An Empyrean Forge: Designing an in-orbit manufacturing system for starship production

by

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Abstract

Current manufacturing and space launches produce several challenges that must be remedied if space exploration is to continue to advance into the new age. By synthesizing a series of case studies and historical research, this paper has developed a system of operations and the beginnings of physical models of a process known as the Empyrean Forge (the "Forge"). By implementing a three-step chain, the Empyrean Forge strives to create a fully-automated, in-situ, spacecraft manufacturing protocol. The goal of this research is to provide the basis for this protocol by combining the harvesting of raw materials from celestial bodies, refining that material into feedstock, and then using that feedstock to print all components of a spacecraft equitable to or superior to the modern space shuttle. In doing so, financial, environmental, and manufacturing inefficiencies are resolved (or at least lessened), which would allow for faster and more effective development as the industry proceeds to enter Space 4.0.

Keywords: additive manufacturing, in-situ manufacturing, 3D printing, automated engineering, aerospace engineering

Table of Contents

List of Figures

List of Tables

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Dedication

This paper is dedicated to my wife, family, cats, and friends. Without their continued support, I would never have made it this far. Your tireless efforts in keeping me on track always pay out in the end. I love you all.

Chapter 1 - Introduction

1.1 Background

Space exploration is currently possible due to rockets and their ability to breach the atmosphere of Earth and reach the heavens. However, rocket launches are inherently stressful on the launch vehicle and its sub-systems due to the violent nature of the launches themselves. Fortescue et al. (2011) state that "Although a space vehicle spends the majority of its life in space, it is evident that it must survive the other environments for complete success" (p. 11). Due to this, a number of constraints are placed upon spacecraft and their systems that allow them to survive and continue to operate after the launch phase of the mission. Some of these factors are the severe acoustic environment, the launch acceleration, mechanical shock, thermal environment, atmospheric pressure environment, and electromagnetic interference (Fortescue et al., 2011, pp. 11-16). All of these can lead to mission failure caused by damage to critical systems or injury/death of human pilots if not properly mitigated or accounted for. These constraints, in combination with the financial costs of rocket launches, impose severe design restrictions on current and future spacecraft. While currently rocket launches cannot be avoided for the purpose of reaching space, a different approach to spacecraft manufacturing could allow for the creation of vehicles that would never have to endure the stresses and limitations of the rocket launch environment.

1.2 An Empyrean Forge

The Empyrean Forge is a place of manufacturing located in orbit, used to create space vehicles made with only the outer-space environment in mind and without the constraints imposed upon design by the traditional rocket launch environment. The name calls on a medieval word to describe the outer-space environment: "Empyrean", meaning "the highest heaven or heavenly sphere in ancient and medieval cosmology usually consisting of fire or light" (Merriam-Webster, 2024). This idea has a few names, as others have called it *In-Orbit Manufacturing* (IOM) or *In-Space Manufacturing* (ISM) but will be referred to as ISM in this thesis. Due to the environment of space and the inherent separation from Earth-based manufacturing, this approach is often seen as a lucrative solution to the restrictions of the space supply chain. It offers a way to fabricate and manufacture parts and components that traditionally are only manufactured on Earth and then launches into space. The particular use case this thesis will be researching will be the use of ISM to create space vehicles without the need to use the traditional methods of rocket launches and assembly of deployables in orbit with Earth-made payloads.

1.2.1 Methods of In-Space Manufacturing considered in this thesis

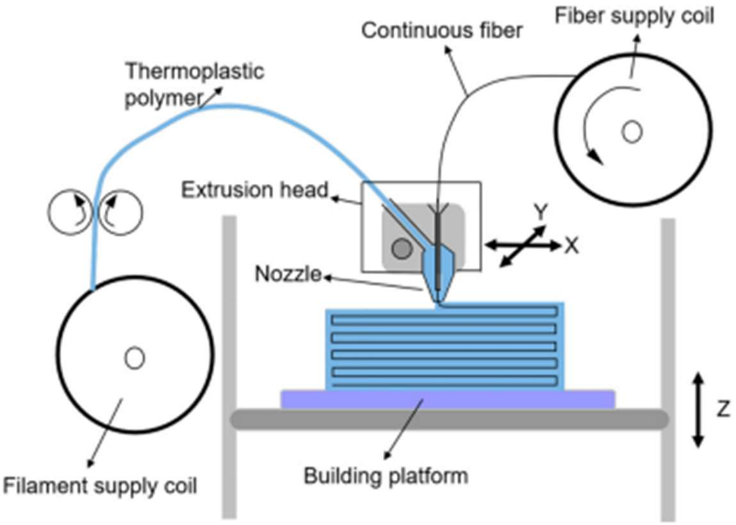
- Additive Manufacturing (AM): A method where three-dimensional (3D) parts are manufactured layer-by-layer using a 3D model of the part as a guide. This is also often referred to as 3D printing.
- Subtractive Manufacturing (SM): Methods where material is subtracted from the initial form by various methods such as drilling, boring, milling, and turning. There are additional methods such as water jet or laser cutting.
- Hybrid Manufacturing (HM): A mixed method system of manufacturing using both additive and subtractive manufacturing in the creation of objects.

1.2.2 Additive Manufacturing Methods

The method of AM is often first determined by the material of choice and the type of item that is being manufactured. In addition to the standard selection criteria, the environments of space have to be considered when choosing and developing AM methods for use. For example, a method that may be useful for a lunar-based manufacturing center may not be as useful in Earth orbit.

- Wire Laser Additive Manufacturing (WLAM): This method used a metal feedstock wire that melts with directed energy deposition (DED), in this case a high energy laser. WLAM also allows for more control in comparison to other methods of DED, enough to build medium or small features with near net shape characteristics (Casalino et al., p. 1, 2023). The metal feedstock wire is preferred over metal powders due to the effects of microgravity on powder deposition.
- Fiber Reinforced Fused Filament Fabrication (FRFFF): This method uses plastic filament that is melted and extruded around a continuous supply of fiber, such as carbon fiber or KEVLAR. Carbon fiber reinforced composites are a verified space material due to their structural stiffness and temperature resistance (Zocca et al, p. 10, 2022). A schematic of this can be seen in Figure 1.1.

Figure 1.1 Schematic of continuous fiber-reinforced composite 3D-printing and some 3D-printed composite components.



Note. From “Challenges in the Technology Development for Additive Manufacturing in Space” by Zocca et al, 2022, *Chinese Journal of Mechanical Engineering: Additive Manufacturing Frontiers,* 1(1), p. 11. CC BY-NC-ND 4.0

1.3 Automated Manufacturing

In order to properly manufacture ships of this size in orbit, it may be necessary to automate the majority of the manufacturing. To solve this, we look at terrestrial manufacturing lines to see what smart manufacturing processes and systems may be needed for an orbital manufacturing line. As with all systems, the more that is added to it, the greater the resources are needed for its operation: in spacecraft systems, this is often seen in the power and fuel requirements for a spacecraft. Though, at the end, if the vessel created in space is meant to be safe for humans to pilot and inhabit for extended periods of time, it must meet safety and quality standards of current spacecraft at a minimum.

1.4 Objectives and Scope of Research

A variety of systems are required for a spacecraft to function. These are including, but are not limited to: propulsion, structural, attitude control, electrical power, thermal control, and telecommunications (Fortescue et al. 2011). While in-orbit manufacturing could be used for some, if not all, of these systems, the primary focus of this research will be on the use case of in-orbit manufacturing of structural systems of spacecraft. The objectives of this research are as follows:

1. Perform a literature review to compile the current state of knowledge on the following relevant areas:
    a. Automated Manufacturing
    b. Additive Manufacturing in Space
    c. In-Situ Resource Usage in Space
2. Conduct numerical simulations of a logistical supply chain and product creation of AM manufactured spacecraft parts using Flexsim 2024.
3. Investigate the simulation results in comparison to current standards for spacecraft logistics in use today.

1.5 The Contents of this Thesis

Chapter 2 will consist of the literature review to establish the current base of knowledge regarding automated manufacturing, additive manufacturing in space, and in-situ resource usage in space. Chapter 3 covers the details of the manufacturing system model, and the simulation software used to run the model. In Chapter 4, the results of these simulations will be presented and discussed. Chapter 5 will cover the conclusions of this research and recommendations for future research in this topic.

Chapter 2 - Literature Review

2.1 Introduction

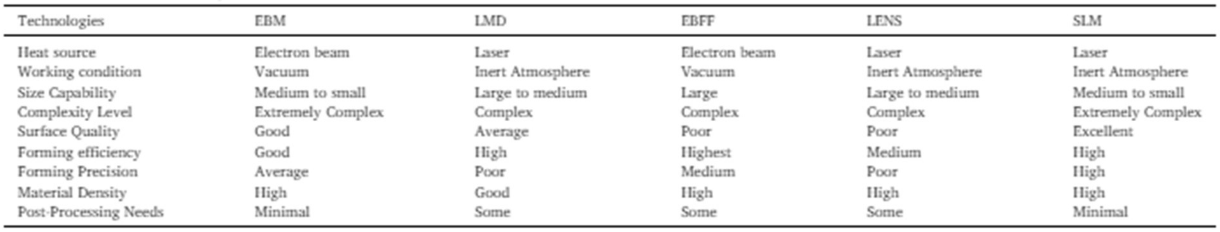
This research covers the intersection between three equally-important factors regarding space manufacturing. Processes and methods of automated manufacturing will be covered with the current research on Wire Laser Additive Manufacturing along with knowledge of how best to use in-situ resources for the purposes of in space manufacturing.

2.2 Metal Additive Manufacturing in Space

Noori Rahim Abadi et al. (2022) conducted a study using a modeling approach based on the feasibility of laser directed energy deposition (LDED) with a metal wire feedstock in a space environment. Their research found that the environment of space alters the melt pool and liquid metal bridge dynamics, resulting in the process stability being affected. However, with proper process control, it was concluded that LDED in a space environment using a metal wire feedstock could be used for manufacturing metal parts in a tempered atmosphere.

