Mapping the unseen: exploring in-space manufacturing and designing a research path for supply chain methodological advancements

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Abstract
In-Space Manufacturing (ISM) involves the production of goods directly in the space environment. This is a paradigm shift from traditional Earth-based manufacturing. The paper aims to identify a structured research pathway to assess the opportunities of ISM from a supply chain perspective. Specifically, it was defined by a collaboration between specialists from different research centers and an industrial partner, following the Design Science Research (DSR) methodology. DSR was studied by identifying five process steps and four guidelines. The five steps were taken into account when considering the ISM supply chain, providing practical guidance for the research path. Importantly, the role of interoperability in enabling efficient data exchange and collaboration across different technological platforms and organizations is recognized as a key enabler for ISM. This led to identifying nine specific areas of contribution to the supply chain for ISM. The four guidelines guided the definition of the research path and enabled the future and sustainable development of a specific methodology for assessing an ISM opportunity from a supply chain perspective, highlighting the critical importance of interoperability in fostering innovation in space-based manufacturing.

Keywords
Design science, factory in space, research path, supply chain assessment, sustainability

1. Introduction

Circular Manufacturing strategies [1] and sustainable communities [2] are innovative approaches that can develop industrial ecosystems. However, the challenges also involve waste management in space [3]. In-space manufacturing (ISM) refers to the process of producing goods and materials directly within the space environment, typically on spacecraft, space stations, or other celestial bodies [4]. Unlike traditional manufacturing, which involves constructing and assembling products on Earth before transporting them into space, ISM leverages advanced technologies to fabricate items in the unique conditions of space. This innovative approach aims to reduce the costs and logistical challenges associated with launching fully assembled structures or components from Earth [5]. ISM holds the potential to enable on-demand production, customization, and repair of critical equipment and infrastructure in space [6], opening new possibilities for sustainable and self-sufficient space exploration and utilization. However, in this scenario, interoperability between these advanced technologies and existing systems may be critical to pursuing ISM processes and ensuring seamless integration with Earth-based supply chains. The exploration of opportunities for ISM requires a comprehensive approach that extends beyond the traditional realms of technical and economic

[1]Proceedings Acronym: I-ESA 2024 12th International Conference on Interoperability for Enterprise Systems and Applications, April 10–12th, 2024, Crete, Greece
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considerations [7]. To fully harness the benefits of cross-organizational collaboration and data sharing, it is important to adopt an enterprise interoperability-focused approach. This paper advocates for the integration of a supply chain analysis as an indispensable element throughout the various stages of assessing the viability of ISM. In doing so, it emphasizes the importance of interoperability in overcoming the logistical and informational barriers to space-based manufacturing. Supply chain dynamics play a pivotal role in shaping the feasibility, efficiency, and sustainability of manufacturing processes in space. Researches for ISM integrated specific assessment frameworks, e.g. for materials [8], additive manufacturing [9] and advanced manufacturing [10]. In this way, a gap in the literature was identified and for this motive, This paper aims to respond the following research question (RQ):

- RQ - What research path is valuable for incorporating a supply chain perspective into the study of opportunities for in-space manufacturing?

The rationale behind this RQ aims to propose a suitable methodology for investigating the opportunities of manufacturing in space from a supply chain standpoint. By addressing this goal, this study, based on the Design Science Research (DSR) theoretical framework, seeks to provide a structured and effective approach that researchers and companies can employ to comprehensively analyze the implications of space-based manufacturing within the broader context of supply chain dynamics.

2. Research method

A research group was formed for the purpose described above. It consisted of specialists from five research centres: the University of Rome Sapienza, the Polytechnic University of Milan, the Polytechnic University of Turin, the University of Padua, the Polytechnic University of Bari, and an industrial partner, Thales Alenia Space. The group met both in person and online, continuously sharing documents and ideas over time. The research group decided to use the Design Science Research [11] after holding meetings with various members. DSR is a research methodology that aims to create innovative artifacts to solve complex, real-world problems and generate design knowledge. DSR is a valuable approach that has been applied in various fields, including industrial design, information systems, and engineering education [12]. The goal of DSR is to develop and evaluate new theories, models, and methods that can be used to design and build effective solutions to practical problems. DSR can produce a research path that leads to the development of a new methodology by following a systematic and iterative process. DSR helps in the development of a new path by suggesting the following steps:

