Space Sustainability and Traffic Management Requires Trusted Space Stakeholder Coordination

Harvey Reed
The MITRE Corporation
Nick Tsamis
The MITRE Corporation
Dr. Nathaniel Dailey
The MITRE Corporation

ABSTRACT

Space sustainability includes in-orbit salvage, reuse, and repair operations by disparate stakeholders, and requires greater stakeholder coordination than presently available. In May 2022 in the House Space and Science Subcommittee, Moriba Jah testified "The US White House recently delivered a strategy on In-Space Servicing, Assembly, and Manufacturing. The need for continuing supervision could not be more important than this developing space sector. In order to meet the needs of this community, there must be an unambiguous and distributed immutable ledger of who did what to whom when and where. As of this very testimony, I would challenge any government to demonstrate that it is currently capable of delivering such a capability. More complaints of harmful interference, damage, and threats will be raised whilst we are left ill prepared to assemble the evidence required to assess and quantify space events and activities." Similarly, traffic management is soon to become more complex and require advanced stakeholder coordination with the introduction of regular cislunar traffic.

Combined, both space sustainability and traffic management require not just a level of coordination which informs stakeholders of activities, but rather a higher degree of trusted and dynamic space stakeholder coordination to enable self-synchronization, enabling dynamic and independent actions. This higher degree of stakeholder coordination may not be achievable with today's legacy approaches and capabilities.

Trusted information means that the information is attributed, available, has known pedigree and provenance, is not controlled by any individual stakeholder or subset of stakeholders, and cannot be maliciously altered. Dynamic coordination means that stakeholders can independently make decisions, based on trusted and shared information. Independent decision making enables stakeholders to self-synchronize their activities, and dynamically respond to events. Examples of trusted space data includes the position of space objects (during launch, in-orbit, or de-orbit), the activity of object X (sustain orbit, maneuver, or decommission), and more. Other trusted space data could include pedigree and provenance of parts used in on-orbit repair operations – establishing a supply chain for space repair depots.

Ecosystems of manufacturing supply chain stakeholders grouping to share critical information is discussed at length in the National Institute of Standards and Technology (NIST) Internal Report NIST IR 8419 published in April 2022, "Blockchain and Related Technologies to Support Manufacturing Supply Chain Traceability: Needs and Industry Perspectives." There is direct applicability from terrestrial manufacturing supply chain to space supply chain (on orbit repair and manufacturing). There is a strong analog from terrestrial manufacturing supply chain to space information supply chain, where pedigree and provenance of critical information is similar in importance as pedigree and provenance for supply chain parts.

Space Information Sharing Ecosystem (SISE) is a candidate ecosystem and ledger approach for trusted and symmetric space information sharing, building on the observations in NIST IR 8419. SISE is a socio-technical enabler that uses decentralized data technology (ledger) in combination with an ecosystem of space stakeholders who govern and agree to share a defined minimal set of information to accomplish ecosystem objectives. All ecosystem stakeholders share a common data picture of information shared in the ecosystem.

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The thesis of this paper is that when individual stakeholders have access to trusted data in a symmetric manner, then one of the emergent effects is coordinated space activities and the increased safety, and the preservation of space. Decentralized socio-technical enablers are required because there is no single controlling authority over space as an international domain. The paper concludes with a call to action to pursue international prototypes of SISE to prove or disprove the thesis.

1. **INTRODUCTION TO SPACE SUSTAINABILITY**

This paper describes activities and challenges of multi-stakeholder space activities across a broad spectrum of applicable space operations, including sustainability, space traffic coordination, and space traffic management. The focus is on the underlying issues of such activities, such as multi-stakeholder cooperation. The thesis is that trust in multi-stakeholder cooperation can be increased, using cryptographically provable methods readily available with decentralized approaches and data technology. Increased trust in multi-stakeholder operations can then lead to improved mission outcomes. As an example of multi-stakeholder activity relevant to space, ongoing efforts are described regarding trusted and traceable provenance of manufacturing supply chains. Supply chain is relevant to space operations in that supply chain products are used in operations, and trust in the products is critical. The trusted and traceable provenance supply chain concept can be extended to data and information to increase trust in sensor and operational data.

Space sustainability and circular economy are often used interchangeably, and this paper treats them similarly. A circular economy is an economic system in which resources are kept in use for as long as possible, extracted, processed, and distributed in ways that minimize waste and pollution, and promote regenerative processes. The idea is to reduce waste and minimize the use of new resources, in contrast to the traditional linear economy, which operates on a "take, make, use, dispose" model.

Circular economy and sustainability both require multi-stakeholder cooperation which is the central topic of this paper. Other activities which also require multi-stakeholder cooperation, and for similar reasons, are space traffic coordination, space traffic management, and space domain awareness. Recently, the International Academy of Astronautics (IAA), the International Astronautical Federation (IAF), and the International Institute of Space Law (IISL) created an agreed single model and taxonomy for all these types of activities, as depicted in Fig. 1 below.