Taghizadeh and Zhu (2024) compiled a breadth of research on AM in space, with a specific focus on metal additive manufacturing (MAM). Their research focused on the different methods of MAM in comparison to the traditional polymer based fused filament fabrication. They highlighted the two major feedstocks used in MAM, powders and wire and determine that metal wire feedstock may fare better for space manufacturing efforts due to not needing a continuous flow of gas in microgravity that powder feedstock would require. In addition, the powder feedstock could result in variable contamination of the environment if not properly managed, whereas the metal wire could not present such a risk (Taghizadeh and Zhu, 2024, p. 405). In addition to the feedstocks, the researchers also compared and contrasted the major energy sources for directed energy deposition, laser based, and electron beam based. Finally, the researchers further reinforced the need for numerical modeling and simulation of these processes, as real-world options would be exceedingly expensive and wasteful. A table of the different characteristics of each method is shown in Figure 2.1.

Figure 2.1 Metal additive manufacturing specifications



Technologies	EBM	LMD	EBFF	LENS	SLM
Heat source	Electron beam	Laser	Electron beam	Laser	Laser
Working condition	Vacuum	Inert Atmosphere	Vacuum	Inert Atmosphere	Inert Atmosphere
Size Capability	Medium to small	Large to medium	Large	Large to medium	Medium to small
Complexity Level	Extremely Complex	Complex	Complex	Complex	Extremely Complex
Surface Quality	Good	Average	Poor	Poor	Excellent
Forming efficiency	Good	High	Highest	Medium	High
Forming Precision	Average	Poor	Medium	Poor	High
Material Density	High	Good	High	High	High
Post-Processing Needs	Minimal	Some	Some	Some	Minimal

Note: From “A comprehensive review on metal laser additive manufacturing in space: Modeling and perspectives” by Taghizadeh and Zhu, 2024, *Acta Astronautica,* 222, p. 406. CC BY 4.0

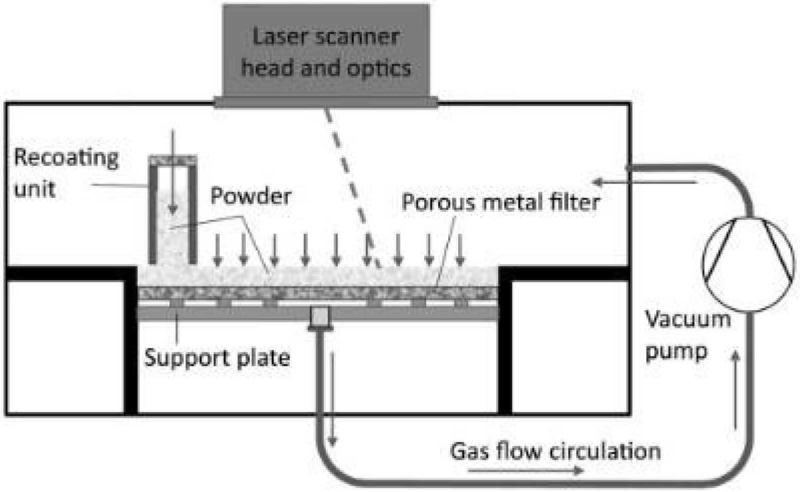
In their article, Kovalchuk et al. (2022) investigate the uses of electron beam metal 3D printing in space. Their process uses an electron beam generated by low-voltage gas-discharge electron beam guns combined with the wire feed to create directed energy deposition. They also mention the unique characteristics of their method, such as a nonstick deposition technique, surface glazing, and the recycling of metal waste directly into wire to be used again in AM (Kovalchuk et al. 2022, p. 6069). This technology is named xBeam, and some examples of products manufactured using xBeam can be seen in Figure 2.2.

Figure 2.2 Products for space applications, manufactured using the xBeam technology

Note: (a) dome with a cylindrical extension, (b) bracket blank, (c) honeycomb structure from “A Coaxial Wire-Feed Additive Manufacturing of Metal Components Using a Profile Electron Beam in Space Application” by Kovalchuk et al., 2022, *Journal of Materials Engineering and Performance,* 31(8), p. 6072. CC BY 4.0

Zocca et al. (2019) focus on the use of laser-beam melting of powder-based feedstocks. In order to compensate for the lack of gravitational force, they look at a gas flow throughout the powder bed. They state that this is because in a normal gravitational environment, gravitation would direct the flow of the powder and allow it to form a homogeneous layer. In addition, gravitation would stabilize the powder bed against outside forces such as vibration or the forces from the energy deposition itself, further clarifying that the gas used for circulation is critical to safe usage of metal 3D printing. Often, a nitrogen or argon atmosphere in the printing area is used to prevent oxidation of the material. However, in a high oxygen environment such as a space station, it could be catastrophic if the print area is not properly sealed, and its print area vented to be replaced by a gas such as nitrogen. A schematic of the powder deposition unit can be seen in Figure 2.3.

Figure 2.3 Schematic of the powder deposition unit.



Note: The area of the porous building platform for the powder deposition was 106.5 × 85.5 mm2. From "Enabling the 3D Printing of Metal Components in µ-Gravity" by Zocca et al., 2019, *Advanced Materials Technologies,* 4(10), p. 3. CC BY-NC-ND 4.0.

Blachowicz et al. (2021) review recent metal additive manufacturing technologies and the potential applications in space, with a focus on satellites and rockets. Their review mentions the drawbacks of current AM methods, such as surface roughness and insufficient mechanical properties, but highlights that these can be eventually fixed over time (Blachowicz et al., 2021, p. 10). In addition, they consider the need for specific AM process design—a design that considers all of the possibilities and limitations—rather than trying to fit them into our preconceived ideas of manufacturing. Furthermore, the parts themselves could also potentially be redesigned, as current parts can be over-engineered due to the launch methods or the current era. These parts, rather than trying to make new models fix around existing designs, should potentially be reimagined in a way to reduce not only mass but also development time and costs of several system components.

Mao Mao et al (2024) claim that the newest innovation of space manufacturing involves the pivotal role of 3D printing. However, due to the lack of actual development regarding printing in space, they identify several challenges: mass reduction, intricate component fabrication, and resource constraints. While acknowledging the existing challenges, they also highlight the constant improvements of such processes: for example, terrestrial experimentation prior to launch. There is a specific focus on environmental impact, noting the harsh atmospheric conditions that exist outside of terrestrial production; these include the vacuum of space, significant temperature differentials, and the impact of cosmic and solar radiation. Mao Mao et all go on to claim that 3D printing is a de facto "bridge of innovation", connecting existing strategies of high-pressure electrostatic driving forces in electrohydrodynamic printing to conceptual advancements in material deposition in microgravity environments.

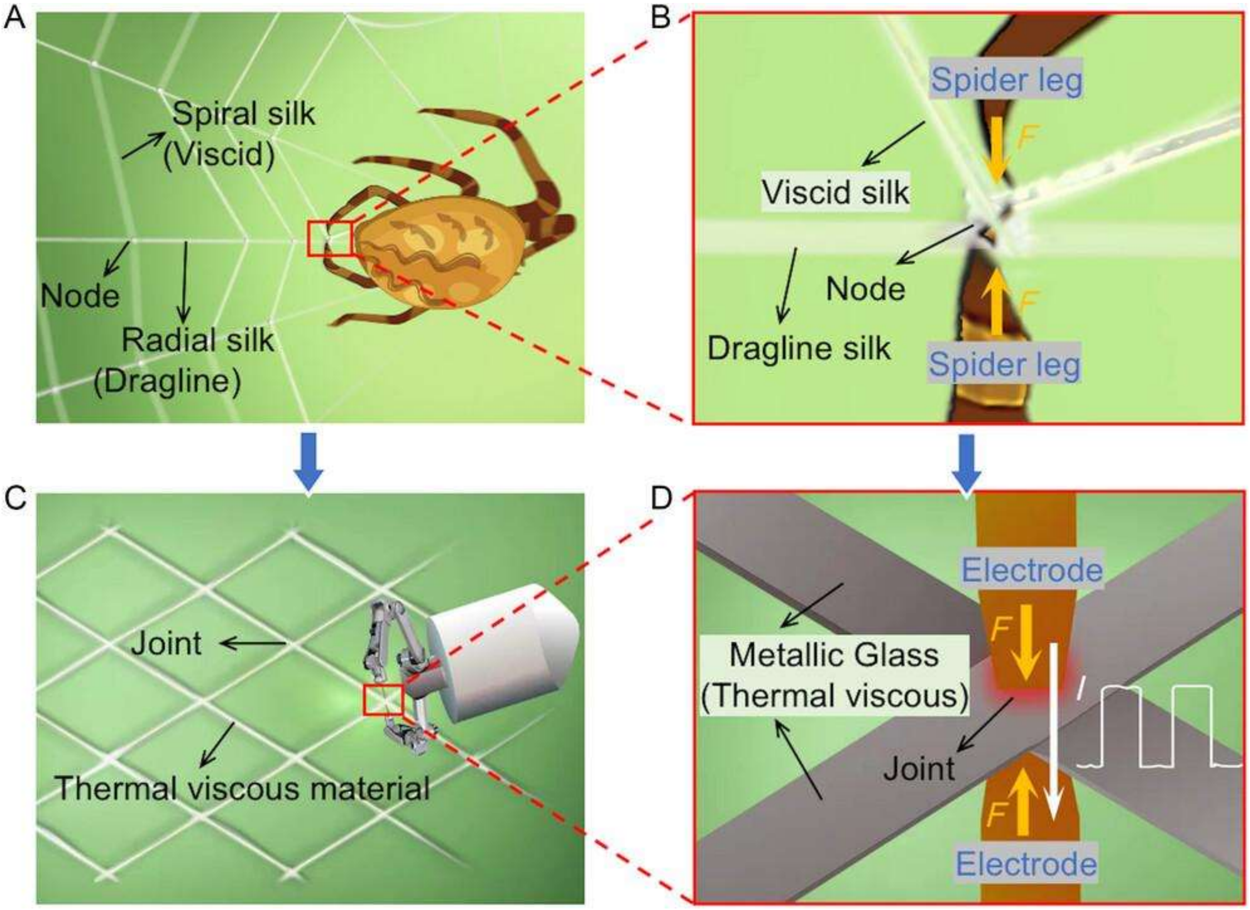
Abdulhameed et al (2019) describes additive manufacturing, defined as "the process of producing parts through the deposition of material in a layer-by-layer fashion", and has been one of many topics of discussion in manufacturing industries regarding innovation and innovative processes. This work acts as a comprehensive and foundational review of additive manufacturing, and includes:

- Additive manufacturing's history and plans for innovation, using AM as a formative basis for Industry 4.0.
- Part orientation, build time estimation, and cost computation as well as the importance of each.
- The challenges associated with different kinds of AM processes and the opportunities that come from each challenge, taking into consideration both controllable, internal weaknesses and external industry challenges.

