challenges in RPO, as well as a definitive need for standards in docking protocols, in-space tracking, and communication technologies. These challenges are exacerbated by the fact that technical advancements currently outpace bureaucratic processes.
- **Economic Constraints:** In the economic Context, high costs of compliance with complex regulations, uncertain commercial business cases for servicing, and fluctuating launch costs all act as system Constraints. Other economic challenges include securing sustained funding for servicing missions and the extremely slow regulatory responses which has driven some commercial servicing companies abroad.



Stakeholder	Needs	Desired Outcomes		EVDT Objectives
Space Enabled Research Group (EVDT developers)	Collaborative development; understanding of Stakeholder Needs; user-centered design	Effective decision support; Stakeholder satisfaction; reusability and adaptability	Synthesized into Objectives for EVDT	1. Design and implement a user-friendly, interactive DSS providing informative analysis and efficient decision-making support for continuing supervision of in-space servicing missions. 2. Equip USG regulators with tools to effectively evaluate policy and process decisions regarding monitoring compliance with national and international regulations, ensuring transparency and accountability, and maintaining continuing supervision. 3. Provide regulators with insights and data from the DSS to inform and refine space policies, regulations, operational processes, and the development of future SSA technologies.
Office of Space Commerce	Data integration into decision-making process; assessment of continuing supervision capabilities; transparency; proactive regulatory support	Regulate commercial activity in accordance with authority: "public health and safety, space sustainability, national security, international obligations, foreign policy interests, and other national interests of the United States"		
Broader commercial space ecosystem	Regulatory clarity and predictability; innovative freedom; operational efficacy	Space environment sustainability; operational safety and security; market growth		

Fig. 9: EVDT objectives, derived from system Stakeholder Needs and Desired Outcomes.

- **Security Constraints:** Finally, in the security Context, Constraints include a reluctance to disclose harmful interference incidents, a need for interoperability in SSA systems, the dual-use nature of ISAM technologies, the proprietary nature of satellite data, a need for interagency review for security compliance, and the fact that national security often dominates the regulatory development process.
- **Update to RQ1 Propositions:** Ambiguity in the definition of "continuing supervision," combined with a lack of standardization and clear legal frameworks across agencies, leads to significant implementation challenges. The increasing complexity of commercial in-space servicing activities is further compounded by uncertain economic viability, fluctuating launch costs, and burdensome regulatory pathways. Limited agency funding and authority, regulatory inefficiencies, fragmented inter-agency coordination, and evolving legislative and technical constraints, along with jurisdictional ambiguities and national security concerns, exacerbate these challenges. Ongoing engagement between Stakeholders is necessary to align regulations with practical realities and industry needs.

RQ2: Explain. What historical Constraints and Opportunities contributed to the development of the governance framework for the authorization and supervision of in-space servicing? How do current U.S. space laws and policies act as Constraints or Opportunities for achieving and maintaining continuing supervision?

- **Historical Constraints:** Interviewees indentified that historical Constraints include outdated frameworks like the ITU's Article 48, the minimal requirements set by the OST, the security-driven origins and regulatory inertia from legacy frameworks, and moratoriums on regulatory development in response to evolving commercial industries.
- **Historical Opportunities:** However, historically Opportunities have arisen such as an increasing transparency and participation in space by more diverse actors, precedents from other technological domains providing lessons-learned for space, and a driving need for new governance due to technological advancements and increased commercialization of space.
- **Current Constraints:** Presently, the Stakeholders identified Constraints such as lengthy and burdensome regulatory processes, an observed slow pace of regulation development, unclear definitions in the OST, a requirement

for legislative and administrative processes in order to expand authority, a segmented regulatory environment, and the difference between authority and appropriations.

- **Current Opportunities:** Updating frameworks like the Registration Convention, using cautious regulation to avoid stifling innovation, establishing foundational frameworks allowing for international collaboration, developing capability-based regulation models, and initiatives like the Artemis Accords for collaborative norms are all examples of current Opportunities.
- **Update to RQ2 Propositions:** The historical development of U.S. space law has been influenced by international agreements, national security considerations, economic interests, and the evolving nature of space technology. These historical frameworks must now address the modernization requirements of outdated governance structures to meet contemporary needs for continuing supervision and coordination. The Outer Space Treaty provides a foundational baseline for supervision but allows for higher national regulatory standards. Current U.S. space laws and policies face constraints due to legislative approval processes, the role of Congress in defining regulations, segmented regulatory environments, and lengthy timelines for regulation development. Opportunities arise for capability-based regulation, enhanced international collaboration, and the exploration of new domains such as cislunar space. The balance between security imperatives and fostering commercial innovation impacts future regulatory adaptations, necessitating anticipation of market trends and effectively allocating scarce government resources.

