INTERNATIONAL DESIGN CONFERENCE - DESIGN 2024
https://doi.org/10.1017/pds.2024.26

Exploring space manufacturing: designing a lunar factory for space-bound products in the new space economy

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Abstract

This study proposes a Moon-based factory for space-bound products, aiming to revolutionize space exploration through In-Space Manufacturing (ISM). It defines key elements for lunar manufacturing by adapting Earth-based factory models to lunar conditions.

Keywords: additive manufacturing, systems engineering (SE), complex systems

1. Introduction

Space has historically served as a fertile ground for pioneering ideas, initially led by governments and major telecommunications entities, evolving with the entry of private enterprises. This sector, integral to business, ushers in a new era of societal evolution (UPO, 2018). The concept of commercial space endeavours and colonies is now closer to reality due to advancements in cost efficiency and technology. The space economy is at a critical juncture, with In-Space Manufacturing (ISM) positioned as a transformative trend, capable of revolutionizing space system design by facilitating the production of goods and materials directly in space, thus bypassing the expensive and resource-intensive Earth-to-space transport (K. Nieman., 2022). A significant advantage of ISM is the accessibility to vast solar system resources, with Earth currently utilizing a minuscule fraction of the Sun's output. As aerospace technology progresses, exploiting these resources becomes economically feasible (R. G. Clinton, 2016). ISM's "just-in-time" production model reduces the need for large spare parts inventories, lowering costs and simplifying inventory management. Coupled with In-Situ Resource Utilization (ISRU), which involves using local resources for production, ISM could significantly lessen dependency on Earth, promoting sustainable extra-terrestrial human presence (I. A. Crawford, K. H. Joy, and M. Anand, 2014; E. J. Faierson and K. G. Logan, 2012). This synergy has the potential to enhance commercial space products and services, enable in-situ repairs, and reduce mission costs. Additive manufacturing could eliminate design constraints related to geometry, enabling more affordable and risk-averse missions.

However, integrating ISM poses challenges, including adapting manufacturing equipment for space conditions and selecting appropriate processes and scales. This requires a close relationship between equipment design and component selection (T. McKendree and R. W. Hall, 2005). Advanced manufacturing in space may require substantial computing capabilities, making Earth-based computation for control and backup essential due to cost and practicality considerations.

Acknowledging these challenges is crucial for ISM's integration and alignment with technological developments. The current gap in sustained beyond-Earth manufacturing needs strategic solutions to transition from concept to reality. ISM and assembly technologies (ISA) could soon facilitate the creation of space infrastructure, enhancing space exploration and manufacturing (Z. Xue et al, 2021). This study proposes a space-based factory layout for space-bound products, leveraging unique space conditions like microgravity and the absence of an atmosphere to produce otherwise unattainable materials on Earth. Integrating ISM with recycling and ISRU promises a sustainable approach to space production (Andrew C. Owens and Olivier L. de Weck, 2016).

This study specifically examines lunar habitats as the setting for a space-based manufacturing facility due to local resources, a constant gravitational field, ample space, and environmental stability, factors that collectively deem the Moon as the prime candidate. This choice allows us to harness ISM's full potential for space-intended products. By conceptualizing a lunar factory, we aim to bridge the existing manufacturing gap and gain a thorough understanding of its structure and operations. Such a facility would be tailored to meet the unique challenges and leverage the opportunities of space manufacturing.

2. Research approach

The transformative potential of ISM has become increasingly apparent. However, despite this promise, there is a notable absence of scalable commercial manufacturing endeavours in space at present. While a variety of products have been demonstrated as proof of concept, there has been little significant repetition or expansion of these operations, highlighting the need for further research to fully exploit the potential of ISM. Consequently, this study aims to address this gap in existing literature by proposing a tailored factory configuration specifically for ISM. To accomplish this objective, a systematic literature review has been used to establish the theoretical framework of ISM, through the investigation of the following research questions:

RQ1: What are the diverse advantages associated with space manufacturing?

RQ2: How can the utilization of these advantages be optimized effectively?

Following the analysis of these research questions, the aim of this research was to develop a framework that underscores the crucial areas and functions to be considered within a manufacturing factory situated on the Moon. This framework will provide a guiding paradigm for organizations intent on transitioning their production operations to space.