AM’s weaknesses related to the newness of its concept, however, are emphasized, and solutions using the synergizing of other methods, like subtractive manufacturing, are showcased by the authors.

Zhang et al. (2023) look to nature for inspiration. Their research describes how spiders can build webs under the effects of microgravity, and this is used to propose the idea of building metallic structures in space that are composed of metallic ribbons and bonded joints. This kind of structure resulted in a tensile strength of about 70% of the raw materials themselves but also maintained their hardness. The schematic for the spider web inspired design can be seen in Figure 2.4.

Figure 2.4 Schematic of the spiderweb-mimetic adhesion strategy.



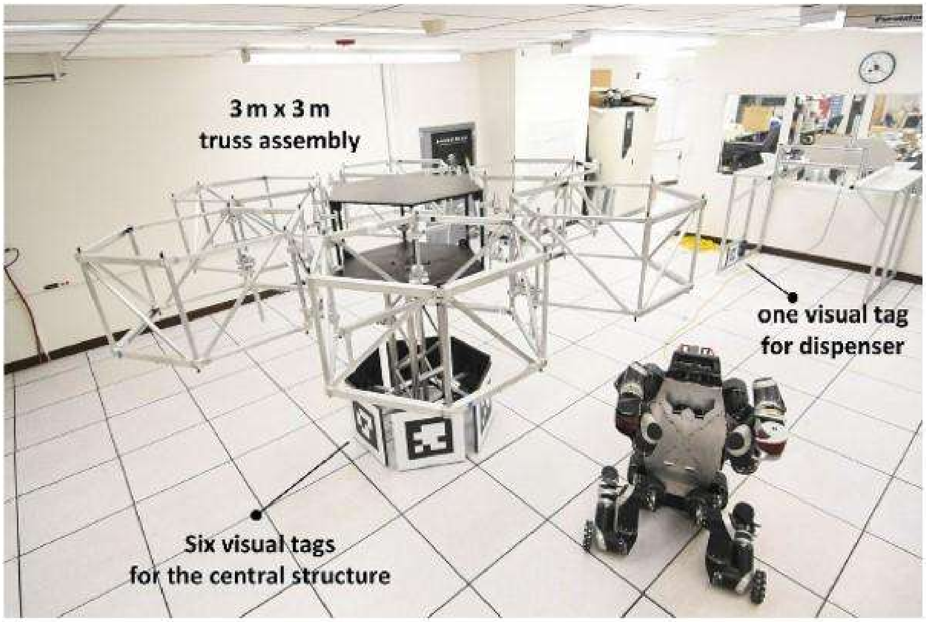
Note: A) The spinning process of the spiderweb. B) Formation of a node. C) Manufacture process based on the spiderweb. D) Formation of a joint. From: “Bioinspired Interlayer Adhesion Strategy for Additive Manufacturing in Space” by Zhang et al., 2022, *Advanced Engineering Materials,* 25(9), p. 2. © 2022 Wiley-VCH GmbH

Hedayati & Stulova (2023) perform an overview of the current advancements in AM. They also address the challenges and concerns regarding the use of AM in space. As part of this review, their research evaluates materials and their requirements for use in ISM, such as thermal properties and phase change solidification. While this research may be geared towards AM for the use of human habitation on a celestial body, it is also relevant to some of the environmental issues that AM in orbit could face.

2.3 Autonomous Manufacturing

Karumanchi et al. (2018) conducted research into the use of autonomous robotic assembly systems to construct large-scale space structures. Their paper reports on a multilimbed robotic platform that uses its limb to deploy the modular structural components and manipulate them in free space; it then assembles the structure using dual-arm force control and is able to form the structure to sub-centimeter accuracy. A photo of this robot and the structure it assembled can be seen in Figure 2.5.

Figure 2.5 Experimental setup for in-lab demonstrations: Autonomous assembly of a 3 m × 3 m truss structure with JPL's RoboSimian robot



Note: From “Payload-centric autonomy for in-space robotic assembly of modular space structures” by Karumanchi et al., 2018, *Journal of Field Robotics,* 35(6), p. 1007. © 2018 Wiley Periodicals, Inc.

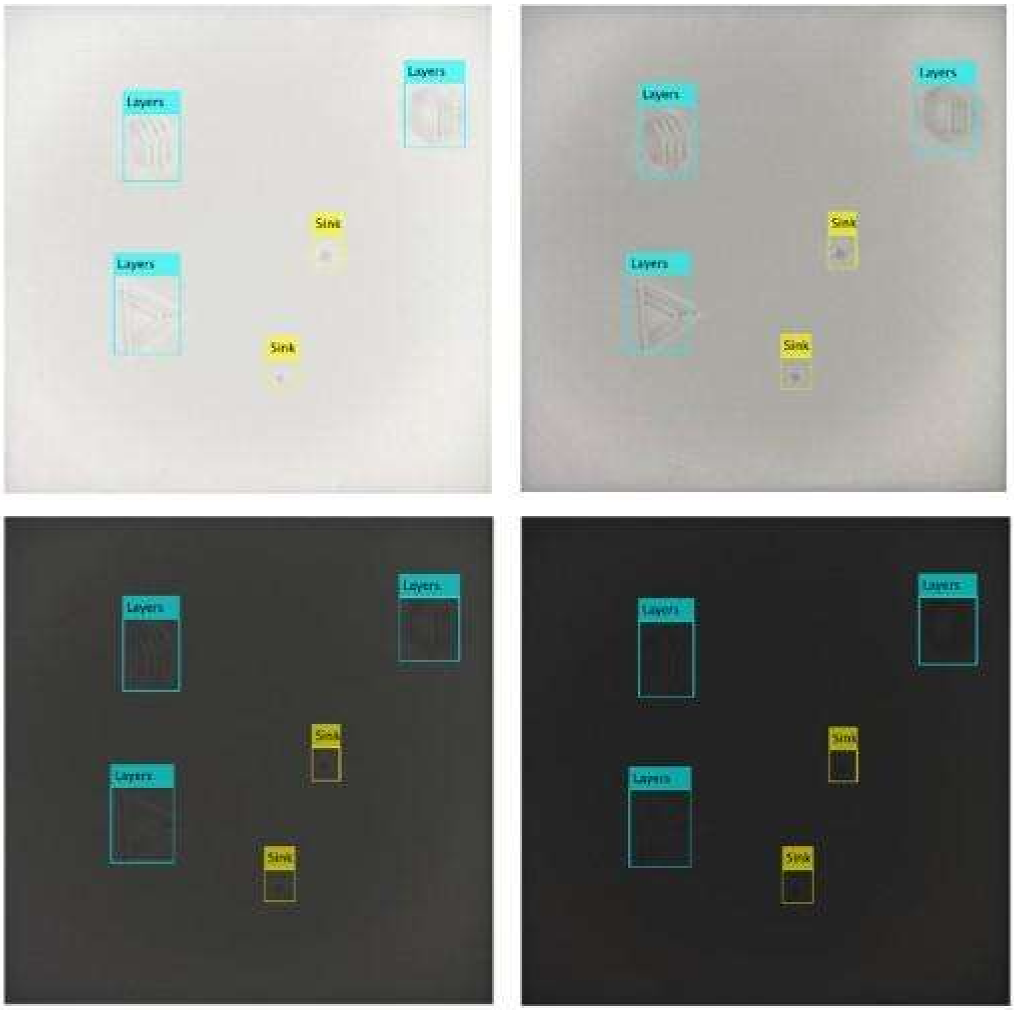
Costa et al. (2017) focus on the need for automatic or semi-automatic processes to still meet quality standards for non-autonomous work. They highlight that while autonomous systems can perform complex manufacturing operations, they may not always meet the required standard of quality. Their research produced “a novel concept of a manufacturing machine was developed based on a careful analysis of the functional, productive, qualitative and safety requirements” (Costa et al., 2017, p. 3057). While this research may focus on automation in an automotive industry, this research intrinsically reflects on the need for quality control processes in automation of any kind.

Bhatt et al. (2022) bring together both automation and wire-based additive manufacturing; their research aims to surpass the limitation of the flat substrate by way of a conformal substrate. In addition, it addresses the complexity of conformal part-making processes by adding five novel contributions: exploratory experiments with copper and iron as conformal substrate materials, development of a corner accumulation detection algorithm for bead defect detection, development of process specific tool path planning algorithms, development of a substrate placement planning algorithm, and building and characterizing of the built parts’ mechanical properties.

Tang and Wu (2023) conduct research on the use of machine learning for quality assessment purposes on space-based 3D printing. In their paper, an automated Quality Assessment approach for space-based 3D printing is proposed: it aims to enable the autonomous evaluation of 3D printed results in space, allowing for the system to have less reliance on human interaction and intervention. The paper addresses three common 3D printing failures: indentation, protrusion, and layering. Their system achieved “a detection rate of up to 82.7%

with an average confidence of 91.6% by training with the artificial samples" (Tang and Wu, 2023, p.1). Some of these detections can be seen in Figure 2.6.

Figure 2.6 The detection under different brightness with actual failures from failed 3D printed part.