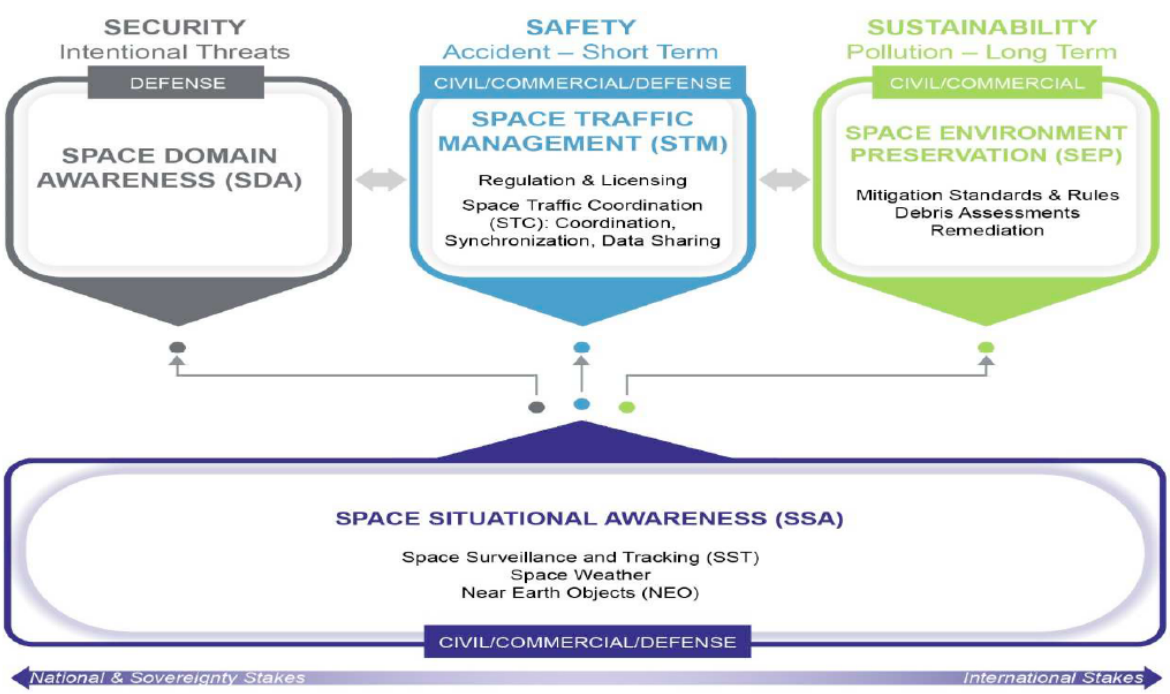

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Fig. 1 Combined Model of Space Activities

These three functional areas are distinct, spanning national/sovereign interests, international interests, defense community needs, and civil community concerns yet are still interdependent in many ways. STM garners high international interest because it exists at the confluence of national and international stakes and defense and civil community concerns [1].

The concept of a circular economy has been discussed for a long time. One of the seminal books, Cradle to Cradle[1] published in 2002. However, with renewed worry about supply chains and climate change, the concept is getting renewed attention. The National Institute of Standards and Technology within the U.S. Department of Commerce has recently started a new effort to research and promote the concept, which it hopes will grow to become a major focus of the Institute[2]. In the past year several major newspapers have run stories on applying circular economy concepts to specific sectors such as clothing and construction.

In order for the space economy to grow rapidly over the next few decades and beyond, circular concepts will have to be central to the practice of designing, using, and repurposing materiel. This is especially true in cislunar space, which is already crowded with debris that not only poses a serious risk of damage to satellites, but also is starting to limit the viability of new uses. Circular economies are particularly critical to enable sustained cislunar operations. This paper includes cislunar to emphasize that multi-stakeholder cooperation challenges will only increase as space operations include increasing numbers of cislunar operations. Nonetheless, the paper applies to all multi-stakeholder space operations, and doesn't necessarily focus on cislunar operations.

Establishing a circular economy in outer space could be challenging because of the unique conditions and constraints present in this environment, such as the limited resources available, the harsh conditions, and the lack of a regulatory framework. However, there are some steps that could be taken to establish a circular economy in space:

#	**Steps to Establish a Circular / Sustainable Space Economy**
1	Resource utilization: All resources should be carefully managed, including air, water, and other consumables. Recycling and reuse of resources should be prioritized over disposal.
2	System design: Space systems should be designed with circularity in mind, so that components can be reused and repurposed, and waste is minimized.
3	Waste management: Effective waste management systems should be developed to minimize the amount of waste generated in space. This could include recycling and composting systems, as well as systems for safe disposal of hazardous waste.
4	Collaboration and standardization: A circular economy in space will require collaboration between different organizations and countries, as well as the development of common standards and protocols for resource management and waste management
5	Regulations and incentives: To encourage the adoption of circular principles, regulations and incentives may be necessary to promote resource-efficient practices, as well as to discourage waste generation and disposal.

Establishing a circular economy in space requires significant investment of time, resources, and expertise. However, it could help to reduce waste, conserve resources, and create a more sustainable and resilient space environment.

A pre-COVID19 assessment by the U.S. Chamber of Commerce projected that the U.S. space market would grow from $385 billion in 2020 to at least $1.5 trillion by 2040. This seven percent (7%) compound annual growth rate (CAGR) is primarily driven by the Low Earth Orbit (LEO) market. The total addressable market (TAM) for U.S. commercial space companies could be far larger if they secured federal and financial support for initiating cislunar space operations and opportunities.

[1] Cradle to Cradle: Remaking the Way We Make Things, William McDonough and Michael Braungart, (Northpoint Press, 2002).
[2] https://www.nist.gov/circular-economy

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In recent years, there has been increasing interest in developing a cislunar circular economy, The term cislunar refers to the region of space around the Earth and the Moon, which includes the Earth's orbit and the Moon's orbit and the transit in between. While the LEO region can benefit from the circular economy approach, the cislunar region requires circular economy sustainable exploration and development, as discussed below in this paper. Commonly asserted circular space economy benefits.