Model conceptualization

The section dedicated to model conceptualization seeks to address RQ1. A methodical approach has been adopted to guarantee a comprehensive evaluation, which includes academic publications, scientific papers, technical reports, and archive documents. A systematic review was conducted using Scopus with the objective of identifying the existing realities and initiatives that are driving the development of the ISM sector. Scopus was selected as the primary source of information for this purpose, employing customized search strings. The initial string was centred on products fabricated in space for space applications, specifically spare parts: *TITLE-ABS-KEY (space AND manufacturing AND spare AND parts) AND PUBYEAR > 2000 AND PUBYEAR < 2024 AND (EXCLUDE(SUBJAREA, "ENER") OR EXCLUDE(SUBJAREA, "CENG") OR EXCLUDE(SUBJAREA, "ARTS")).*

The objective of the search was to identify articles that discuss the production of components, assemblies, or spare parts in space (Lunar, Low Earth Orbit, Geosynchronous Orbit), while excluding articles from subject areas that are not pertinent to the research scope. Moreover, to emphasize recent advancements and insights, the research was intentionally confined to articles published since 2000. This deliberate time frame selection was driven by the need to base the analysis on more concrete studies and up-to-date research. Notably, earlier investigations often viewed ISM as too speculative and distant from practical realization. In this way, the refined research approach resulted in the identification of 57 relevant articles. A meticulous screening process was conducted, involving an initial examination of titles followed by a detailed analysis of abstracts. Employing a color-coded classification (red, yellow, green), articles were assessed based on their importance and relevance to the overarching research objectives. The classification process centered around two key parameters:

- Alignment with the research topic: determining whether the topics covered in the articles relate to the research question under examination.
- Level of technical specificity: evaluating the extent to which the articles delved into technical details and specialized concepts. Articles providing qualitative information about the context under analysis without delving into specific use cases were prioritized.

The authors employed this ranking system, and the resulting outcomes were subjected to rigorous comparison and discussion. This iterative process led to the selection of 6 papers deemed highly relevant, technical, and crucial to the field of space manufacturing. Subsequently, snowball sampling was used to detect additional relevant publications, resulting in the 17 documents presented in this paper.

Model development and validation

To answer RQ2, the establishment of a space-based manufacturing factory dedicated to the production of products intended for space applications was hypothesized. This hypothesis is intricately tied to insights garnered during the conceptualization phase of the model. indeed, the analysis revealed a notable gap — despite the considerable potential of ISM, no operational manufacturing currently exists in space. Consequently, the proposed solution involves the creation of a space factory, strategically designed to maximize the benefits of ISM and effectively address RQ2. Prior to model development, the lunar environment was selected as the location for the factory due to the potential to harvest substantial amounts of energy through solar power, and accommodating larger manufacturing structures, a condition largely constrained by the capacity of the launch vehicle on Earth. A significant contribution influencing this research was the book "Project Management in Manufacturing and High Technology Operations" (A. B. Badiru, 1996), which facilitated the identification of key aspects necessary for a lunar production facility. Additionally, insights from earlier literature facilitated the identification of various categories and variables. After meticulously defining the crucial operational procedures for the facility's success, it became possible to develop a model outlining the foundational structure of a lunar manufacturing facility. This model can be deemed heuristic as it aims to provide a structured framework and guidelines for the design of a lunar facility. Its heuristic nature stems from the fact that it is not grounded in a complete set of data or real-world applications but recognizes the continuously evolving specificity of the lunar manufacturing environment. The final step involved the application and validation, which was accomplished through an interview with an expert in the aerospace industry. The interview was instrumental in merging the author's analytical viewpoint with the expert's technical and domain-specific knowledge, resulting in a more robust and comprehensive understanding of the topic. The interview was dedicated to evaluating and determining the optimal factory configuration tailored to the specific product intended for production in a lunar facility. The ultimate aim was to provide a thorough set of guidelines that a manufacturing company can depend upon when transitioning its production processes to the lunar environment. This interview was conducted using the Google Meet platform for an initial call, followed by an in-person meeting.