Note: From "A Quality Assessment Network for Failure Detection in 3D Printing for Future Space-Based Manufacturing" by Tang and Wu, 2023, *Sensors,* 23(10), p. 12. CC BY 4.0

Lu et al (2020) speak on the topics of personalized, small-batch manufacturing, which puts a strain on the abilities of manufacturers. As it is objectively easier, lower-cost, and lower-skill to create mass batches of the same product ("batch production"), manufacturers have to adapt to the current trend in the demand market when faced with a need for specialized, small-batch production. The authors claim that the response to this is the concept of *smart manufacturing*, a general concept describing manufacturing systems or processes with advanced intelligence and, within the context of this paper, a specific manufacturing paradigm. The paper identifies and discusses well-recognized manufacturing standards that address synergy of operations while enduring compliance with all existing and recognized safety, security, and standard protocols. In order to create these standards, the authors must address the driving forces for smart manufacturing and the effect those forces have on already-existing manufacturing standards from the perspectives of processes and systems. Additionally, the environment is reviewed, and the authors discuss already-existing initiatives regarding smart manufacturing and how it cohabitates with existing automation practices and innovations.

Çınar et al (2020) describes that humanity is going through its fourth industrial revolution (coined Industry 4.0 by the Germans), a phenomenon that has become unavoidable in manufacturing industries of prognostics and health manufacturing (PHM). Offering a valid answer for the health of industrial equipment, the intention is to make PHM autonomous by using a combination of data analytics and machine learning techniques. By synthesizing existing applications and use of machine learning techniques in tandem with PHM, the study looks to form a full showcase of existing studies and applications of machine learning, allowing practitioners to select techniques and data to apply to their machine learning applications and techniques. Using autonomous techniques to achieve near-zero performance, these applications provide advantages, like reductions in many manufacturing dimensions and an increase in revenue. The authors go so far as to identify the techniques, including several forms of pre-emptive and fixative maintenance, rendering that product-data management (PdM) is the most promising of the proposed strategies due to its ability to optimize assets. The article intends to categorize machine learning techniques based on a specific set of categories and variables.

2.4 In-Situ Resource Usage

Shaw et al. (2021) identify the metals available for extraction on the lunar surface as well as the conditions for extraction; afterwards, they analyze the challenges associated with the comminution, beneficiation, and the metal extraction process. They identify the most promising metal reduction process to be molten regolith electrolysis, followed by vacuum thermal dissociation. In conclusion, the researchers found that there was a significant need for more research effort in all areas of astrometallurgy before industrialization efforts could begin.

Sirk et al. (2010) performed an investigation of direct electrolysis of molten lunar regolith at 1600° C. These investigations found the generation of oxygen gas is concomitant with the production of both iron and silicon. These experiments were then verified by subsequent experiments with larger electrodes at constant current by analyzing oxygen concentrations. Their research found that "Current efficiencies of 60 – 100% were measured in the iron-free melt. Reduced efficiencies of 30 – 60% were observed in the iron-containing melt, due to competing oxidation of Fe2+ to Fe3+ and increased electronic conductivity." (Sirk et al., 2010, p. 373).

Grossman et al. (2018) discuss the usage of regolith-derived ferrosilicon as a potential material in wire-based feedstock additive manufacturing. Their research synthesized and categorized multiple alloys of "compositions ranging from pure iron to 12 wt% Si" (Grossman et al., 2018, p. 2212). The characteristics evaluated revolve around their electrical and mechanical properties; as part of the testing, it was determined that alloys "above 3 wt% Si were too brittle to be pulled into a wire form and ruptured" (Grossman et al., 2018, p. 2212). Following this, studies were conducted on the materials microstructures and composition between the samples that were deemed ductile and brittle. These studies found that differences between the two categories were the complete ferrite phase presence in both the iron and low-Si content samples. Their research then set “an upper limit for Si content in the alloy to be 3 wt% in ferrosilicon materials to be used in wire feedstock in additive manufacturing for in-space applications” (Grossman et al., 2018, p. 2212).

William and Butler-Jones (2019) build claims and research on already-existing proof-of-concepts in regard to in-orbit additive manufacturing (AM). Only recently have the sources used in this article begun to spring forth with allusions to physical research and development by way of testing. The authors acknowledge environmental concerns due to the infancy of the field and note that due to the lack of literal observation by human senses, we are unable to draw actual conclusions regarding certain parameters. The authors reiterate the infancy of the field, even going so far to claim that the field as it stands currently is unable to provide any sort of beneficial contribution to reach the needs of in-flight construction. They do add, though, that in order for the field’s maturity to be able to reach those contributions, successful production of AM-produced hardware that can endure spaceflight will be the first benchmark. The paper is then limited to the manufacturing of products using AM techniques and regolith while acknowledging the kinds of materials made in waste.

Ferrone et al. (2022) prepared research on the usage of lunar resources for colonization efforts. Their research focused on the construction of a multilayer construct using surface regolith mixed with a binder material that they named Regishell. Following this, they conducted Monte Carlo simulations into the usage of this construct as a radiation shield; they found that the regolith layer itself was adequate to substantially reduce astronaut radiation dosage.

Chapter 3 - Methodologies

3.1 The Problem: Operational Inefficiency

One of the major problems in the current era with sending materials into space is operational inefficiency. This inefficiency can be broken down into several aspects, but the ones that will be focused on in terms of this research are 1) financial inefficiency, 2) environmental inefficiency, and 3) manufacturing inefficiency.

In 2018, the cost of SpaceX's *Falcon 9* was advertised at $62M USD to launch 22,800kg of material. (Jones, 2018, p.1) Ergo, the cost for a single kilogram of material to be sent into space would be a minimum of $2,719. It is highly inefficient to send small batches of material into space, making specialized projects completely inaccessible at present. If SpaceX's cost is considered the industry minimum (and it is, given that it is cheaper than the cost to send material to the ISS by government-funded projects), the industry finds itself at a disadvantage: they must either wait and send massive amounts of material at a time to justify the financial burden of a launch, or they must repeatedly take on these burdens for smaller-scale, focused projects. Alongside that, launches must take into consideration the environmental impact that a single rocket launch has.

Ozone-depleting substances (ODSs) are, as the name would suggest, a series of chemical compounds that have a direct counteraction to the ozone layer. These "radical catalysts" cause immense amounts of destruction to the layer itself, with the most common being nitrogen oxides (NO_x), chlorine (Cl_x), bromine (Br_x), and hydroxyl (OH). (Dallas et al., 2020, p.4) It is found in many of the existing or historical rocket launches that three of these compounds exist in the exhaust caused by launches: NO_x and OH are the most prominent. They are often produced alongside the less-concerning water vapor. For example, Dallas et. al. (2020) found that the following launches have produced both mentioned ODSs:

- United States: Space Shuttle, Saturn I, Saturn V, Delta IV, Titan IIIE, Atlas III, Atlas V
- Japan: H-IIA, H-IIB
- Europe (European Space Agency): Ariane 1, Ariane 2, Ariane 3, Ariane 4, Ariane 5 ECA, Ariane 5 G+, Ariane 5 GS, Ariane 5 ES
- India: GSLV

Modeling the effects these ODSs, Prather et. al. (1990) found that if there were “nine space shuttle launches and six Titan IV launches in a year”, the ozone layer would deplete would be 0.25% per year. For the purposes of this research, it is important to note that in comparison to the space shuttle, the Titan IV was intended to launch “space-shuttle size payloads”, making those launches require significantly more fuel, therefore producing significantly more exhaust as a result.

Now that both the financial and the environmental impacts have been established, it can be concluded that there are significant issues with not only the manufacturing efficiencies, but also the supply chain management. At present, the industry finds itself entering a new age of technological advancement with regards to space manufacturing, dubbed “New Space” or “Space 4.0” by the influx of commercial and private-sector introductions, that is heavily led by the concept of additive manufacturing (AM). (Aglietti, 2020, p. 1) Many organizations and companies have chosen to pursue the path of additive manufacturing, and this research also centers itself around the concept.

Spacecraft manufacturing requires that all components built on Earth satisfy the safety parameters needed for in-orbit use. They [the components] must be hardened to not only withstand the launch, which includes “severe vibrations, acoustics, acceleration loads, and thermal loads”, but also these safety parameters can “limit payload capabilities and increase launch costs”. (Boyd et al., 2017, iii.) It is even acknowledged that there are some materials that do not allow for Earth production as there is no solution to the issues of gravitational forces; these include any material that may be bent by the effects of the launch or any material that is thin enough to warrant the concern of damage in transit. Therefore, these materials are produced/assembled in-orbit. The question here is finally posed: *how do we mitigate these financial, environmental, and manufacturing inefficiencies?*

3.2 Data Collection Approaches

Because this research involves an innovation on already-existing concepts and manufacturing, this thesis opts for the collection and synthesis of theoretical material. It uses historical study, implementing already-existing material, patents, concepts, and theories; these abstract references will be supported by multiple case studies that will be identified throughout the paper, all which have a unifying factor that supports the use of additive manufacturing to create a conceptual design and process for in-orbit manufacturing.

In order of reference in this research, the following case studies are addressed:

- SpaceX’s Falcon 9
- A series 42 of environmental studies conducted by 28 different researchers that discuss the impact on the ozone layer, synthesized by J.A. Dallas et. al.
- The International Space Station’s existing 3D printing experiments regarding internal, small-scale productions
- Relativity Space’s Terran 1 and Terran R
- Relativity Space’s Stargate 3D printer and printing process

- NASA’s human certification safety protocols and certifications
- Agnikul Cosmos’ Agnibaan

3.3 The Solution: The Empyrean Forge

Headlined as a “forge of the heavens”, the Empyrean Forge (referred to henceforth as “the Forge”) is a conceptual design for a manufacturing method that implements the use of additive manufacturing and automated engineering to reduce the number and expense of launches of materials and staff. In addition, the materials used by the Forge will predominantly come from mining expeditions of extra-terrestrial objects (“asteroid mining”) to supplement the intended goals of reducing the number of launches per year. This paper does acknowledge that the Forge will not completely eliminate the need for launches, as there may need to be materials or already-manufactured goods that *must* come from Earth to be successful or staff to oversee key or prototype steps in the manufacturing process. It is, however, the goal of the Forge to be the foundational building blocks for unmanned, automatous manufacturing and a step towards lunar/Martian habitation.

