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Manufacturing in Space: An Operations Management Nightmare

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ABSTRACT

Operations management (OM) involves the activities related to producing goods by transforming input into output. Operations managers typically organize the design of goods and manage the processes to ensure a quality product. Many of these processes also apply to the future production of goods in space. Space resources are enablers for space travel and life on other bodies, but they must be processed from raw material to a finished good that can be used. Using terrestrial OM processes, we can imagine the procedures and processes needed to operate production plants in space. Some critical issues will be interoperability, sustainability, and high-quality control, but many other OM factors must be considered and explored.

Keywords: Space; Operations; Manufacturing; In-situ resource utilization operations.

INTRODUCTION

Malshe *et al.* (2023, p. 24) stated, "Sustainable human existence in space requires robust infrastructure to support survival and growth." Currently, space operations rely on material produced on Earth and lifted into orbit, a very costly process (Malshe *et al.* 2023). Operations management will be crucial in future building and running space-based manufacturing. Space's challenges and unique conditions require careful planning, coordination, and optimization of various processes to ensure successful and efficient manufacturing operations. Space resources are enablers for space travel and life on other celestial bodies, but they must first be mined and processed. Operations management (OM) is the activity of producing goods by transforming input into outputs (Heizer *et al.* 2020). Operations managers typically deal with organizing the design of goods and managing the processes to ensure a quality product can be produced at the right price point. Many of these OM processes also apply to the future of in-space manufacturing (iSM).

It is predicted that widespread manufacturing will be conducted in space by 2035 (Bruno 2021). Initially, the demand for supplies will support exploration and manning of operations in Earth orbit, on the Moon, or Mars. However, future demand will also be needed to produce fuel for a return-to-Earth orbit to support future space missions launched from Earth.

Future factories must be reliable, autonomous, and highly specialized; however, this is difficult in harsh space environments and on extraterrestrial bodies. Fortunately, many of the same OM principles we use terrestrially can be used extraterrestrially, with some modifications. This research will explore the parallels between OM processes currently used on Earth and how they can be applied to manufacturing in space. This research will focus on producing goods for human consumption in extraterrestrial environments, mainly on producing goods on the lunar surface.

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A literature search based on iSM produced a very limited number of works in this area. Hence, this research is one of the first published studies on OM in space operations. As the demand for space resources increases, this will become an important area of research. Therefore, this research is the start of a growing body of literature.

Background

Operations management helps in optimizing the use of resources to maximize production efficiency and minimize waste. Heizer *et al.* (2020) outline ten strategic OM decisions (Table 1) critical to managing any operations, whether a service or a physical good. In the case of iSM, the goal will be the production of a physical good. While not all of these OM decisions will be critical in the early days of space production, as settlements are established on celestial bodies and the industry matures, they will all one day be necessary for the optimization of production operations.

Table 1. Ten strategic OM decisions.

Operations Management
Design of goods and services
Managing quality and statistical process control
Process and capacity strategies
Location strategies
Layout strategies
Human resources, job design, and work measurement
Supply chain management
Inventory management
Scheduling
Maintenance

Source: Adapted from Heizer *et al.* (2020).

A resource has value by its utilization. Humans have been designed to live on Earth, and most of us will stay here and never go to space. However, before permanent life on other bodies can be established, factories must be built and set up on these celestial bodies, or an alternative supply chain must be established. Table 2 outlines the main types of products that will be needed for space habitation.

Table 2. Products needed for space habitation.

Need	Use
Human consumables	Support basic needs of life (oxygen, food, water)
Manufacturing	Demand items and repair parts
Construction	Habitats and landing pads
Propellant	Refueling for travel
Scientific advancement	Tools needed to support research

Source: Elaborated by the author.

DISCUSSION

The priority for production will be to produce the materials necessary to support human life, such as oxygen, water, and food on the Moon's surface, which is the focus of this research. Initially, autonomous remote plants will have to be established to mine and produce oxygen and water to build an inventory large enough to support demand. It might take several years to build a large enough inventory to meet demand, depending on the technology used. During this time, no on-site human intervention would be possible. Just as on Earth, the first step in the process is prospecting for the needed raw materials using remote sensing and sample collection. Once a deposit is found, mining operations and refining can be conducted on-site. Next is the transportation of the raw material, most likely over a very short distance to the production factory for transformation into the finished goods and storage until needed. While there are many small steps in this process, each with its own technological complications, we will focus on the OM processes at a production plant on the Moon's surface.