3. State of the art

The establishment of a manufacturing facility on the Moon would be a transformative event, serving as a nexus for advanced space exploration and exploitation. Embracing circular economy principles, this facility would utilize the Moon’s unique environmental features—its abundant solar energy, suitability for large-scale constructions, and the low gravity environment (16.6% of Earth’s). These features could facilitate unprecedented manufacturing processes, extending beyond our current capabilities and redefining the technological limits of space industry.

The Moon's regolith is rich in Helium-3, an isotope scarce on Earth yet abundant on the lunar surface, which could potentially serve as a clean and efficient fuel for nuclear fusion reactors, potentially revolutionizing energy generation (H. Benaroya, 2017). Additionally, the potential presence of H20 beyond the permanently shadowed regions can be exploited, through electrolysis, to produce hydrogen and oxygen, critical for rocket propellants and life support systems, respectively. This underscores the Moon's role in fostering self-sustaining space habitats and long-duration missions, fundamentally advancing the state-of-the-art in space exploration logistics.

NASA's intent to decommission the International Space Station (ISS) by 2031 (S. Kuthunur, 2023) marks a pivotal shift in space infrastructure, creating a vacuum that could be filled by commercial and international space facilities. This paradigm shift opens up substantial opportunities for private-sector innovation, potentially accelerating the development of commercial space platforms (J. Dinner, 2022).

These platforms are envisioned to circumvent the limitations of terrestrial manufacturing, such as Earth's significant gravitational constraints, resource depletion, and complex supply chains, thereby catalyzing the evolution of the space industry and promoting the synthesis of novel materials and manufacturing techniques tailored for space conditions (S. Kuthunur, 2023).

In the comparative analysis of potential locales for such a facility, the Moon distinctly outshines Low Earth Orbit (LEO) for several strategic reasons. The consistent lunar gravity simplifies many manufacturing processes when compared to the challenges presented by the microgravity conditions in LEO. Although the Moon is more distant than LEO, it offers closer proximity than further celestial bodies such as Mars, easing the logistical complexities associated with the transport of resources, equipment, and personnel. The implications of this are significant for the state-of-the-art in space logistics and infrastructure development, as the Moon could serve as a more practical and efficient springboard for deeper space missions (P. Zhang et al., 2023). Moreover, the Moon's surface allows for the construction of expansive structures, uninhibited by the spatial constraints of orbital platforms. The lunar environmental conditions, though harsh, present a more predictable and stable backdrop compared to the dynamic environment of Earth's orbit. This aligns with the strategic objective of achieving sustainable, long-term exploration endeavors, diminishing Earth-reliance, and enhancing the cost-efficiency of space missions. These considerations are reinforced by the ongoing Moon Village initiative, which encapsulates a global vision for collaborative space exploration and utilization (J. Woerner, 2017). Such international initiatives not only foster cooperation but also bolster the commercialization of space, offering a sustainable path forward for lunar industrialization.

In analyzing the feasibility of a lunar factory, it is crucial to consider the variety of products that could be manufactured in space. This involves a comprehensive examination of product-specific requirements, enabling the design of a facility optimized for space conditions. In-space manufacturing (ISM) is bifurcated into products intended for Earth's markets and those designed for use within the space environment (E. Kulu, 2022). The manufacturing of space-bound products can leverage the benefits of microgravity, such as the minimization of forces that could affect precision assembly and material quality (Crane. K. et al, 2017). For instance, the production of fiber optics in microgravity leads to fewer defects than those produced on Earth, highlighting the unique advantage of space manufacturing and its impact on the state-of-the-art in materials science. Manufacturing for space-use can also bypass the considerable costs and risks associated with transporting goods from Earth, as demonstrated by the significant investments in developing the capability for in-space production of spare parts and repair equipment (S. S. Schreiner, 2015). This approach is anticipated to be a linchpin for future long-duration missions, enabling on-the-spot manufacturing which is a leap forward in space mission autonomy.