There are three main developments that the Forge must develop upon and solve for its success: 1) the needs of additive manufacturing in a large-scale environment, 2) the needs of the vessel that will be created by the Forge, and 3) the needs of the printer(s) that will be used by the Forge to create these vessels.

3.1.1 Defining the Process

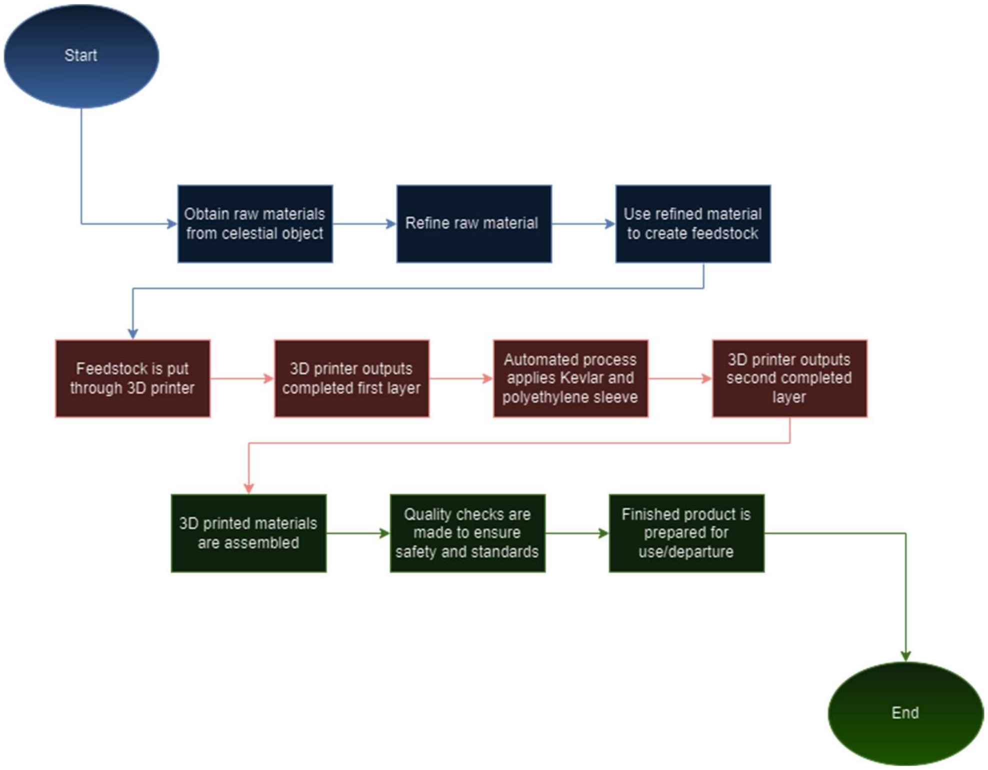
To understand the needs of the pieces that make up the Empyrean Forge’s overall process, it is critical to first explain and define the process that the Forge’s methods involve. While the entire manufacturing process has been referred to as “the Forge”, the methods refer to a workflow best defined by Figure 3.1.

With the manufacturing process of “the Forge” being the central point of the manufacturing chain, the stages of the process are referred to in relativity to that point. The process that obtains and refines materials is referred to as the “Pre-Forge” phase, containing of a three-step system. Using Assumption 3, the system obtains raw materials from a celestial object, which will then be refined and later used to create feedstock for the 3D printing phase.

From there, the “Forge” process begins. The feedstock previously created using the Pre-Forge phase is put into a 3D printer, and the first layer of the material used to manufacture the spacecraft is completed. Before the second layer can be created, however, an automated system must attach a “sleeve” of Kevlar and polyethylene atop the first layer, which will protect the spacecraft from radiation and puncture while in flight. After the sleeve has been successfully attached, the process will briefly repeat to create a second layer to secure the sleeve in place.

Finally, the QA or “Post-Forge” process will occur; the 3D-printed materials are assembled as per existing parameters by an automated system. Quality checks are made to ensure safety and standards (and it is understood that the preliminary rounds of these quality checks will need to be done with human supervision, despite the goal of the process being fully automatous), and when the spacecraft is secure with all necessary protocol completed, the spacecraft is ready for flight.

Figure 3.1 A visual representation of the Forge process, defining all three phases of the larger-scale procedure.



3.2.2 The Needs of Additive Manufacturing in a Large-Scale Environment

It is the intention of the Forge to begin by creating a spacecraft that is akin to or equitable to the space shuttle. By beginning with shuttles for the first attempts at creation, the Forge's limits of creating spacecraft that fit within the parameters of necessary safety regulations can be met. It should also be noted that that the first attempts at creation by the Forge should remain unmanned until there is no room for safety error that would damage or otherwise result in the death of travelling pilots. The Forge acknowledges the lack of room for error and prioritizes safety over efficiency in the case of human health.

Regarding using additive manufacturing (or "3D Printing"), the case study of the International Space Station (ISS) is used as the most-referenced example of in-orbit manufacturing in this research. To summarize, the ISS has already used “polymer-based 3D printers” which “use plastic material that is heated at the printer’s head, then deposited to build up the desired object, one layer at a time”. (European Space Agency, 2024) With the scale at which the Forge is to operate, the systems needed would need to be much bigger. A more apt comparison in case study would be the Relativity and their Terran I. At 85% additively manufactured materials, Relativity’s 3D printer served as the basis for the design of the Forge.

3.2.3 The Needs of the Vessel

Pelton and Jakhu (2010) define the concept of “space safety” as “including the protection of human life and/or spacecraft during all phases of a space mission, regardless of whether or not it is a manned or unmanned activity”, and covers the following phases of activity:

- “aspects of pre-launch, launch, orbital, and sub-orbital operations through re-entry and landing;
- the protection of ground and flight facilities and surrounding population and buildings in proximity to launch sites; and
- the protection of space-based services, infrastructure, and unmanned satellites such as communications satellite networks, global navigation systems, and remote sensing surveillance systems, as well as scientific satellites”

In tandem with the aforementioned external safety protocol, NASA has created the “Human-Rating Certification” process, which is used as the basis for the Empyrean Forge’s safety protocols when autonomously creating manufactured materials and structures. The Forge strives to meet NASA’s goal of upkeeping “a world-class safety program based on management and employee commitment and involvement; system and worksite safety and risk assessment; hazard and risk prevention, mitigation and control; and safety and health training”.

3.2.4 The Needs of the Printer

In order for the 3D printing device to perform at the rate it would need to, the printer would need to be significantly larger than the structures that already exist. Therefore, the case studies used to identify what the needs of the Forge would be are: Relativity's Stargate and AgniKul Cosmos' Agnibaan.

The Relativity Stargate is responsible for the creation and printing of Relativity Space's *Terran* line of rockets, which was comprised of:

- *Terran 1 (or the GLHF, "Good Luck, Have Fun"),* an "expendable two-stage small life launch vehicle" that was comprised of 85% materials produced by additive manufacturing, which was retired after one failed launch in 2023. (Relativity, 2023)
- *Terran R,* a "two stage rocket" that prioritizes "rapid reusability". While the Terran R has not yet launched, the first launch is expected to be in 2026 into low-Earth orbit in "reconfigurable configuration". (Relativity, 2024)

The Stargate printer is responsible for the printing of both spacecrafts. While there are few details about the creation of the Terran R, we can ascertain through existing data and calculations that I performed that the Terran 1 took approximately 60 days to complete from start to finish, including assembly and preparation time. Using Assumption 1 in the following section, we can determine that of the 1,440 hours of manufacturing time, the Stargate printed at a rate of 0.057m/hour to create a structure those components produced by additive manufacturing was 28.498 meters tall and a diameter of 2.286 meters wide. (Relativity, 2019)

Meanwhile, India's Agnikul Cosmos has successfully developed the *Agnibaan,* a fully formed, ready-to-launch spacecraft formed of 100% 3D printed material. From raw materials to ready-to-launch in 75 hours, and using Assumption 2 in the following section, the print rate of this rocket was determined to be approximately 0.24m/hour. The dimensions of this rocket, however, are much smaller than the Terran R, at 18 meters in height and 1.3 meters in diameter. With this information synthesized, the thesis determines that in order to create space vessels capable of in-orbit aircraft, the printing capabilities of the Forge must either be equitable to or surpass the standards and results of the case study. (Agnikul Cosmos, 2024)

3.4 Assumptions

The Empyrean Forge was designed under the standards of a supply chain; this supply chain does not take into consideration how the materials will be obtained, instead leaving that to other suppliers. For the purposes of the scope of this research, the following assumptions are to be made, in order of addressing:

1. Relativity's Terran 1 team had a 7-day work week in which at least one eight-hour shift was worked. This team had to consist of at least one human monitoring and correcting the printing of the material for the full 8 hours.
2. Agnikul Cosmos' Agnibaan team had a 7-day work week in which at least one eight-hour shift was worked. This team had to consist of at least one human monitoring and correcting the printing of the material for the full 8 hours.
3. There will be an existing, available method of gathering raw materials from nearby celestial objects (i.e. asteroid mining).
4. There will be an existing method of obtaining Kevlar and polyethylene for the textile that will be between the two layers of 3D-printed material that comprises the bulk of the vessel's body.

3.5 Prototype Modeling and Conceptual Explanations

With these assumptions in mind, the model was developed using Flexsim 2024 simulation software for discrete simulation purposes. Following the processes defined in Rao et al. for the extraction of titanium and aluminum from lunar ilmenite and anorthite respectively, the material of choice for the vessel was decided to be Ti-6Al-4V due to its current use in spacecraft (1979, p. 257).