RQ3: Evaluate. What misalignment exists between Stakeholders' Needs/Objectives and the current Forms/Functions of in-space servicing authorization and supervision? How might "continuing supervision" be more precisely defined and operationalized to address the misalignment?

- **Misalignments:** The interviewees point to a gap between regulatory expectations and the satellite operators' practical realities, as well as an incomplete understanding of ISAM's economic viability and a lack of resources and clear legal frameworks for continuing supervision. Additionally, there is a perceived mismatch between the rapid innovation needs and the slow, security-centric regulatory processes.
- **Definition and Operationalization:** In practice, "continuing supervision" could be better defined and operationalized through frequent and detailed updates about mission changes and interactions with other space objects, a context-dependent supervision adaptable to differing space activities' risks and requirements, ensuring regular regulatory reviews, and establishing specific monitoring protocols. Some interviewees recommended requiring the use of SSA sharing systems like TraCSS by operators, clarifying liability issues, enabling broad-based mission authorization, setting explicit timelines for regulatory decisions, and clarifying data sharing requirements. Most interviewees agreed on the importance of involving industry feedback in rule-making, balancing innovation and safety needs, enhancing transparency in decision-making, and establishing clear standards for compliance and operational adjustments.
- **Update to RQ3 Propositions:** Both strategic gaps, such as the lack of agency-level funding, clear responsibilities, legislative authority, and disconnects between appropriations and authority, and operational gaps, such as limited data sharing, inefficient regulatory processes, and a lack of exquisite space situational awareness resources, pose challenges to achieving effective continuing supervision in the U.S. Additionally, complex economic and legal frameworks, along with proprietary and security concerns, further complicate the issue. A more clearly defined and adaptable framework for context-specific continuing supervision—emphasizing frequent updates, inter-operator transparency, data sharing, and advanced SSA systems—can enhance U.S. compliance with Article VI of the Outer Space Treaty. This framework should be informed by industry feedback, ensuring efficiency, transparency, clarity, and market awareness to address these challenges.

RQ4: Design. How can a Decision Support System be designed to meet U.S. Government Stakeholders' operational Needs for continuing supervision, and what new Forms/Functions are proposed to effectively aid in these activities?

- **DSS Design:** One interviewee suggested that a useful DSS for regulators could include enabling a more fluid relationship between space operators and the UN space object catalog allowing for real-time updates for object interactions, as well as cataloging space objects with countries of origin. Other interviewees recommended that any DSS for the continuing supervision application needs to have flexibility to adapt to evolving regulatory requirements and industry practices, should enhance interoperability among international SSA systems, allow for integration of more comprehensive SSA data, and mimic TraCSS design with cloud-based, modular architecture using containerized microservices for scalability.

- **New Forms/Functions:** Interviewees suggested a variety of recommended functionality for a hypothetical DSS including registering and updating operators' interactions with space objects for trust and confidence-building, incorporating multiple data sources including commercial SSA data and owner/operator TT&C, utilizing user-friendly graphical interfaces, enabling machine-to-machine communication APIs, and establishing clear legal and economic frameworks for liabilities, salvage, and sustained funding.
- **Update to RQ4 Propositions:** Effective integration of Decision Support Systems in operational procedures can lead to enhanced coordination, monitoring, and continuing supervision of commercial servicing activities. Tailoring these systems to incorporate real-time updates, multi-source data, user-friendly graphical interfaces, and machine-to-machine communication APIs can significantly improve transparency and confidence-building about space object interactions. Incorporating cloud-based, modular architectures and ensuring interoperability with international SSA sharing systems, alongside proactive industry engagement and international data-sharing agreements, can further enhance the DSS effectiveness. Investigating these approaches can inform the design of governance mechanisms in the future, aiding U.S. Government Stakeholders in achieving regulatory efficiency and protecting the long-term sustainability of the space environment.

From the analysis conducted in this section, combined with author expertise and experience, Tab. 2 presents a basic set of minimum viable product (MVP) requirements for each submodel within the Continuing Supervision EVDT prototype. In summary, the basic functionality goal of the prototype is to use object catalogs and a simple propagator to simulate the space environment, mission details and characteristics to simulate mission phases of a servicing mission and identify vulnerabilities such as collision consequences and gaps in continuing supervision of the activity, and use the tool to investigate various outcomes based on regulator policies and the use of different SSA technologies to achieve continuing supervision.