Additionally, the use of advanced technologies such as 3D printing in zero-gravity conditions allows for the construction of complex geometries with optimized material use, which is not possible under Earth's gravity. This advancement is not merely theoretical but has been increasingly demonstrated on the ISS and is set to be a cornerstone within the proposed lunar factory, thus driving the next wave of innovation in manufacturing processes (All3DP, 2023). Additive manufacturing also offers a shift in logistics, enabling on-demand production of parts, which could significantly diminish the mass and volume constraints of space missions by eliminating the need for large, pre-manufactured spares inventories (M. Moraguez and O. De Weck, 2020).

Prioritizing the development of products and technologies for space use aligns with the strategic focus of the study, laying the groundwork for the burgeoning field of space-based enterprises and high-value production. This focus directly impacts the state-of-the-art by setting a precedent for the commercial viability and scalability of space manufacturing operations, heralding a new era of space industrialization.

4. Model development

The upcoming section consolidates the insights gained from the preceding chapters and constructs a comprehensive blueprint for the lunar factory, referred to as the Lunar Manufacturing Environment (LME). To achieve this, a foundational source was indispensable in shaping the model's structure: "Project Management in Manufacturing and High Technology Operations" (A. B. Badiru, 1996). The initial chapter of the book, titled "Manufacturing Systems Analysis," offers a thorough exploration of the manufacturing process. It delineates the key divisions and, in a broader sense, the functional domains that define a typical earth-based manufacturing plant. This further analysis was conducted since, to conceptualize an effective manufacturing facility in space, it is crucial to begin by studying real-world examples, which, given their absence in space, require research on Earth-cases. Thus, given the recognition of the potential of ISM it was necessary to establish correspondences with Earth-based manufacturing practices. The concepts presented in the book have then been merged with the insights acquired from the previous literature review, enabling the definition of the crucial aspects to consider in the design of the factory, carefully taking into account the environment and the related conditions in which the facility is located. Subsequently, a structured framework was developed by initially identifying the principal departments considered essential for the facility:

- Research & Development: Focuses on new techniques and materials.
- In-situ Resource Exploitation (ISRU): Dedicated to extracting and processing lunar resources.
- Recycling Department
- Procurement & Logistics: Manages imports from Earth and distribution on the Moon.
- Manufacturing and assembly: Houses manufacturing technology and assembly.
- Quality Assurance: Ensures all products meet standards.
- Sales & Distribution: Manages customer relations and deliveries.

It is imperative to recognize that divisions such as Research & Development, Procurement and Logistics, Production and Assembly, Quality Assurance, and Sales and Distribution are foundational to the terrestrial manufacturing paradigm, essential for any manufacturing facility's efficiency, regardless of location. Conversely, the integration of In-Situ Resource Utilization (ISRU) and Recycling has been considered to address the spatial dimension (Andrew C. Owens and Olivier L. de Weck, 2016). Thus, operational procedures for the factory were iteratively developed, defining application alternatives for aspects including material acquisition (ISRU or Earth-sourced), processing, design and prototyping (using CAD), manufacturing and assembly, quality testing and assurance, and distribution. An analysis of key technologies for the lunar factory followed, scrutinizing various 3D printing technologies (All3DP, 2023), such as Material Extrusion (MEX), Vat Polymerization (VAT), Powder Bed Fusion (PBF), Material Jetting (MJ), Binder Jetting (BJ), Directed Energy Position (DEP), and Sheet Lamination (SHL). This analysis extends from Earth-based factory paradigms to insights from ISM research. The formulated heuristic model (Table 1) offers structured overview for designing a lunar factory, providing a practical foundation for space manufacturing ventures. The goal is to reliably examine factors crucial for transitioning production to the lunar environment.

Table 1. Organizational framework of LME

Departments	Operational Procedures	3D Printing Technologies
R&D focuses on new technologies and materials	Material Acquisition: ISRU or Earth-sourced	Material Extrusion
ISRU: dedicated to extracting and processing lunar resources	Material Processing: conversion of raw materials into useable forms	VAT Polymerization
Procurement and Logistics: manages imports from earth and distribution on moon	Manufacturing: production of a final product	Powder Bed Fusion
Quality assurance: ensures all products meet standards	Quality Testing & Assurance: testing for durability, efficiency, safety, etc.	Material Jetting
Sales & Distribution: manages customer relations and deliveries	Distribution: getting the product to the end-user	Directed Energy Deposition
Recycling Department		Sheet Lamination