Using the processed materials, titanium, aluminum, and vanadium would be combined into the required alloy and extruded into a 4mm wire for the manufacturing process. This would be fed into the additive manufacturing printer head that would melt the wire using a high-power laser onto a rotating substrate bed. This process would be used to create a hollow cylinder measuring 28 meters in length with an inner diameter of 2.996 meters and an outer diameter of 2.3 meters to account for the 4mm wire thickness. To achieve this cylindrical shape the print would be done in what is essentially one long line creating a helix spiral with a pitch of 4mm and approximately 7,000 revolutions. When the first print is done, a 2mm layer of polyethylene and Kevlar would be applied to the outside as a radiation/puncture lining and then a second print layer would be printing around the inner cylinder. This second print would measure 28 meters in length, 2.302 meters in inner diameter, and 2.306 meters in outer diameter. The combination of these three layers would lead to a single combined cylindrical structure measuring 28 meters in length, with an inner diameter of 2.996 meters, an outer diameter of 2.306 meters, and a wall thickness of 10mm with a 4mm outer Ti-6Al-4V layer, a 2mm middle layer of radiation/puncture lining, and then a 4mm inner layer of Ti-6Al-4V.

In order to create the above titanium alloy cylinders, I first needed to determine the necessary mass of each element by weight. Due to the nature of the printing device creating essentially a 28-meter-tall spool of tightly packed 4mm titanium alloy wire, I needed to calculate the helical length necessary to create a 28-meter-tall structure. The equation necessary to calculate a single revolution helical length is shown in (3.1).

$$Helical\ Length = \sqrt{Height^2 + Circumference^2} \tag{3.1}$$

However, this equation would only work by itself if there was only one single revolution around a cylinder. I had to calculate how many revolutions would be necessary to account for a multi-layered structure. The modified equation can be seen in (3.2).

$$Helical\ Length = \sqrt{Height^2 + Circumference^2} \times Revolutions \tag{3.2}$$

Revolutions are easily determined by splitting a total of 28 meters in height into sections of 4mm (the height of a single layer due to the thickness of the cylindrical wire). By dividing 28 meters by 0.004 meters, it gives us a total number of revolutions of 7,000. I used the equation in (3.3) to find the circumference of a single revolution with the diameter of 2.3 meters and a radius of 1.15 meters. This gave me a circumference of the inner cylinder equal to 7.225 meters.

$$Circumference = 2\pi \times radius \tag{3.3}$$

Finally, by inserting the height of a single revolution of 0.004 meters, the circumference of 7.225 meters, and 7,000 revolutions into equation (3.2). I got the final helical length of the inner cylinder equal to 50,571.01 meters. This would be the length of wire necessary to print a 28-meter-tall cylinder with an outer diameter of 2.3 meters in one single continuous line onto a rotating substrate. The next step would be to find the volume of the wire, which in combination with the density of the Ti-6Al-4V, could be used to find the total mass of the wire and in turn the cylinder. The equation for volume of a cylinder can be found in (3.4).

$$Volume = \pi \times radius^2 \times height \tag{3.4}$$

Height (in the case of the wire) would be equal to the total length of the wire, or 50,575.01 meters, the radius would be half the diameter of the wire or 0.002 meters. When inserting these into equation (3.4), I determined the total volume of the wire would be equal to 0.636 m^3. The density of Ti-6Al-4V is 4.43 grams per cubic centimeters (g/cc) or 4,430 kilograms per cubic meter (kg/m^3) (Wang et al., 2018, p. 1471). Combining the volume of the wire, 0.636 m^3, and density of the titanium alloy, 4,430 kg/m^3, into equation (3.5) gave me the mass of the wire, 2,817.48 kg.

$$mass = density \times volume \tag{3.5}$$

I would then repeat this entire process using the dimensions of the outer cylinder, 28 meters in height, 2.306 meters in diameter. Using (3.3) I determine the circumference of the outer cylinder to be 7.245 meters. Then using (3.2) I determined the total helical length of the outer cylinder to be 50,711.59 meters; since the cylinder would be the same height as the inner cylinder, it would also take 7,000 revolutions. Once that was done, I then used (3.4) to determine the total volume of the outer cylinder wire, 0.637 m^3. Using that volume and the density of the titanium alloy in equation (3.5), I determined the total mass of the outer cylinder and wire to be 2,821.91 kg. By adding the mass of the two cylinders, I determined the total final mass of the Ti-6Al-4V necessary for the Forge to complete printing would be 5,639.39 kg. The titanium alloy being used for construction is 90% by weight titanium, 6% by weight aluminum, and 4% by weight vanadium. Using these values multiplied by the total alloy mass gave me 5,075.451 kg Ti, 338.36 kg Al, and 225.57 kg V.

The theoretical amount of reactant and products in various metal extraction processes table in Rao et al. states that for every kilogram of anorthite, 0.0101 kg of aluminum can be extracted (1977, p.272). The table also states that for every kilogram of ilmenite, 0.277 kg of titanium can be extracted (Rao et al., 1977, p. 272). I used these as a basis to determine how much total raw ore would be needed to get the final product necessary to create the titanium alloy. To be on the safe side, I then rounded each number down to 1 kg of ilmenite to 0.225 kg Ti, and 1 kg anorthite to 0.01 kg Al. I then divided the mass of each pure metal needed by the reacted amount listed above. To produce the 5,075.451 kg of titanium needed for the cylinder, the Forge would need a total amount of 22,557.56 kg of ilmenite. To produce the 338.36 kg of aluminum needed for the cylinder, the Forge would need a total amount of 33,386 kg of anorthite.

Using these numbers, I was able to determine how much ore the "mines" would need to produce per hour in order to fulfill the requirements in 72 hours. I divided the total mass of raw ores needed by 72 hours and determined the ilmenite mine would need to produce 313.29 kg/hour, the anorthite mine 469.94 kg/hour, and the vanadium mine 0.313 kg/hour. I was then also able to determine the power requirements in order to process the required amount of aluminum in 72 hours using the modified version of the Hall-Hèroult process developed by Alcoa (Rao et al., 1977, pp. 261-262). The chemical reaction used is shown in (3.6).

$$2\,AlCl_3 = \ 2\,Al + 3Cl_2 \tag{3.6}$$

The molar mass of aluminum is 26.98 grams per mol. Since the mass needed of Al is 338.36 kg or 338,360 grams, I was able to determine that the reaction would need 12,541.14 mols of Al. This number is then multiplied by Faraday's constant (96,485 Coulomb) to determine the total charge for the chemical reaction of 1,210,031,893 coulombs. Then using the equation in (3.7) I determined the total amperage necessary for the reaction taking place over 72 hours to be 4,668.33 amps.

$$Current\ (amps) = Charge\ (coulombs) \div time\ (seconds) \tag{3.7}$$

Assuming direct current (DC) with a voltage of 160, and using equation (3.8), I determined the kilowatts (kW) to be 746.9328.

$$kilowatts\ (kW) = (Amps\ (A) \times Voltage\ (V)) \div 1{,}000 \tag{3.8}$$

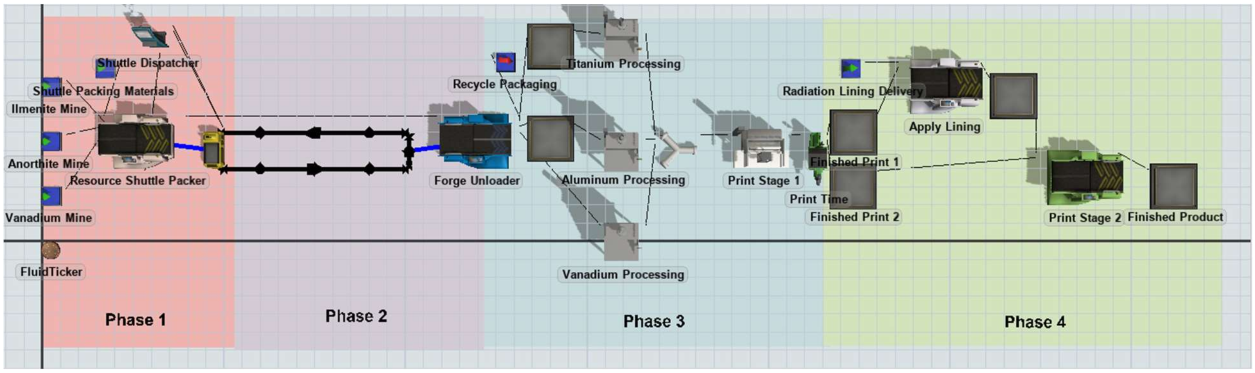
Using these processes in combination with assumptions one, three, and five, I determined the following mathematical rules for the model.

1. The Required amount of Ti-6Al-4V by mass is 5,639.39 kg.
2. Following the theoretical number of products from reaction in Rao et al. (1977, p. 272), it was determined that the raw material needed for production is:
    a. 22,557.56 kg ilmenite
    b. 33,836 kg anorthite
    c. 225.57 kg vanadium
3. The transportation time of supplies is 72 hours.
4. Refining time of Al from anorthite is 4.699 kg/hour with an amperage of 4,668.33 and voltage of 160 direct current, giving us a power of 746.9328 kW.
5. The refining time of Ti from ilmenite is 0.375 kg/hour per reactant tube. This would require a total of 20 reactant tubes measuring 10 cm in diameter and 122 cm in length, to be able to process the required amount of titanium in 72 hours.
6. The 4mm Ti-6Al-4V wire extrusion process is equal to, if not slightly faster, than the rate of material deposition for the forge.
7. Derived from Assumption 1, the total printing time for each layer of the vessel would be approximately 72 hours.

8. This in combination with the application of the radiation and puncture shielding and the printing of the second layer would lead to a final time of approximately 144 hours of printing.

In addition, I would also prefer to include mathematical modeling on the effectiveness of layer deposition and joining as well as heat treatment of the titanium alloy, but due to the financial costs of the required software, even for educational versions, it is not within the scope of this research. With this in mind, the simulation outline can be seen below.