Commonly asserted circular space economy benefits:

#	**Space Circular Economy Benefits**
1	Less Debris, Increased Sustainability: By reducing the creation of new space debris, removing existing debris, and developing ISRU technologies, a cislunar circular economy would increase the sustainability of human activities in space.
2	Reduced Resource Dependence: Using resources that are already available, a space economy would reduce dependence on resources transported from Earth, reducing the cost and risk associated with space missions.
3	Improved Space Safety: By removing existing space debris and reducing the creation of new debris, a cislunar circular economy would improve the overall safety of the region and reduce the risk of collisions with operational satellites and other spacecraft.
4	Increased International Cooperation: By promoting international cooperation, a cislunar circular economy would encourage the development of common standards and regulations for the safe and sustainable exploration and development of space.
5	Economic Benefits: By enabling the recovery and reuse of resources and the development of new technologies and markets, a cislunar circular economy would generate economic benefits and create new opportunities for growth and innovation.
6	Advancements in Technology: The development of ISRU technologies and other systems required for a cislunar circular economy would advance the state of technology in fields such as materials science, propulsion systems, and life support.

Overall, a space circular economy would support the long-term, sustainable exploration and development of earth orbit and the cislunar region, promoting growth and innovation while minimizing the impact on the environment and preserving the region for future generations.

Circular economy activities by definition require greater stakeholder cooperation across commercial and governmental organizations than the dominant present-day single actor, disposable materiel approach. For example:

1. Reducing the Creation of Space Debris – One of the key challenges facing the development of a cislunar circular economy is the accumulation of space debris in the region. The creation of new space debris through the launch and operation of satellites, as well as the natural accumulation of meteoroids and other debris, creates a hazardous environment that threatens the safety of spacecraft and astronauts. To reduce the creation of new space debris, it is essential to implement measures that minimize the quantity of debris generated during the launch and operation of satellites. These measures require increased stakeholder agreement regarding standards, practices, and operational multi-stakeholder coordination.
2. Removing Existing Space Debris – Another important step towards enabling a cislunar circular economy is the removal of existing space debris. This can be done through a combination of active and passive measures. Active removal involves the use of spacecraft equipped with propulsion systems to move debris to a lower altitude where it will re-enter the Earth's atmosphere and burn up. Passive removal involves the use of drag sails, which increase the atmospheric drag on debris and cause it to re-enter the Earth's atmosphere more quickly. These measures require increased stakeholder agreement in standards, practices, and operational multi-stakeholder coordination.
3. Developing In-Situ Resource Utilization (ISRU) Technologies – In-situ resource utilization (ISRU) refers to the extraction and use of resources that are available in space, on the Moon or other celestial bodies. Developing ISRU technologies is crucial for enabling a cislunar circular economy because it will reduce the need for the transportation of resources from Earth and increase the sustainability of human activities in space. ISRU technologies includes the extraction of water ice from the Moon's polar regions, which could be used as a source of hydrogen and oxygen for life support and rocket propulsion, or the extraction of

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metals and other materials that could be used to construct habitats, power systems, and other infrastructure. These measures require increased stakeholder agreement in standards, practices, and operational multi-stakeholder coordination or the extraction of metals and other materials that could be used to construct habitats, power systems, and other infrastructure. These measures require increased stakeholder agreement in standards, practices, and operational multi-stakeholder coordination.

4. Promoting International Cooperation – International cooperation is essential for enabling a cislunar circular economy. Space agencies, commercial companies, and governments must work together to develop common standards and regulations for the safe and sustainable exploration and development of space. This could include agreements on the responsible disposal of spacecraft at the end of their operational life, the sharing of data and tools for tracking and monitoring space debris, and the development of shared resources and infrastructure for supporting human activities in space. These measures require increased stakeholder agreement in standards and practices, and operational multi-stakeholder coordination.

Many of the critical circular economy activities and processes by definition require increased stakeholder agreement in standards and practices, and operational coordination. This requirement is new and puts strain on legacy capabilities which were acquired/built assuming disposable materiel and single stakeholder actors who do not need to coordinate activities, other than occasionally making way for a disabled craft or debris.

2. **CHALLENGES TO ESTABLISH A CIRCULAR / SUSTAINABLE ECONOMY**

A space circular economy is a paradigm shift from the legacy approach of lifting the mass you need for on-orbit activities, conducting your operations, then deorbiting. Longer stays in LEO out to cislunar demand an increase in reuse and other circular economy activities. Reuse is but one aspect. Other activities such as debris removal and repair require a level of multi-stakeholder cooperation that so far has only been achieved in limited scope efforts such as the Apollo-Soyuz and ISS. Such wide-spread cooperation requires coordination, which in turn requires trusted and symmetric information sharing.

Significant Challenges

Establishing a circular economy in space is a complex and challenging task that faces a number of significant challenges.