1. Artifact Creation: DSR involves the creation of innovative artifacts to solve real-world problems. These artifacts can include new models, frameworks, algorithms, or systems. The process of creating these artifacts can lead to the development of new methodologies or the enhancement of existing ones.
2. Theory Building: DSR often involves the development of new theories and models to guide the design and creation of artifacts. These theories can contribute to the development of new methodologies by providing conceptual foundations and guiding principles.
3. Evaluation and Validation: DSR emphasizes the evaluation of artifacts in real-world settings. Through rigorous evaluation and validation processes, researchers can gain insights into the effectiveness of different methodologies, leading to the refinement or creation of new methodologies.
4. Iterative Improvement: DSR is an iterative process that involves cycles of design, implementation, evaluation, and refinement. Through this iterative approach, researchers can continuously improve and evolve methodologies based on empirical evidence and practical experience.
5. Knowledge Contribution: DSR aims to generate design knowledge that can be shared with the research community. By contributing new knowledge about effective design and development processes, DSR can inform the development of new methodologies in various domains.

Moreover, the DSR could foster a new research path considering the recently defined guidelines for DSR of Table 1**Error! Reference source not found.**, adopted by the research group.

Table 1: The overarching adopted methodology (from [11]).

Guideline	Description
G1. Initiate a DSR project.	At the beginning of a DSR project, examine the context and select the strategy based on the project's characteristics.
G2. Build initial knowledge.	Starting from a strategy, examine the prototype and exemplars to identify potential paths of knowledge types.
G3. Progress ongoing research by matching path and exemplars.	Identify the strategy to which this research pertains, and match the path traveled to the exemplars of this strategy to identify the next possible nodes.
G4. Progress ongoing research with new path.	If matching the path traveled with the prototype and exemplars of a given strategy no longer leads to alternatives, switch to a different strategy. For disruptive strategies, attempt to conduct research by drawing an edge between strategies.

3. Application of DSR

The research team used the five steps of the DSR outlined above to define the research path. Each step contributed to specific elements of the research path presented in section 4, as described below.

1. Artifact Creation. The artifact creation strongly suggested a systematic literature review, but the research theme is so challenging and new that there are no specific contributions about the supply chain of products to be made in space. Starting from this situation the research group identified the need of a supply chain reference model as a starting point of the research path. The artifact used in the research path should rely on a strong phase 1 to establish objectives and developing a comprehensive terminology.
2. Theory Building. The theory building activity was focuses on the definition of the viable research path, shaping the conceptual framework for assessing ISM supply chains. To this end, the research team embarked on a comprehensive exploration of existing theories within the broader domains of logistics, manufacturing, and supply chain management in unconventional environment. The emerging theory should not only guide the design of the proposed supply chain assessment methodology but also provide a conceptual lens through which practitioners and researchers can better understand and address the distinctive challenges posed by in-space manufacturing.
3. Evaluation and Validation. The research path was objected of a review, that emphasized it could benefit from a high level point of view. The research suggests that a wide range of artifacts can be discovered by focusing directly on the ISM. However, it is important to avoid losing elements. Thus, the research group considered as an important step of the research path the study of the most general problem of manufacturing in unconventional environment. This analysis should lead to a methodology to assess the supply chain for manufacturing in an unconventional environment. To validate this methodology, an instantiation on the ISM is expected in the research path.
4. Iterative Improvement. Recognizing the evolution of knowledge about ISM, as an emerging research field, the research path embraces an iterative methodology. Initial designs and methodologies will be subjected to continuous feedback from experts in space exploration, supply chain management, and related fields. This iterative process aligns with the evolving landscape of space exploration and manufacturing technologies, allowing the research path to stay responsive to emerging challenges and advancements in the field.
5. Knowledge Contribution. The research path considered the opportunities from the knowledge sharing within the ISM research fields. To this intent, the research team identified 9 areas of contribution of the research path (Table 2).

The areas of contribution are input of the research path, by considering the supply chain from different points of view that emerged from the literature and sharing of knowledge in the research group.

The research group followed the guideline G1 (Initiate a DSR project) and, considering the RQ, then chose a specific strategy of DSR, that is "Build and instantiate artifact, adding to definitional or descriptive knowledge", because it starts from experts' knowledge, to provide contribution in terms of "Definitional (construct) or descriptive knowledge", often coupled with method [11].