Using Heizer *et al.*'s (2020) 10 strategic OM decisions, let us explore the type of considerations needed to run large-scale factories on extraterrestrial bodies.

Design of goods and services

The very first step is to fully understand demand fully. Some of the products that will be needed are energy, regolith, volatiles, metals, oxygen, and water. Contl (2021) estimated the demand for space exploration as follows: regolith 25%, energy 25%, engineering metals 16%, water 14%, oxygen 12%, other volatiles 7%, and platinum-group metals (PGM) at 1%. Water is key, since it can be converted to oxygen, and rocket propellant (fuel: liquid oxygen [LOX] and liquid hydrogen [LH2]) and energy to support local operations. It is estimated that propellant production on the lunar surface would cost about $ 500·kg as opposed to $ 36,000·kg if supplied from Earth (Vittorl 2021). Refueling in Earth orbit or on the Moon would also allow rockets departing the Earth to carry more payload since they can reduce the fuel needed at liftoff.

Recycling materials can reduce demand for products produced from raw materials through a circular economy process. This minimizes environmental impact, as we have seen on the Earth, and reuse is easier than *in-situ* resource mining.

Once the demand for goods can be determined, the process of designing and establishing a factory can begin, but first, let us look at the quality aspect of space factories.

Managing quality

The space industry has long understood the need to manage quality and reliability in space systems. The use of traditional high-reliability (HR) processes within the space industry has led to very few failures; however, there have been some notable ones, such as the Hubble Space Telescope mirror flaw (Newman 2001). Space is an extreme operating environment with harsh conditions. Machines must be designed and built to deal with these harsh conditions. If something breaks down, you cannot easily fix it, so all system components must be highly reliable. This is especially true if what is being produced is used to support life, such as oxygen or water. The traditional total quality management (TQM) processes focus on continuous improvements; however, changes to space factories are complex, if not impossible, to change once built. Since human presence will be limited or not feasible at the production location, methods to automate quality assessments will need to be developed to ensure the reliability of processes (Tang and Wu 2023).

Process and capacity strategies

Process strategies refer to the approach used to transform raw materials into goods, whereas capacity strategies indicate the production rate of a facility (Heizer *et al.* 2020). Most space-based manufacturing will fall into a product-focused process strategy since most factories will be built to perform one function, i.e., producing oxygen from regolith. However, 3D printing will be extensively used to make small quantities of demand items and repair parts. The design of these factories will need to be sized to meet projected demand since it is challenging to increase throughput. These continuous processes are best run at a steady pace, so demand for raw materials and production rates are easy to forecast. Terrestrial-based continuous processes tend to be more automated with limited human interaction, which is another advantage for space-based manufacturing. *In-situ* manufacturing will most likely occur in uncontrolled environments on a planetary body, so it will need to be designed to withstand these harsh environments (Norman *et al.* 2023).

Locations strategies

Location strategies typically address items such as government regulations, workforce, infrastructure, logistics, and customer and raw material locations. For our space-based factory, the last two will be the most critical. *In-situ* resource utilization (ISRU) is essential in obtaining raw materials for processing and reducing the cost of exporting materials from Earth (Malshe *et al.* 2023). Most likely, any space settlement will be located on the sunny side of space bodies since sunlight will be needed to produce electricity. However, water ice occurs in permanently shadowed regions or on the dark side of a space body (Honniball *et al.* 2022). Therefore, supply and demand may be some distance apart, which might require supplying electricity over long distances (from the sunny to the shadowed regions). Alternative power sources, such as nuclear, could be used to provide power on the Moon's dark side. Additionally, the finished goods (water for example) will be required to be transported to the location of demand (human settlement). Alternatively, a significant deposit of water must be found on the lit side of the Moon or other bodies, such as a mineral host of molecular water (Honniball *et al.* 2022). Either way, finding a location for a human settlement and the local source of raw material for water production will be critical to long-term space habitation.

Location strategies on extraterrestrial bodies will require a tailored approach based on local terrain and resource availability. Operations managers must carefully plan and adapt processes to efficiently locate, extract, and utilize resources, considering each site's unique conditions. This includes designing flexible and modular infrastructure to handle various terrains, implementing a sound logistics system for potentially long-distance transportation of materials, and ensuring that energy sources and machinery are suited to the operational constraints of the extraterrestrial environment.