- Limited resources. Space is a harsh and resource-constrained environment, and resources such as air, water, and fuel must be carefully managed, especially as in-situ resources on the Moon are non-renewable.
- High costs. Developing and operating a circular economy in space is likely to be expensive, given the need for specialized equipment, infrastructure, and processes.
- Technical complexities. Creating a circular economy in space requires overcoming significant technical challenges, such as developing efficient and effective waste management systems, and designing spacecraft and equipment that can be reused and repurposed.
- Lack of regulatory framework. There is currently no clear regulatory framework for space activities, which makes it difficult to establish a circular economy that is consistent and enforceable.
- International cooperation is necessary but problematic. Establishing a circular economy in space will require international cooperation, given the global nature of space activities and the need for common standards and protocols.
- Public perception is a challenge. Changing public perception of the importance of a circular economy in space and building support for this concept may also be a challenge.
- A circular economy currently depends on linear economies. Many of the systems and processes used in space today are based on a linear economy, and significant changes will be required to shift towards a circular economy.

Despite these challenges, the benefits of establishing a circular economy, including space traffic management, in space are significant and include reducing waste, conserving resources, and creating a more sustainable and resilient space environment. Addressing these challenges will require multi-stakeholder collaboration between different organizations and countries, as well as investment in research and development to develop new technologies and systems.

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Multi-stakeholder Coordination and Cooperation Challenges

The following multi-stakeholder challenges are foundational and must be resolved prior to addressing high-level economic and geopolitical challenges:

- **Trusted situational awareness** – a foundational component of space domain awareness, is crucial for space traffic coordination. The root of the challenge is that there is no single entity which has ownership or operational responsibility for all space sensors. Thus, countries and commercial entities must coordinate and cooperate to share and aggregate more complete situational awareness of space traffic, but present-day situational awareness technology was not acquired/built for this purpose. Further, space situational awareness does not formally extend to cislunar traffic.
- **Trusted operational info** – Such as authority to "direct traffic" or even provide basic services such as conjunction analysis. Different governmental bodies may take on responsibility for space craft under their flag, per the Outer Space Treaty. However no single government or international body has both the sole authority and ability to coordinate traffic. Thus, all countries must cooperate, but their supporting technology was not acquired/built for this purpose.
- **Trusted supply chain materiel** – the pedigree and provenance of supply chain components are difficult to verify; yet without the ability to verify parts, the circular economy cannot be achieved.
- **Trusted maintenance** – rip-and-replace strategies will quickly prove an inviable option due to the increased costs associated with space operations in space. The information collected within a trustworthy supply chain must allow stakeholders to verify operational functionality, including determination of substitutability of parts. The capability to repair or replace components or perform effective maintenance relies upon the ability to support: (a) commensurate functionality and performance, e.g.: "Does the repair or maintenance service meet my mission's functional and performance requirements?" and (b) verifiable proof that no unintended functionality is present post-maintenance (including test), e.g.: "Did the repair or maintenance service incorporate additional unacceptable functionality?" Verifying information elements that prove operational functionality and performance can allow stakeholders to measure historical, real-time, and forecast future needs related to operational risk. Facilitating conditions for circular economies within the space domain will rely upon the domain's ability to maintain assets. This highlights the particular importance of effective coordination among space ecosystem supply chains.
- **Trusted knowledge of operational dependencies** – in a circular economy, as parts will be reused, so will space services. This enables a division of labor and greater efficiency. However, similar to the need to verify the pedigree and provenance of supply chain parts (a prerequisite to maintenance), dependencies of services must also be known and verifiable. Knowledge of operational dependencies informs risk management and establishment of mitigations. This operational dependency knowledge must be explicit (not hidden), and must be shared (as needed) among stakeholders. For example, if party A depends on party B, party A may also need to know what services party B uses. This dependency knowledge must be protected (data integrity).
- **Trusted reporting/handling of cybersecurity events** – Cybersecurity information shared in the space domain is used to inform operational decisions. Increasing the value, impact, and efficiency at which we can describe the operational relevance of shared information correlates to better informed decisions. Better informed decisions, in turn, results in increased understanding, certainty, and control of operations in the space domain, benefitting an international ecosystem. This highlights the importance of effective coordination among space stakeholders to share operationally relevant cyber information during incidents. This coordination needs to be enabled by socio-technical enablers including decentralized data approaches and technology.

3. SOCIO-TECHNICAL ENABLERS FOR THE CIRCULAR ECONOMY

Socio-technical enablers are factors that support the development and implementation of a technology or system. In the context of a circular space economy, numerous key socio-technical enablers exist:

- The development of technical infrastructure, such as recycling and waste management systems, will be important for establishing a circular space economy. This will require investment in research and development, as well as the development of new technologies and systems.

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- Standardization and interoperability of systems and processes will be important for ensuring the efficient and effective functioning of a circular space economy. Resulting in reduced waste and potential for increased substitutability of parts and systems, this will require the development of common standards and protocols, as well as collaboration between different organizations and countries.
- A human-centered design approach will be important for ensuring that a circular space economy is accessible and user-friendly for astronauts and other space personnel. This will require the development of user-friendly systems and processes, as well as the integration of feedback from users.
- Effective data and information management will be important for ensuring the efficient and effective functioning of a circular space economy. This will require the development of robust and secure information systems, as well as the collection and analysis of data to support decision-making.
- Sustainable supply chains will be important for ensuring that resources are used efficiently and effectively in a circular space economy. This will require the development of sustainable procurement practices, as well as the establishment of partnerships with suppliers to ensure the availability of sustainable materials and components.
- Social and cultural factors, such as attitudes and values, will also play a role in the success of a circular space economy. This will require education and outreach efforts to build public support and understanding of the importance of a circular economy, as well as the integration of cultural considerations into system design and development.