Figure 3.2 A Discrete Event Simulation Model of the Empyrean Forge



3.6 The Model Explored

When developing the model in Flexsim 2024, I had to determine the base units for the model for both mass and time. For this I chose kilograms for mass and hours for time in order to follow the mathematical assumptions of the model. However, due to the computational power required to run large scale models with items getting into hundreds of thousands, as the model shows each resource as a three-dimensional object, I did have to constrain the values to a more computationally manageable size by multiplying each kg by 10^{-2}. This would make 100 of an item represent 10,000 of an item or 100 kg representing 10,000 kg. Initially, I attempted to fix this by using metric tons as my unit for mass but due to how the software works, it would not allow me to use much smaller significant figures that I needed for the underlying math to run properly. This also allowed me to run the simulation in a representative way using the hardware that I had available.

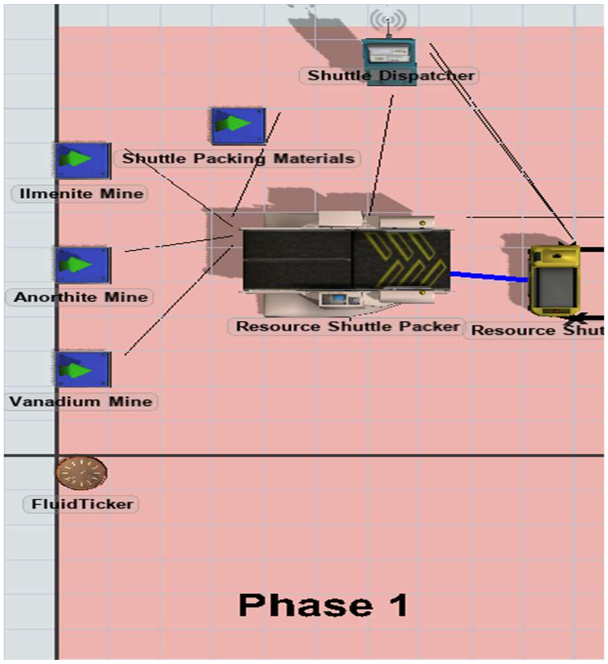
3.6.1 Phase 1

Phase 1 consists of the three resource mines for ilmenite, anorthite, and vanadium. In order to produce the required amount of ore in 72 hours, the mines produce at the following rates:

- ilmenite – 313.29 kg per hour
- anorthite – 469.94 kg per hour
- vanadium – 0.313 kg per hour

These are all mined and packaged together into a shuttle that is then sent on a 72-hour journey to the Empyrean Forge. The shuttle is only sent when the exact amount of ore from each mine is received at the Resource Shuttle Packer, and it is packaged together. Phase 1 can be seen in Figure 3.3.

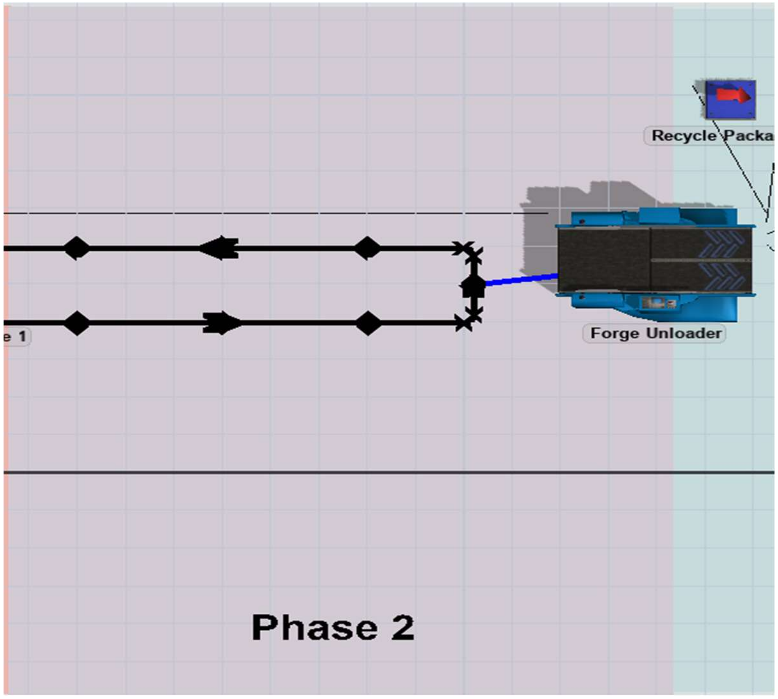
Figure 3.3 An overview of Phase 1 of the discrete event simulation



3.6.2 Phase 2

Phase 2 consists of the 72-hour journey from the mines to the Empyrean Forge itself. There are two shuttles that make this journey, one will arrive at the forge at the same time another would arrive at the mines to prepare for another shipment of resources. Phase 2 can be seen in Figure 3.4.

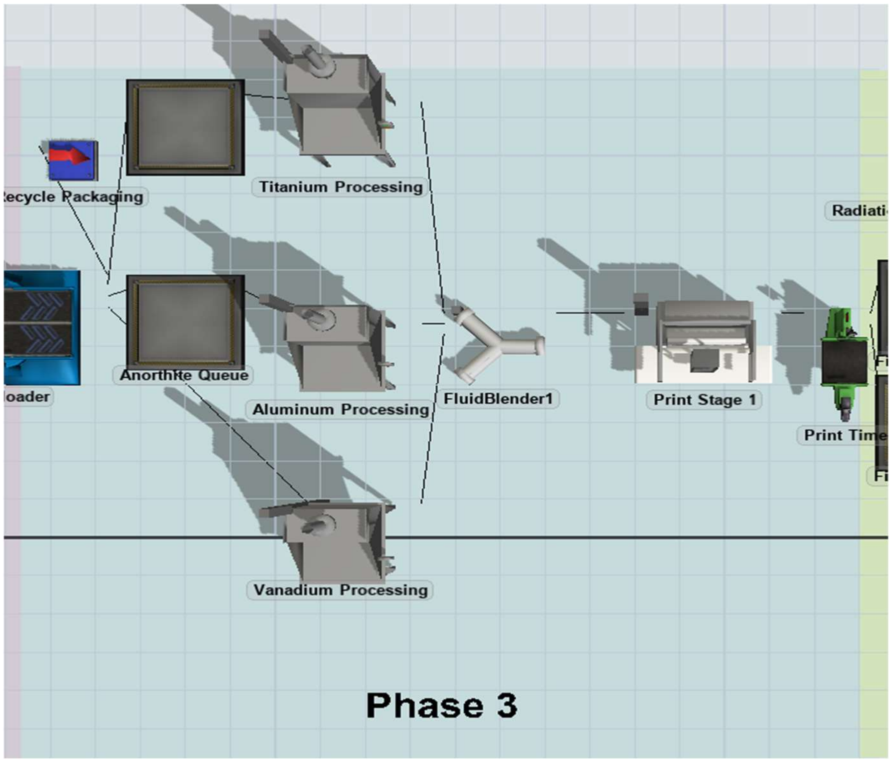
Figure 3.4 An overview of Phase 2 of the discrete even simulation



3.6.3 Phase 3

Phase 3 consists of the ore refinement process and the first print stage. During this phase, ilmenite is refined into titanium using the processes described above in section 3.5; it is then melted down and fed into a fluid blender. Concurrently, anorthite is refined into molten aluminum and fed into the same fluid blender, and the vanadium is melted down into a molten state and fed into the fluid blender. This fluid blender is set to a recipe of 90% titanium, 6% aluminum, and 4% vanadium. When this ratio of metals is met, it will output the fluid into the Print Stage 1 processer; this represents the extrusion and printing of the titanium alloy wire described above in section 3.5. These are sent into two queues in a “round robin” fashion to represent the printing of both the inner and outer cylinder. I chose to style the simulation in this fashion because both cylinders will be printed using a singular printer in the same place. Phase 3 can be seen in Figure 3.5.

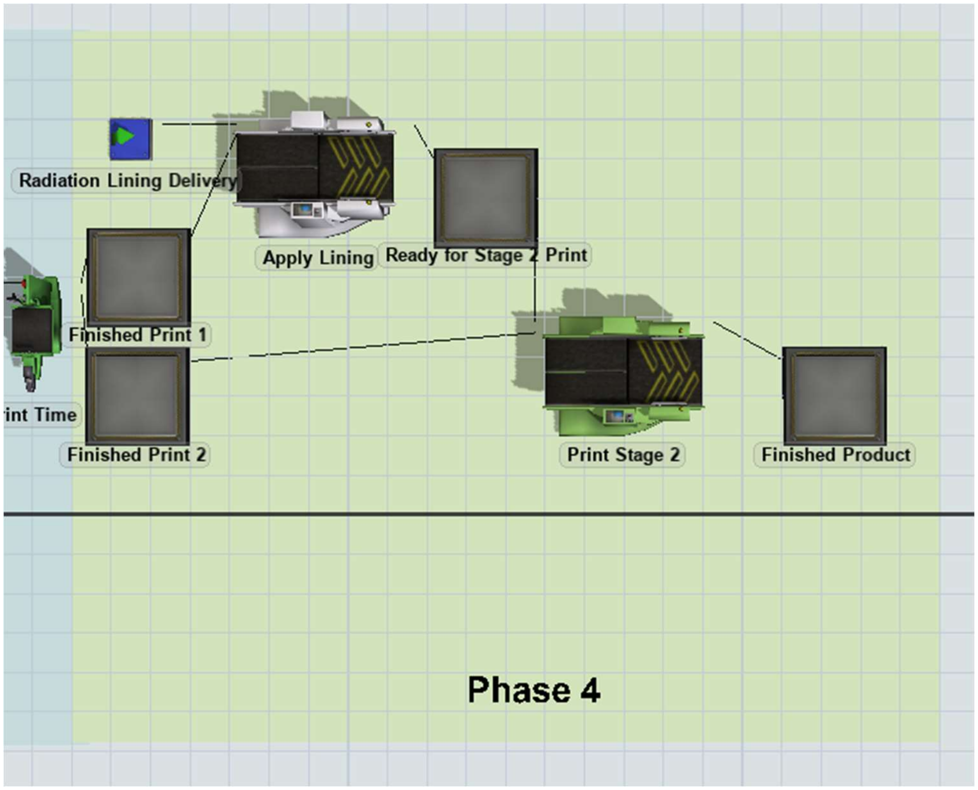
Figure 3.5 An overview of Phase 3 of the discrete event simulation



3.6.4 Phase 4

Phase 4 consists of applying the polyethylene/Kevlar radiation and puncture lining, followed by the final print stage for the outer cylinder. This radiation/puncture lining is delivered via a third shuttle that also arrives at 72-hour intervals, totaling 60 shipments over the course of the simulation. Once this is wrapped around the exterior of the inner cylinder, the second print stage is completed around the outside of this lining. This is represented by taking the product of the application lining (the inner cylinder plus a lining) and combining it with another printer cylinder (the outer cylinder) in the Print Stage 2 machine. It was done this way due to the fact that the materials and printing process for both cylinders is done with the same machines and location, the outer cylinder cannot be printed until the inner cylinder is completed and had its lining applied. When the second print stage is finished, the final product is complete and ready to go. The entire model is run over the course of 8,832 hours, this time corresponds to a calendar year plus the time to finish the last product started in that year. Phase 4 can be seen in Figure 3.6.