Layout strategies

Layout strategies affect the long-term efficiency of an operation and focus on the competitive cost of production for a product. From a production point of view, in the short term, competition will not be an issue; however, as industries mature and the monetization of space takes the lead, competitive cost will someday play a role. But, in the short term, as outlined in the process strategy section above, space-based production will most likely be product-focused, which uses a continuous production process with very high machine utilization (Heizer *et al.* 2020). These factories will need to be modular in design for delivery from Earth and assembled on location (Norman *et al.* 2023). Product-oriented layouts allow for standardized production and rapid throughput, but any breakdown in the process stops the whole operation.

Human resources, job design, and work measurement

"The objective of a human resource strategy is to manage personnel and design jobs so people are effectively and efficiently utilized" (Heizer *et al.* 2020, p. 406). Space-based factories must be designed to operate with little human intervention; however, there will always be a need to keep humans in the loop. Employees running these factories will mostly be terrestrially based, with maintenance being conducted on-site either by robots or direct human intervention. Both terrestrial and extraterrestrial workers will need to be highly trained and technically competent. To maintain job satisfaction, a high level of responsibility and independence will need to be granted. However, they will need to be able to work in teams to solve problems.

Supply chain management

The concept of supply chain management is how many and which suppliers to source material from. For our space-based factory, the selection of suppliers will be critical during the terrestrial construction phase. Suppliers will need to be selected on the basis of technical competency; however, once the plant is established, the raw material mining and storage of the finished product will be fixed. Since the space-based factories will be process-focused, this process allows for the mass production of a single product, which can be produced in advance of demand and stored. The biggest risk is the failure of the factory, especially for critical, life-supporting products such as water and oxygen. Early on, it will be critical to have a backup, second factory, that can quickly come online in case of a failure of the primary factory. Alternatively, a supply of enough backup inventory that can be used until the primary factory can be fixed or replaced.

Inventory management

Typically, inventory management aims to balance inventory investments with customer demand. There is a cost to holding inventory, so a for-profit firm attempts to hold just enough to meet demand plus a little safety stock in case of a short-term failure in the supply chain. However, production and holding inventory to cover shortfalls are critical in space, especially for life-sustaining products. Demand will be very predictable, but not disruptions to the supply chain, so enough inventory will need to be held to cover any interruptions. On the front end of the process, raw material must be mined a very short distance from the processing plant, and inventory should be held close to the location of demand, human habitat in this case. However, this is easier said than done. Rewind to location strategies as discussed above, and most likely ISRU will have to be mined from different areas on the Moon, often distant from each other, so a robust transportation system will need to be established to move goods from distant production plants to the point of demand.

Scheduling

Scheduling typically deals with having the correct people and machines ready to produce a product in the correct sequence. Since large-scale space-based factories will be highly automated and designed to produce only one product, this will greatly reduce the need to schedule people and machines. However, until a significant number of humans occupy an extraterrestrial body, most operations will be controlled from Earth. Just as with terrestrial operations, operation control rooms will need to be established and staffed on Earth so the traditional staffing models can be used.

Maintenance

The harsh environment of space will require routine maintenance. The two most important issues with maintenance in running a space factory are difficulty in the ability to repair something and interoperability. At least in the early days of production on foreign bodies, factories will be uncrewed, so they must operate with little to no human intervention. The other issue is interoperability in space operations. It is critical that all space systems work together seamlessly. Therefore, a set of standards and protocols must be developed so that all systems can connect. This includes standards for power systems, propulsion, communication equipment, and scientific instruments. For humans to be able to survive and travel in space, there will be many providers of services, and all of the systems must be designed to work together. One of the techniques that can be used to improve maintenance is the use of a digital twin (Malshe *et al.* 2023). A digital twin of a factory will allow problem scenarios to be examined digitally on Earth before changes are made to the operating factory.

Smaller scale production

The above description focuses on the large-scale production of water and other mass-produced items required to support life in outer space. Smaller-demand items such as tools will most likely be produced using additive manufacturing, also called 3D printing. NASA proved this concept in 2014 using a zero-gravity printer on the International Space Station (Millard 2019). The production of such items will require some but not all of the OM principles described above.