Socio-technical enablers help to establish a multi-stakeholder circular space economy, including space traffic management, that is sustainable, efficient, and effective, and that supports the long-term exploration and development of space. However, the challenges below must be addressed as the socio-technical enablers are implemented and adopted.

- Infrastructure to facilitate required multi-stakeholder information exchange to support circular economy must be in place to enable verifying trust in data. While existing trust relationships and infrastructure may be leveraged to form the basis for such a system, current cybersecurity methods and means for verifying trust may quickly prove incompatible within space domain ecosystems.
- Verification methods, related to cybersecurity, that are commonplace with highly accessible and readily available terrestrial systems may not be able to meet the increased demand that space system components will require. For example, characteristics often relied upon for cybersecurity testing (another form of validation) within terrestrial supply chains may not be available (e.g., physical access to components for testing on acceptable timeframes).
- Validating trust of replacement components on-orbit will likely need to be performed remotely, with data that was captured prior to component launch, perhaps months or years prior. If not performed remotely, these operations will need to be performed directly on-orbit or excluded.
- Validating the operational characteristics of a repaired object may require multiple pieces of test infrastructure and other space test objects. Traditionally, testing has required complete ownership of the test infrastructure used to verify trust. Yet, for a circular economy, and to enable rapid repair and validation, test equipment and objects may need to be shared. Sharing of such equipment and objects must also come with a means to maintain pedigree and provenance, but also to keep track of dependencies to shorten future iterations of repair and test.
- The expansive nature of the space domain may require that cyber infrastructure and resources used to collect and analyze data to measure trust be shared. In addition to verifying data contents, verification of secure data provenance practices (e.g., "chain of custody" and collection through dissemination) itself will be required.

A recurrent theme presented by cybersecurity, and especially regarding Zero Trust Architecture (ZTA), within the space domain is the importance played by our ability not to simply trust, but instead to proactively and continuously verify entities within supply chains supporting the space ecosystem. With means to verify entities present within the space ecosystem, stakeholders are provided with a level of assurance that exchanges across parties can be trusted, providing conditions to enable a circular economy. Trust, but verify – is simple in concept yet challenging to achieve with the terrestrial-focused tools and mindset we largely operate within. Building in the mechanisms and capabilities to address challenges discussed requires focused thought on how information security concepts will be not only present but championed in this environment. The integration of cybersecurity capabilities must be

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coordinated with the development of a circular space economy. This will ensure that cybersecurity within the space economy can be an integral part of operations, rather than an afterthought; a lesson we continue to grapple with terrestrially. Beyond ZTA, the topic of multi-stakeholder cooperation requires decentralized approaches and technology, explained below, which addresses ZTA tenets such as "1. All data sources and computing services are considered resources" [2]. Decentralized approaches and data technology enables each actor to be identified and enables cryptographic verification of data integrity.

4. CENTRAL THESIS OF SOCIO-TECHNICAL ENABLERS

Hypothesis:

- **If** socio-technical enablers are used to share data among stakeholders in a trusted and symmetric manner;
- **then** stakeholder cooperation and norms are possible.

Multi-stakeholder coordination and cooperation requires decentralized approaches

Decentralized approaches avoid the limitations of siloed or centralized information sharing where some stakeholders may not trust a single stakeholder being in control of information flow and storage. Since presently there is no single stakeholder government or commercial entity which all other stakeholders would trust, the only path forward for trusted and symmetric information sharing may be decentralized shared capabilities. A set of socio-technical enablers to consider for the circular economy for space and cislunar are in development and are described next.

Socio-technical enablers in progress

Trusted situational awareness (SNARE) – The SNARE (Sensor Network Autonomous Resilient Extensible) concept was inspired by the need for SMC/SPG GSW to pursue positional awareness of objects in space in real-time or near real-time. The current system, SP Tasker provides the regimen in place for the space surveillance network (SSN) to accomplish this goal. SP Tasker is a scheduling algorithm that is computed once per day, which analyzes information collected by the network in previous days and outputs a sensor schedule for collecting further information the next day. The SP Tasker, however, is limited by both the cadence at which it is executed and the approach of creating a global schedule. Such global schedules are computationally expensive and are based on untenable assumptions such as fixed orbits (no maneuvers since the last schedule). SNARE is conceived to be a computationally simple and deterministic prioritization algorithm that allows SNARE-enabled sensors to act autonomously (coordinating with shared real time data) to make collections throughout the day. The result is an emergent network effect of reactive and dynamic sensor observations, versus a static and brittle global sensor schedule [3].

Trusted operational information sharing (SISE) – The SISE (Space Information Sharing Ecosystems) concept addresses effective knowledge sharing and management for space, which requires appropriate tools that enable access to trusted and symmetrically shared information. The alternative to siloed bilateral and consortia-based information sharing is a whole of ecosystem approach, to symmetrically share information that SISE stakeholders agree should be shared. Note, this is not the same as sharing all information with all actors in the space domain. Rather it is the identification of the appropriate subsets of information and the appropriate subsets of participants in a minimum viable ecosystem. The minimum viable SISE first establishes the minimal set of relevant data to share that has sufficient value to motivate stakeholders to participate. Second is to establish an initial set of decentralized sharing principles to assure information is both symmetric and trusted for all ecosystem participants. Finally, it is necessary to establish initial decentralized information sharing capability, constructed, tested, and operated in the open with transparency. The SISE model of information sharing maintains parity of information/knowledge awareness among stakeholders. This information sharing protocol, is accomplished by reading prior posts of information, and making your own posts of new information, yielding a two-way conversation effect, viewable by the SISE stakeholders. Further, there may be need for more than one SISE ecosystem of stakeholders, for example cybersecurity reporting and supply chain [4] [5].