LME represents a ground-breaking vision to establish a state-of-the-art factory on the Moon. The objective of the LME is to unlock the possibilities of extensive production within a microgravity environment, becoming a key element in supporting launch operations from the Moon and providing resources, maintenance, and operational support for deep space missions. Upon examination of the identified literature (Table 2), a lunar factory should consider the following aspects: **Manufacturing Technology** evaluates the most suitable 3D printing technology for lunar operations, guided by the specific properties of the product being manufactured, such as its input material, strengths, and weaknesses (All3DP, 2023). **Material Acquisition Strategy** involves an analysis of techniques for obtaining the necessary raw materials for production. It is essential to assess situations when relying solely on In-Situ Resource Utilization (ISRU), a technique for obtaining and refining lunar resources, or situations in which it is necessary to use materials sourced from Earth (E. J. Faierson and K. G. Logan, 2012). **Assembly Line Configuration** makes decisions on the most efficient assembly line setup, depending on the nature of the production process. It's crucial to determine whether integrating robotics and automation within the lunar facility is advantageous for ensuring proper assembly or if astronauts' presence is needed based on the specific requirements of the production process (Z. Xue et al, 2021). **Structural Design** considers the optimal structural configuration for the lunar facility, critical for functionality and longevity. It takes into account the needs for astronaut presence, lunar-specific conditions like lunar gravity, radiation shielding, and thermal management. It determines whether the integration of the inflatable shell, crucial for human safety, is required or if relying solely on the regolith outer part is sufficient (E. J. Faierson and K. G. Logan, 2012). Below is outlined a reference framework for selecting the ideal factory configuration according to the specific situation.

Table 2. Organizational framework of LME

Manufacturing Technology	Material Acquisition	Assembly Line	Structural Design
Material Extrusion - Vat Polymerization - Powder Bed Fusion - Material Jetting - Binder Jetting - Directed Energy Position - Sheet Lamination	In-Situ resource utilization (ISRU) - Earth-sourced - Hybrid	Robotic - Human based - Hybrid	Regolith outer part - Composite structure (regolith part + inflatable shell)

Then, the structural configuration of the LME was analysed, and the solution is represented by an inner inflatable module, which provides the pressurized shell for the breathable environment of the habitat, and the outer part of the outpost being 'printed' with Moon regolith by a rapid prototyping system (V. Colla and E. Dini, 2013). This choice is supported by several factors such as its inherent strength in tension, its ability to facilitate the integration of outer and inner parts, and its avoidance of introducing bending moments. However, in scenarios of a fully automated production process, with production lines functioning autonomously and requiring no human interaction, the inclusion of such an outer regolith shell would be unnecessary. With such a high degree of automation, the facility achieves comprehensive self-reliance, obviating the need for radiation shielding to accommodate human operators. In this context, human monitoring could be conducted remotely from a centralized location, facilitated by specialized monitoring systems. Regarding the layout design of the facility, four basic layout types have been identified: fixed-position, process, manufacturing cell and product layout. The optimal choice for the space-based factory with a primary focus on 3D printing of components leans towards the process layout. This decision is grounded in the distinctive demands and capabilities associated with additive manufacturing using 3D printing technology. The process layout, characterized by grouping similar processes or functions together, aligns seamlessly with the inherent flexibility and versatility of 3D printing. By clustering machines and resources in accordance with processing similarities, the process layout supports the production of diverse components without compromising efficiency. Then, Spare parts and in general support components, have been selected as a suitable example to delve into discussions regarding LME's production initiatives. The selection of this specific product is driven by the need to minimize the logistical mass of spare parts for extended space missions, there's a need to transition from the conventional Earth-based resupply model to a novel approach known as on-demand manufacturing (ODM) of spare parts. The analysed departments include the Research and Development department, in charge of exploring advanced production processes, cutting-edge technologies, and innovative materials; an ISRU (In-Situ Resource Utilization) department, primarily focused on lunar natural resource excavation, transformation, extraction, storage, conversion, and utilization technologies on the Moon; The recycling department responsible for recycling and repurposing materials sourced from decommissioned equipment and available on the lunar surface, enabling the establishment of self-sustaining closed-loop system (Andrew C. Owens and Olivier L. de Weck, 2016); the Logistic department which plays a pivotal role in overseeing diverse tasks essential for the production of components; the Manufacturing department, defined by the adoption of 3D printing technology for an innovative and effective production; the Quality assurance department, that delineated guidelines for ensuring the safety and sustainability of production processes in the lunar environment; the Sales and Distribution department, for overseeing crucial aspects of customer interactions and product deliveries (A. B. Badiru, 1996). Then, the essential procedures that are central to the operational management of the LME have been taken into account: Material acquisition, involving the evaluation of options between utilizing ISRU (In-Situ Resource Utilization) or Earth-sourced materials; Material processing, to efficiently process lunar materials and create essential components; Design & Prototyping, which utilized Computer-Aided Design (CAD) software to digitally design components and then printing them; Manufacturing and Assembly, that requires fabrication, assembly (which can be Human-based or Robotic), and integration; Quality testing and Assurance, to ensure that all materials, processes, and products adhere to the established standards and specifications; Distribution, responsible for leveraging sophisticated distribution system tailored to the factory customer base, the companies utilizing the lunar facility for their own production. Finally, the model explores in depth the array of technologies integral to the lunar factory's operations (All3DP, 2023): Material Extrusion; Vat Polymerization; Powder Bed Fusion; Material Jetting; Binder Jetting; Directed Energy Deposition; Sheet Lamination.