On-orbit vs. manufacturing on a celestial body

So far, in this paper, the focus has been on manufacturing on celestial bodies, mainly focusing on the Moon. However, in the short term, iSM will occur on the Moon and in-orbit, with Mars to follow. It is important to recognize the differences between the two environments to address the operational challenges of iSM, on-orbit vs. a celestial surface. On-orbit manufacturing faces challenges such as microgravity, high radiation levels, and the vacuum effects on heat transfer, which can impact material properties and equipment operation (Millard 2019). Additionally, on-orbit manufacturing involves transporting raw materials from Earth or other celestial bodies to the orbiting station. In contrast, celestial surface manufacturing must contend with gravity, which aids some processes but hinders others. Other challenges include thin atmospheres, dust, and utilizing in situ resources like water, ice, and metals to reduce the need for material transport from Earth. Solar energy supply may be more unpredictable due to long nights or dust storms. However, this can be rectified with the use of nuclear power sources, but these have their own drawbacks.

Despite these differences, several general principles apply to both environments, as presented in the discussion section. Given the difficulty of repairs, high levels of quality, automation, and autonomy will be necessary to minimize human intervention and ensure reliability. Efficient resource use and recycling will also be critical for sustainability, and modular scalable designs with interconnectivity will be beneficial for facilitating upgrades and expansions to production plants. Table 3 provides an expanded comparison of factors that affect iSM for on-orbit manufacturing vs. lunar and martian surfaces.

Table 3. Factors affecting production in space.

Factor	On-orbit manufacturing	Lunar surface manufacturing	Martian surface manufacturing
Gravity	Microgravity	Low gravity	Moderate gravity
Radiation	High	High	Moderate
Resource availability	Transported from Earth	Regolith, water ice	CO_2, water ice
Energy supply	Solar, battery	Solar, nuclear/fission	Solar, nuclear/fission
Dust/regolith	Minimal	High, fine dust	High, coarser dust
Maintenance	Difficult in microgravity	Fine dust issues	Challenging due to dust storms
Logistics	High complexity	Moderate, proximity to Earth	High complexity, distance from Earth

Source: Elaborated by the author.

In the shorter term, manufacturing operations on the Moon and Mars present iSM challenges that need specific consideration. For the Moon, the primary issues include dealing with extreme temperature fluctuations, managing lunar dust (regolith), which is very fine, low gravity (17% of the gravity found on Earth), and leveraging the proximity to Earth for more frequent resupply missions (Broome n.d.; Davis 2017). On Mars, challenges include harnessing local resources such as CO_2 and water ice (currently of unknown purity), dealing with reduced gravity (38% of the gravity on Earth), and ensuring production equipment can withstand frequent global dust storms (Broome n.d.; Davis 2017). Operations managers must build strategies to address these environmental factors, focusing on developing resilient infrastructure, efficient resource extraction and utilization processes, and reliable life-support systems to ensure sustainable manufacturing operations in extraterrestrial environments.

CONCLUSION

This paper has focused primarily on producing goods on the Moon's surface; however, many of the same principles can be applied to the production on other celestial bodies and in orbit. The challenges of iSM will require a measured approach that leverages terrestrial OM principles while adapting them to the harsh and unpredictable conditions in which extraterrestrial production plants must operate.

This research highlights OM's role in space-based manufacturing and underlines the necessity of robust infrastructure to support a sustainable human presence in space. One of the primary operational challenges is the reliance on ISRU, which requires locating, mining, and processing local materials to produce life-sustaining materials such as oxygen, water, and fuel. This will require advanced prospecting, mining, and processing technologies that can operate autonomously in harsh space environments. The ability to design modular, highly automated factories that can withstand extreme conditions will be crucial for the success of iSM.

In conclusion, space manufacturing is a technical and operational management challenge. Applying well-established terrestrial principles to extraterrestrial manufacturing is a step forward in understanding how large-scale factories in space can be designed and operated efficiently. This research marks the start of a broader discussion on this future body of literature, highlighting, at a high level, the complexities and opportunities in the field of iSM. The insights provided here are hoped to serve as a foundation for future research and development, paving the way for sustainable human exploration and habitation beyond Earth.

CONFLICT OF INTEREST

Nothing to declare.

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Data sharing is not applicable.

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