Further, consider a particular use case: on-orbit repair. This is in the news recently as the White House recently issued a strategy document "IN-SPACE SERVICING, ASSEMBLY, AND MANUFACTURING NATIONAL STRATEGY" in April 2022. Shortly afterward, in May 2022, Dr. Moriba Jah testified regarding manufacturing in space. Notably, he said on p.3 of his written testimony:

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"*The US White House recently delivered a strategy on In-Space Servicing, Assembly, and Manufacturing. The need for continuing supervision could not be more important than this developing space sector.* ***In order to meet the needs of this community, there must be an <u>unambiguous and distributed immutable ledger</u> of who did what to whom when and where.*** *As of this very testimony, I would challenge any government to demonstrate that it is currently capable of delivering such a capability. More complaints of harmful interference, damage, and threats will be raised whilst we are left ill prepared to assemble the evidence required to assess and quantify space events and activities.*"[3]
Dr. Moriba Jah May 2022, Testimony to House Science, Space, and Technology Subcommittee

Trusted supply chain materiel (NIST) – Tracing the pedigree and provenance of supply chain components throughout manufacturing supply chains and critical infrastructures, as well as space and cislunar environments, is critical to operational health and cybersecurity safety. The project "Manufacturing Supply Chain Traceability Using Blockchain Related Technologies"[4] will explore creating traceability chains composed of traceability records spanning multiple manufacturing supply chain domain blockchains. Thus, a critical infrastructure, or space repair depot, can examine a part and verify pedigree and provenance by comparing the product markings (e.g., provable unclonable function, as explained in NIST IR 8419)[5] with traceability records written to blockchain enabled ecosystems (e.g., MediLedger case study[6]).

Trusted operational dependencies – CISA (Cybersecurity & Infrastructure Security Agency) defines infrastructure dependencies as "relationships of reliance within and among infrastructure assets and systems that must be maintained for those systems to operate and provide services." These concepts can be extended to critical dependencies among space services and capabilities. Once discovered, these dependencies should be recorded and shared in a trusted and symmetric manner, similar to SISE.

Cybersecurity Considerations – Decentralized information sharing mechanisms like SISE can be used to share cybersecurity information in the space domain, to inform operational decisions. However, there must also be agreement among stakeholders on what type of information to share under what circumstances, while also minimizing sharing of private or intellectual proprietary data. The key is to share the minimum amount of information, yet which is still **operationally relevant**, to inform and defend operations. The tenets of operationally relevant information below are informed by tabletop exercises with Space ISAC [6].

Tenets of Operational Relevance – Four key tenets are presented by which we can reason about operational relevance:

1. **Comprehensibility** – information shared must be easily understood by the consuming organization. Removing the need for organizations to interpret intent enables organizations to comprehend shared information more easily. Performing this analysis before sharing maximizes efficiencies gained.
2. **Applicability** – all shared information will not be applicable to every consuming organization. Consideration must be taken prior to dissemination to equip organizations with the ability to determine what is or is not applicable for resource allocation.
3. **Timeliness** – information must be presented for action within appropriate time scales. Different data elements present risk or operational impact on different timelines. It is imperative that collection, analysis, and dissemination of shared information occur within the time constraints of possible impact based on the information under consideration.
4. **Actionability** – the value of information is ultimately limited by the actions it is able to support in an operational setting. Consuming organizations must know what to do with shared information. Providing complete sets of information necessary to address requisite actions in an unambiguous fashion empowers organizations to make informed operational decisions.

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[3] Statement of Dr. Moriba K. Jah, The University of Texas at Austin to the Committee on Science, Space, and Technology Subcommittee on Space and Aeronautics United States House of Representatives on Space Situational Awareness: Guiding the Transition to a Civil Capability, May 12, 2022.
[4] https://www.nccoe.nist.gov/projects/manufacturing-supply-chain-traceability-using-blockchain-related-technologies
[5] NISTIR 8419, Blockchain and Related Tech for Mfg Supply Chain Traceability | CSRC: https://csrc.nist.gov/pubs/ir/8419/final
[6] https://www.fda.gov/media/168283/download?attachment

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Trusted and traceable provenance is fundamental to several of the efforts described above. The reason is that trusted and traceable provenance enables cryptographically verifiable trust in materiel (incl. hardware, software, AI, data, and more). Advanced capabilities can be built on trusted materiel, which in turn enables complex multi-stakeholder activities. Trusted and traceable provenance is discussed in detail next.

5. TRUSTED AND TRACEABLE PROVENANCE FOR SUPPLY CHAIN AND STM INFORMATION

Trusted and traceable provenance is critical to prove validity of manufacturing supply chain products, and assemblies, as well as software, data, and AI. After initial manufacture, parts in repair and substitution can be validated. Further, provenance can also be used for space traffic management data, such as SSA data, used as input for conjunction analysis and subsequent decisions and recommendations. Pedigree of a manufactured product is in part determined by the provenance, including where the product was manufactured, and where the product was shipped to/from after the manufacture.