4.1. Model application and validation

In this section, the preliminary validation process of the previously developed framework is detailed, following the outlined methodology. To validate the model, the authors interviewed with an expert operating within the aerospace industry, namely a researcher associated with NASA. Leveraging the interviewees' expertise, the authors integrated analytical perspectives with specialized knowledge required for the model. The interview, conducted in two phases, involved introducing the framework and validating it through discussions on specific use-case scenarios, considering the expert's domain knowledge and NASA experience. Through this collaborative effort, a more robust and well-rounded understanding of the theme was achieved. The ultimate goal was indeed to provide a comprehensive set of guidelines that a manufacturing company can rely upon when transitioning its production processes to the lunar environment. The interviewee analysed the developed model and used it as a guide for making decisions regarding the key variables previously identified: Manufacturing Technology, Material Acquisition Strategy, Assembly Line Configuration, and Structural Design. To enable informed decisions regarding the transition of the production to a lunar facility and to further reinforce the insights gained from the preceding sections, the interviewee introduced three use-case scenarios. The three use cases are presented in the figure below.

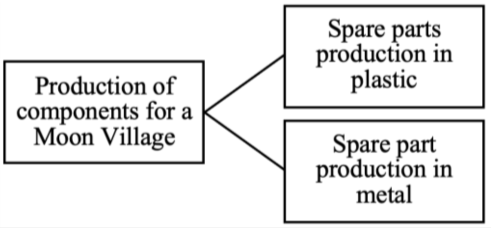

Figure 1. Proposed use case

The analysis began by considering the broader and more generic scenario, specifically, the components of the Moon Village. According to the interviewee, In-Situ production is particularly critical for the development of the Moon Village, given the current reliance on resupply models for space missions, which prove unsustainable for permanent human settlement on the Moon. Indeed, facilitating the production of components within the lunar factory would alleviate the existing constraints associated with the transportation of equipment and materials in space. The resulting outcomes allowed for the definition of the following choices according to the decision variables present in the model:

Table 3. Reference framework applied to the first use case

Manufacturing Technology	Material Acquisition	Assembly Line	Structural Design
Material Extrusion - Vat Polymerization - Powder Bed Fusion - Material Jetting - Binder Jetting - Directed Energy Position - Sheet Lamination	In-Situ resource utilization (ISRU)	Hybrid	Composite structure (regolith part + inflatable shell)

Subsequently, this provided a starting point to delineate two more detailed use cases, enabling a more practical application of the model: Plastic Spare Parts and Metal Spare Parts. The final facility configurations for the identified use cases are presented in the following figures. The former pertains to the scenario involving the production of spare parts in plastic, while the latter corresponds to the use case involving the production of spare parts in metal.