3.2 Software design and development strategies

One of the key tenets of EVDT is modularity and re-use. Modularity means the software design approach divides the program into separate, self-contained modules, each with a specific functionality. This methodology enhances the organization, readability, maintainability, and reusability of the code. In this case, the four submodels can be segmented into four modular components. This will allow for future work to more easily re-use or replace specific components rather than starting a new space EVDT project from scratch. Each submodel must address separate functionality and fully encapsulate that operation, with defined interfaces between the other components. Object-Oriented Programming (OOP) is appropriate for a modular structure because it inherently promotes encapsulation, abstraction, inheritance, and polymorphism, which are key principles for creating modular, reusable, and maintainable code. Encapsulation allows modules to hide their internal state and expose only necessary functionalities, while abstraction provides simplified interfaces. Inheritance facilitates code re-use and organization into hierarchies, and polymorphism enables the interchangeability of components through common interfaces. Together, these features ensure that different parts of a system can be developed independently but work together seamlessly, enhancing overall system flexibility and maintainability. To this end, the Continuing Supervision EVDT prototype will be written in MATLAB. MATLAB allows for functions, scripts, and classes, making it suitable for encapsulating different functionalities into separate, reusable modules. Additionally, MATLAB's relevant libraries and toolboxes can be easily integrated into a modular structure, facilitating efficient code development. The code will be stored in a Github repository to enable collaborative development, another key tenet of the EVDT methodology. Storing the code base in a GitHub repo provides robust version control, enabling multiple developers to work on the same code base simultaneously. GitHub tracks changes, making it easy to review and merge contributions, and its branching and merging features allow for parallel development and integration. The platform also offers collaboration tools such as issue tracking, pull requests, and project management boards, which help teams organize tasks and facilitate communication if needed.

Table 2: MVP requirements for the Continuing Supervision EVDT prototype.

Submodel	MVP Requirements
Environment	• Ability to ingest updated space object catalogs from space-track.org. • Low-fidelity propagation method for simulating through time. • Simulate through general mission phases of a space servicing mission: launch, early orbit, parking orbit, rendezvous, proximity operations, inspection, capture, service, disposal operations, release and departure, return to parking orbit, etc. [53].
Vulnerability	• Ability to predict collision consequence of accident during servicing activity using NASA Standard Break-up Model. • Simulate USG ability to supervise activity through mission phases based on current capabilities and processes.
Decision	• Simulate various potential OSC policies for context-dependent continuing supervision for evaluating how well current SSA technologies meet these needs. • Model decision making based on outcomes of collision consequence identified in Vulnerability model.
Technology	• Simulate SSA data from current ground stations supporting observation and continuing supervision of the servicing activity. • Incorporate how new technologies (O/O data sharing, additional ground stations, international SSA data, space-based SSA capabilities, etc.) could change outcomes.

4. DISCUSSION

This work has potential impacts on policy-making, commercial space operations, environmental preservation, and compliance with international laws. The Continuing Supervision EVDT prototype can significantly influence policy-making by providing a data-driven, systems engineering approach for enhanced decision-making, aligning regulations with emerging novel space technologies. Tools like these can enable USG regulators to better understand the socio-environmental-technical implications of policies and operational practices. For example, this EVDT prototype will illuminate both the short- and long-term impacts of various in-space servicing mission paradigms on the space environment. Additionally, it helps USG regulators align with international laws and obligations by clarifying the concept and practice of "continuing supervision" for in-space servicing, as mandated by the Outer Space Treaty. A question that Continuing Supervision EVDT could help regulators answer is whether or not there are sufficient resources available to be confident in their ability to meet their obligation for continuing supervision for a given servicing activity, and if not, what additional technologies or protocols would be necessary to close the gap?

Future work can build on the generic Space Sustainability EVDT Framework and apply it to other applications, for dynamic space operations across various scenarios, policies, and regimes. Several ideas for future use-cases include:

- Cislunar space traffic management, space traffic coordination, and collision avoidance
- Long-term debris mitigation and removal efforts
- Space environmental sensitivity to types of ISAM activity proliferation
- Sustainable resource utilization practices on celestial bodies
- Environmental impact assessments for other emerging space mission types, such as in-space assembly or manufacturing
- Mega-constellation environmental analysis
- Asteroid mining and other deep space mission paradigms
- Evaluating use of the Space Sustainability Rating in the mission authorization process

5. CONCLUSION

In conclusion, this research effort demonstrates the necessity for evolving governance frameworks that are both comprehensive and adaptable to the rapid advancements in the commercial space sector, specifically within the context of in-space servicing activities. By leveraging the Systems Architecture Framework and the Environment-Vulnerability-Decision-Technology framework, we can develop Decision Support Systems to meet the dynamic Needs of Stakeholders, ensuring compliance with international treaties while fostering sustainable and secure space operations. The results of this study not only address current regulatory and supervisory challenges but also pave the way for innovative approaches to policy-making and policy evaluation in the future.

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