As supply chains supporting critical infrastructure grow more complex and the origins of products become harder to discern, efforts are emerging that improve traceability of goods by exchanging traceability data records using ecosystems enabled by Distributed Ledger Technologies (DLTs) and other blockchain related technologies that provide provenance and integrity [7]. Presently, the NIST (National Institutes of Standards and Technology) NCCoE (National Cybersecurity Center of Excellence) is working to produce a Minimum Viable Product to demonstrate traceable provenance records, written across multiple industry ecosystems, each of which contains a DLT, as may be the case in manufacturing supply chains in the future. In the coming months, the NCCoE will be publishing a Federal Register Notice based on the final project description[7].

The goal of such an ecosystem-oriented provenance traceability approach is to enable:

- Manufacturers to post traceability records to their respective industry ecosystem DLTs. Each traceability record written to the DLT links to the prior traceability record(s), going back to the original traceability record(s) (e.g., 'making' the product) where the traceability record links to the originating manufacturer.
- Traceability records to link and form an immutable traceability chain. Traceability records can link to multiple prior traceability records in the case of combining components in higher-order assemblies and products.
- Associating traceability records link to relevant context. In addition to linking to previous traceability records, traceability records point to relevant context such as the author (e.g., who wrote the record) and additional data in external repositories as needed.
- Establishing traceability record links to external data as required. In addition to the minimal data in the traceability record, traceability can link to external data as needed (with appropriate access controls) for larger data sets, images, audio, video, etc.

Supply chain participants are motivated to increase traceability in complex manufacturing supply chains to mitigate risk of supply chain vulnerabilities [8]. Vulnerabilities can arise in any manufacturing supply chain and are exemplified by the OT (Operational Technology) domains. OT includes hardware, software, and managed services, where consequences of OT supply chain vulnerabilities can impact the daily operation of U.S. critical infrastructure [9]. Today, organizations lack the ability to readily distinguish between trustworthy and untrustworthy products. Having a repeatable, quick, and provable means to determine if a product is trustworthy is a critical foundation of cybersecurity supply chain risk management [10].

An ecosystem perspective of the manufacturing supply chain serves to define cryptographically provable traceability for a subset (an ecosystem) of the manufacturing supply chain stakeholders (e.g., suppliers, critical infrastructure), and to share and store applicable product traceability data records (e.g., pedigree, provenance). Traceability requirements and their means of implementation will be unique for each ecosystem (e.g., microelectronics, operational technology, critical infrastructure).

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[7] https://insidecybersecurity.com/daily-news/nist-releases-description-supply-chain-traceability-project-focused-manufacturing-sector

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Trusted and traceable provenance chain

A traceability chain is a chain of linked traceability records. A traceability record is a transaction recorded to an ecosystem DLT, which is tamper evident and difficult to destroy. The manufacturing traceability records are of the sub-types: make, assemble, transport, receive, employ. The traceability record sub-types link to each other, providing an immutable traceability chain.

Fig. 2 below illustrates the **traceability record sub-types** (make, assemble, transport, receive, employ), and how they can be linked to form a traceability chain:

- **Make** –traceability records express the provenance of manufactured products (e.g., microelectronics, software, mechanical apparatus) and are the leaf nodes of the resulting linked traceability chain
- **Assemble** – derivative traceability records express the provenance of higher order assemblies
- **Transport** – traceability records express transporting a manufactured / assembled product
- **Receive** – traceability records express receiving a manufactured / assembled product
- **Employ** – traceability records express whether or not an end customer decided to use a received product; incl potential links to relevant enterprise systems and operational data

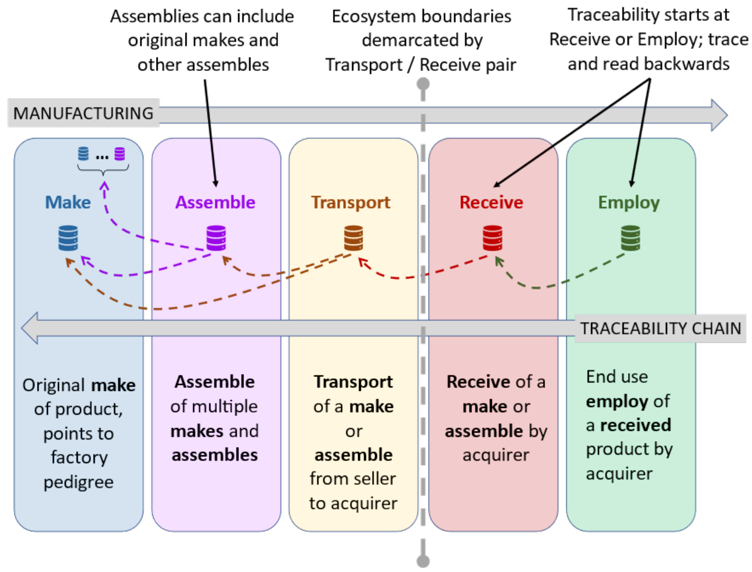

Fig. 2: Traceability Records Form a Traceability Chain

When a traceability chain is crawled backward, as shown in Fig. 2 above, each link to the preceding traceability record can be followed, even to a different ecosystem, to the preceding traceability record. This link includes a hash of the preceding traceability record. For early prototypes, the hash of the preceding traceability record can serve as simple authorization to access the preceding traceability record. The hash linking of traceability records is conceptually similar to linking blocks in a DLT, except a traceability chain is an inverted tree not a linear chain and spans multiple ecosystems. Thus, the traceability chain is a higher order data construct retaining the property of tamper evident data. Retaining the tamper evident property requires that each DLT also have the data integrity property of being tamper evident.