Table 2: Areas of contribution of the research path

Area	Deployment for in-space manufacturing
Market Research [13]	Evaluate the existing supply chains for space-related materials and components. Identify potential suppliers for raw materials and necessary components for in-space manufacturing.
Technical Feasibility [14]	Analyze how the manufacturing process in space might affect the supply chain dynamics. Consider the adaptability of existing supply chain processes to support space-based manufacturing.
Infrastructure Requirements [15]	Assess the logistics and transportation requirements for shipping raw materials to space and bringing finished goods back to Earth. Evaluate the need for specialized storage and transportation systems to support the supply chain.
Cost-Benefit Analysis [16]	Include supply chain costs in the overall economic analysis, considering transportation, storage, and handling of materials at each stage. Evaluate whether in-space manufacturing provides cost advantages or disadvantages compared to traditional supply chains.
Regulatory Compliance [17]	Consider how existing international trade regulations and agreements may apply to the supply chain for space-based manufacturing. Address any regulatory requirements related to the transportation of materials to and from space.
Collaborations and Partnerships [18]	Identify potential partners in the supply chain, such as logistics providers, to optimize efficiency and reduce costs. Explore collaborations with companies experienced in space logistics and transportation. Engage with government agencies to address any regulatory aspects of the supply chain. Establish relationships with international partners to optimize global supply chain operations.
Risk Analysis [19]	Evaluate risks related to supply chain disruptions, including delays in material shipments or issues with transportation. Develop contingency plans to mitigate supply chain risks.
Testing and Prototyping [20]	Test the performance of supply chain processes in simulated space conditions. Conduct pilot projects to assess the effectiveness of the supply chain in supporting in-space manufacturing.
Environmental Impact [5]	Assess the environmental impact of the entire supply chain, from raw material extraction to end-of-life disposal. Implement sustainable practices in the supply chain where feasible.

Instantiation as secondary contribution. ISM research is missing any application, so already the definition of artefacts and knowledge constitutes a significant contribution to research. To follow the Guideline 2, the brainstorming session was structured and focused on expectations and concerns related to ISM. It covered the current and desired states in terms of technology, target market, and Intellectual Property Rights (IPR) strategy. An impact vs. effort analysis was conducted for ISM, comparing what is currently available to what is needed.

For the Guideline 3, the strategy identified focus group analysis as a suitable research method for studying ISM from a supply chain perspective. The definition of activities for the focus group was developed, identifying anticipated inputs and outputs. Guideline 4 led to a review of the research path draft, review it by adding the refinement of design principles through successive action research cycles. This brought to a deductive approach that suggested to work on a general methodology for unconventional environment, and to instantiate the methodology for unconventional environment to ISM context.

4. Results and future directions

As a result, the research group agreed on a three-phase research path to assess the supply chain in space manufacturing. The research method should be followed by a focus group activity.

Phase 1: Establishing objectives and developing agreement on terminology

In this phase, the focus group engage in an in-depth discussion to define the objectives of the study and develop a collection of terms to analyze the supply chain in unconventional environments. With terms we should consider not just lemmas, but conceptual elements to describe the supply chain, and the environment. The terms should be robust and adaptable, ensuring its applicability across diverse scenarios related to supply chain modifications. The output of phase 1 is consensus about terminology, boundaries, knowledge expected for the use of the final methodology, outcomes in terms of added knowledge, and applicability. This output could benefit of the identification of a supply chain reference model.

Phase 2: Defining the methodology building upon the agreed-upon objectives

The focus group dedicates the second phase to defining a comprehensive methodology. This involves structuring a systematic approach that considered the complexity of supply chain dynamics, with a specific focus on the unique challenges posed by unconventional environments. In addition, the importance of data transmission and cross-organizational collaboration between Earth and space is emphasized. The methodology is designed to be robust and adaptable, ensuring its applicability across diverse scenarios related to supply chain modifications. The output of phase 2 is a methodology to assess the opportunity of production in unconventional environment considering the supply chain perspective.

Phase 3: Instantiating the methodology for in-space manufacturing

In this phase, the focus group instantiates the developed methodology to a specific unconventional environment, that is, in-space manufacturing. This step included adapting and tailoring the methodology to the characteristics of the space environment, considering factors such as reduced gravity, limited resources, and the unique challenges associated with extraterrestrial production. Through this process, the group gained valuable insights into how the methodology changes in a real-application scenario, refining it for future validation on real-case production. The output of phase 3 is the instantiation on ISM of the methodology of phase 2, to validate the research methods, and obtain an ISM assessment tool for ISM considering the supply chain perspective. Further research direction of this work could be to identify relevance among the nine areas of contribution of the research path through multicriteria decision-making approaches. Moreover, the focus on interoperability provides a foundational perspective for future research aimed at overcoming logistical and informational barriers in space-based manufacturing. This study aims to support the sustainable and circular transition in the space that inevitably relies on the exchange of information between different know-how (academic, entrepreneurial) and the role of informal factors essential for transferring the knowledge of individuals to the knowledge of an organization in a unconventional environment.

Acknowledgements

This study was carried out within the MICS (Made in Italy – Circular and Sustainable) Extended Partnership and received funding from the European Union Next-Generation EU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.3 – D.D. 1551.11-10-2022, PE00000004). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

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