Table 4. Reference framework applied to the second use case

Manufacturing Technology	Material Acquisition	Assembly Line	Structural Design
Material Extrusion	In-Situ resource utilization (ISRU)	Hybrid	Composite structure (regolith part + inflatable shell)

Table 5. Reference framework applied to the third use case

Manufacturing Technology	Material Acquisition	Assembly Line	Structural Design
Vat Polymerization	Hybrid	Robotic	Regolith outer part

After establishing the optimal factory configurations for each usage scenario, the next step involved applying the model to a real product, specifically the lunar rover. The focus during the interview centred on a specific component of the vehicle: the wheels. This choice was influenced by numerous ongoing experiments in the manufacturing of rover wheels using 3D printing technology, utilizing more readily accessible materials such as polymers and metals. For this reason, the expert believed that the lunar factory could offer an opportunity to support and enhance this innovative practice. The discussion encompassed both plastic and metal wheel scenarios. For the pivotal variables, the expert reaffirmed the choices made for the two use cases previously analysed, specifying FDM 3D printing technology for polymer wheels and DMLS for metal wheels. Through the discussion and evaluation of these case studies, the expert confirmed the lunar factory's validity, as he recognized its alignment with the ongoing trends in the advancement of ISM.

5. Discussion and conclusion

The comprehensive investigation of the evolution of In-Situ Manufacturing (ISM), from its nascent stages in academia to its application within the aerospace industry, have been instrumental in shaping the model presented herein. By tracing the significant milestones marking ISM's evolution, it becomes evident that its influence extends beyond the aerospace sector, permeating various domains extending to the broader industry and humanity. This comprehensive understanding catalysed an integrative approach, merging the examination of ISM with an assessment of the prevailing terrestrial manufacturing framework and a meticulous analysis of the lunar environment. This shift in focus from context-specific space production to the establishment of a comprehensive production framework in space lays the groundwork for future human colonization beyond Earth. This integrative approach underscored the primary implications of ISM and addressing key issues such as resource utilization and permanent human expansion into space. It highlighted how advancements in ISM could revolutionize space exploration, redefining our understanding of industry, economy, and human habitation. Building on this holistic perspective, the primary contribution of this research is the development and validation of a comprehensive model bridging terrestrial and space-based manufacturing perspectives. This model serves as a valuable tool for organizations considering transitioning their manufacturing operations to space. The integration of these perspectives facilitated the definition of a space factory framework, referred to as the Lunar Manufacturing Environment (LME), a concept currently absent in the literature. This model makes a significant contribution to both theory, by defining the basis for the development of new research paradigms, and practice, by outlining the essential elements within a hypothetical structure of the facility. However, it is important to acknowledge that this model represents an initial phase which encompasses the fundamental elements for a lunar factory design. As the potential of ISM applications advances, several aspects warrant further exploration and research.

5.1. Limitations and future research opportunities

While the developed model significantly advances our understanding of the intricacies involved in transitioning manufacturing operations to space, it is essential to recognize certain inherent limitations. One such limitation is the model's focus on specific departments, whereas additional departments may be required for establishing a permanent human settlement on the Moon, based on production needs. The exploration of manufacturing technologies beyond 3D printing, such as traditional subtractive or CNC manufacturing, could potentially offer higher repeatability and precision. A more comprehensive cost-benefit analysis is also needed to fully comprehend the economic benefits of the Lunar Manufacturing Environment (LME) beyond the economic advantages associated with In-Situ Manufacturing (ISM). This analysis should consider the facility's overall impact and implications. Given the current utilization of on-demand manufacturing primarily for emergency situations, it becomes crucial to shift from this emergency-driven paradigm to a fully normalized and routine operational framework. This transition is key to establishing sustainable, self-sufficient space manufacturing systems that support long-term space exploration and colonization goals. Acknowledging these limitations not only points to areas for improvement but also opens up intriguing avenues for future research. By identifying these challenges, we can guide researchers into unexplored realms, fostering deeper investigation and enhancement of the current model. Addressing these hurdles will lead to a more comprehensive understanding of the complexities of space manufacturing, thereby actively contributing to the ongoing development of this pioneering field.

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 – DD 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.

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