The use of multiple DLTs reflects the nature of manufacturing supply chains which include many affinity groups of similar manufacturers, and importantly can agree on the data fields of traceability records which are pertinent to the types of goods they manufacture. Using independent groupings of manufacturers which share affinity with each other gives rise to enabling ecosystems each of which use a DLT. These ecosystems expose an access-controlled application program interface (API) to the enclosed DLT within. Thus, the ecosystems and enclosed DLTs retain confidentiality, and the supporting DLTs provide data integrity. Further, the affinity groups can independently and incrementally update their ecosystems and DLTs, enabling rapid adaptation and encouraging adoption.

Traceability records are written as DLT transactions, of which the data types for the DLT transaction data payload are specialized and sub-typed according to use. The traceability DLT transactions are written by an ecosystem authorized actor as the activity or transaction is confirmed to occur and will include any required back linked (hash link) to the preceding traceability record(s).

Lifecycle of trusted and traceable provenance

Early prototypes are focused on the primary manufacturing supply chain actions (Make, Assemble, Transport, and Receive) prior to and including end customer disposition (Employ) and recorded in the respective traceability records. However, as shown below in Fig. 3, there are opportunities for future research in exploring what may be linked to the Employ record after initial deployment, as a result of sustainment chain activities (Repair, Update, etc.).

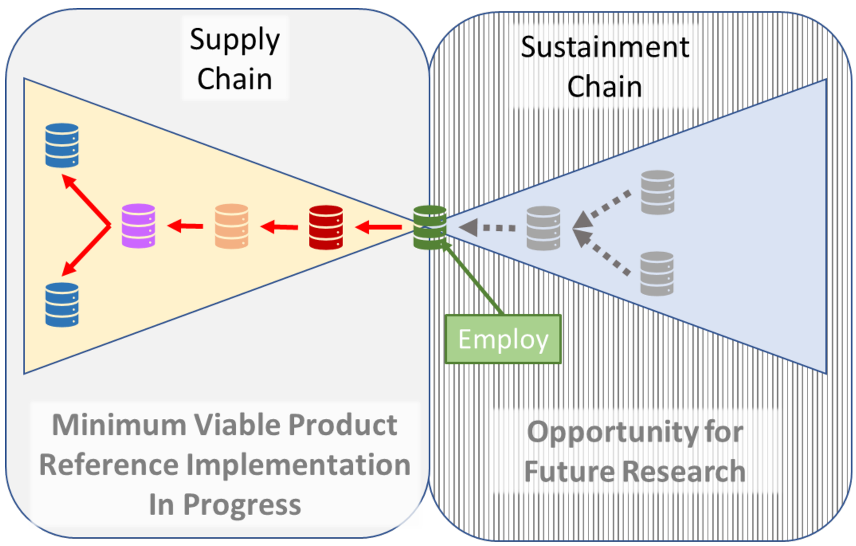

Fig. 3: Sustainment Chain Opportunity for Future Research

Further, trusted and traceable provenance for the sustainment chain also has value, building on supply chain provenance, and capturing sustainment provenance. The utility of positive ID of parts when making repair or substituting parts is critical to enable space repair and maintenance depots, key aspects of sustainable space.

Readiness of trusted and traceable provenance

The trusted and traceable provenance navigation linking and traceback mechanisms described above are being developed by NCCoE in its ongoing project. There are additional complementary efforts which bring structure and definition to each traceability record. In addition to NCCoE traceback navigation, IETF (Internet Engineering Task Force) SCITT (Supply Chain Integrity Trust and Transparency) project is a chartered standard (v1.0 in progress) focused on a standardized notary service (attestation) for ledger records. Present use cases are for SBOM (Software Bill of Material) however, the notary service could be used for a variety of provenance types. Further, there are standards orgs (e.g., SEMI[8] for semiconductors) which may add detailed data definition for provenance records for specific manufactured products.

6. NEXT STEPS

Trusted and traceable provenance can be used for hardware, software, data (SSA data, operational data, and more), as well as AI (models, software, tools). The combination of efforts described above (NIST NCCoE, IETF, and other

[8] https://store-us.semi.org/collections/standards/lang-english

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industry standards orgs) suggest that trusted and traceable provenance is at sufficient level of readiness to consider exploratory pilots.

An exploratory pilot for trusted and traceable provenance could either be a standalone pilot or augment an existing pilot. The pilot should emphasize multi-stakeholder activities, where trust in materiel and data exchanged is an important feature. The hypothesis should remain as described above, updated with "socio-technical enablers" substituted with "trusted and traceable provenance." The updated hypothesis then is:

- **If** trusted and traceable provenance is used to share provenance and other data with stakeholders in a trusted and symmetric manner;
- **then** stakeholder cooperation and norms are possible.

7. CONCLUSION

In this paper, activities and challenges of multi-stakeholder space activities were discussed, especially those activities relevant to sustainable space activities and space traffic management. The challenges may be mitigated with socio-technical enablers, many of which include decentralized data technologies, including ledgers / blockchain. Among socio-technical enablers, trusted and traceable provenance is recently making significant progress. The NIST NCCoE Traceability Chain effort postulates how to create a trusted and traceability chain of linked provenance records which are written as blockchain records in permissioned ledgers / blockchain. Each ledger / blockchain instance supports affinity groups of industry stakeholders (e.g., microelectronics, operational technology). Other efforts such as IETF SCITT complements the NIST NCCoE Traceability Chain, such that the trusted and traceable provenance concept is ready for a pilot. Please contact the authors of this paper to discuss further.

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