Figure 3.6 An overview of Phase 4 of the discrete event simulation



3.7 Simulation Case Studies

As this is a model of a supply chain, it needed to be tested like a supply chain. I devised three experiments to test the model:

1. In Case 1, the ilmenite mine is only able to operate at half productivity. This idea was derived from the 1966-1976 price hike of cobalt during the socioeconomic impact of

the Cobalt Crisis in the Congo. It simulates the effects of a long-term shortage with no quick fix.

2. In Case 2, the Forge is supplied with three times the amount of radiation linings per shipment. This is used to examine the effects of excess inventory and the “bullwhip effect” it could cause. It simulates what could happen if the Forge is unable to manage having more resources than it is designed to handle at once, and to test if the surplus would inevitably result in a shortage, as the bullwhip effect suggests.
3. In Case 3, the entire second stage of the printing process is broken. This represents what would happen if after a single inner cylinder is printed and had its lining applied, the printer head breaks. This would completely halt production and simulates what parts of the system would be impacted in such a scenario.

3.8 Remaining Challenges & Opportunities

This research does leave room for innovation on the idea, as well as expansion and improvement on the ideas presented in this thesis. This thesis leaves the following challenges and opportunities behind for further expansion and review:

- The Forge will, without a doubt, produce an excess of heat due to the nature of additive manufacturing. The thesis can briefly identify two main methods of relieving that heat (either via radiator panels that expel the heat into blank space, or a water-cooling system similar to the existing technology in xEVA suits), however, both processes have equal amounts of benefits and drawbacks that leave that aspect of research inconclusive.

Chapter 4 - Results & Interpretation

4.1 Results of the Control Run

The results of the simulations will be presented here in table format. For the mines the relevant data collected is as follows:

- Output – in kilograms
- %Blocked – this represents the amount of raw ore that is mined and has nowhere to go due to blockages later in the system.

The relevant data collected for the Shuttle Packer and Forge Unloader machines are as follows:

- Output – in kilograms

The relevant data collected for the titanium, aluminum, and vanadium processing machines are as follows:

- Output – in kilograms

The relevant data collected for the Print Stage 1 Machine is as follows:

- Output – in kilograms
- %Idle – this represents the amount of time the machine was idle for the course of the entire simulation.
- %Process – this represents the amount of time the machine was active for the course of the entire simulation. In combination with %Idle, they should always add up to 100%.

The relevant data collected for the Radiation Lining receiver is as follows:

- Output – in number of linings

- %Blocked – this represents the amount of linings that are blocked from continuing due to blockages further in the system.

Finally, the following results are also gathered:

- Finished Product Queue – in number of finished products
- Stage 2 Print Ready Queue – in number of products, this represents how many prints have had their lining applied and are waiting for the second print stage. In normal circumstances, it will always be equal to zero due to the just-in-time manufacturing principle of the system.

Table 4.1 Results of the Control Run

Process	Output	%Blocked	%Idle	%Process
Ilmenite Mine	2,774,880 kg	99.0%	N/A	N/A
Anorthite Mine	4,166,010 kg	99.10%	N/A	N/A
Vanadium Mine	28,250 kg	95.90%	N/A	N/A
Shuttle Packer	6,970,360 kg	N/A	N/A	N/A
Forge Unloader	6,857,030 kg	N/A	N/A	N/A
Titanium Processing	614,196 kg	N/A	N/A	N/A
Aluminum Processing	40,946 kg	N/A	N/A	N/A
Vanadium Processing	27,298 kg	N/A	N/A	N/A
Print 1	120	N/A	4.80%	95.20%
Radiation Lining	61	97.50%	N/A	N/A
Print 2	0	N/A	N/A	N/A
Finished Product	60	N/A	N/A	N/A

The results in Table 4.1 set the basis for what the Forge can do in 8,832 hours (a year and 72 hours). While the mines do have a high base %Blocked, this is due to the fact that it takes time to load all the raw resources into the delivery shuttle. As a result, the mines are still producing while there is an excess of raw material waiting to be placed into the shuttle or waiting for the next shuttle to arrive. The radiation lining will also have a high %Blocked due to the fact that there is no storage for more than a single lining at a time. As a new lining arrives, the old lining will be applied to the inner cylinder shortly after. The values of change from control to each case will be shown after the results from each individual case in Table 4.5.

4.2 Results of Case 1 – Halved Ilmenite Production

Table 4.2 Results of Case 1 - Ilmenite Production Halved

Process	Output	%Blocked	%Idle	%Process
Ilmenite Mine	1,324,650 kg	00.0%	N/A	N/A
Anorthite Mine	1,998,330 kg	99.40%	N/A	N/A
Vanadium Mine	13,750 kg	97.60%	N/A	N/A
Shuttle Packer	3,337,130 kg	N/A	N/A	N/A
Forge Unloader	3,286,280 kg	N/A	N/A	N/A
Titanium Processing	294,278 kg	N/A	N/A	N/A
Aluminum Processing	19,619 kg	N/A	N/A	N/A
Vanadium Processing	13,079 kg	N/A	N/A	N/A
Print 1	56	N/A	55.20%	44.80%
Radiation Lining	29	97.50%	N/A	N/A
Print 2	0	N/A	N/A	N/A
Finished Product	28	N/A	N/A	N/A

By halving the production of ilmenite, the entire system has a -53.33% change in number of final products, a change from 60 to 28. In particular, the ilmenite mine has a significantly smaller %Blocked to 0.00% compared to the control value of 99.0%. This is due to the fact that the Shuttle Packer machine requires the exact amount of ilmenite required for a single cylinder before it can ship a delivery of raw resources. This has a commiserate effect on the other mines, as they produce what is necessary for a shipment at their regular rates. By the time that the Ilmenite Mine has produced enough ilmenite for a single shipment, the anorthite and vanadium mines will have produced enough of their resources for two shipments. However, as storage for these excess resources are not accounted for in this model, the excess anorthite and vanadium ends up being held up for the next shipment. This further blocks the anorthite and vanadium mines, leading to a change of -52.03% and -51.96% in the amount of each resources used respectively. This effect can be seen on the Shuttle Packer and Forge Unloader machines as they have a change of -52.12% and -52.07% respectively. Each of the metal processing machines also show a change of -52.09% across the board.

The biggest percentage change in Case 1 comes from the Print Stage 1 machine. In total the printer has a change of -53.33% in output but has a 1050.00% increase to the %Idle time with a -52.94% percentage decrease in %Process time. This is due to the just-in-time manufacturing principles the system is built with, and the printer will not operate unless it has the exact amount of each metal to make a cylinder. Since the resources are coming in effectively halved, that means it takes approximately double the time to make each individual cylinder.

One other change of note is the output of the Radiation Lining receiver. This also has a (-52.46%) change in output linings. This is a consequence of a lack of storage for more than one lining at a time. This essentially represents wasted shipments of lining as they are turned away from the Forge due to not being necessary at that time.

4.3 Results of Case 2 – Tripled Radiation Linings

Table 4.3 Results of Case 2 - Tripled Radiation Linings

Process	Output	%Blocked	%Idle	%Process
Ilmenite Mine	2,774,880 kg	99.10%	N/A	N/A
Anorthite Mine	4,166,010 kg	99.00%	N/A	N/A
Vanadium Mine	28,250 kg	95.90%	N/A	N/A
Shuttle Packer	6,970,360 kg	N/A	N/A	N/A
Forge Unloader	6,857,030 kg	N/A	N/A	N/A
Titanium Processing	614,195 kg	N/A	N/A	N/A
Aluminum Processing	40,946 kg	N/A	N/A	N/A
Vanadium Processing	27,298 kg	N/A	N/A	N/A
Print 1	120	N/A	4.80%	95.20%
Radiation Lining	60	98.30%	N/A	N/A
Print 2	0	N/A	N/A	N/A
Finished Product	60	N/A	N/A	N/A

While at first there may seem to be not many changes between Case 2 and the Control run, as the values are almost exactly the same as the control case, there is just as much learned from what is not shown. In particular, the %Blocked of the Radiation Lining receiver increased by 0.82%. This may not appear substantial at first glance, but observed is that the number of radiation linings has tripled, meaning that for every delivery of the linings the forge received, three linings were received instead of the normal one linings per delivery from the control case. This means that instead of 60 linings delivered, 180 total linings were delivered. However, as stated before, the Forge only has storage for one lining at a time. This leads to 66% of all delivered linings to be turned away and wasted.

4.4 Results of Case 3 – Stage 2 Forge Break

Table 4.4 Results of Case 3 – Stage 2 Forge Break

Process	Output	%Blocked	%Idle	%Process
Ilmenite Mine	45,243 kg	99.10%	N/A	N/A
Anorthite Mine	67,924 kg	99.10%	N/A	N/A
Vanadium Mine	461 kg	95.80%	N/A	N/A
Shuttle Packer	113,628 kg	N/A	N/A	N/A
Forge Unloader	111,780 kg	N/A	N/A	N/A
Titanium Processing	10,238 kg	N/A	N/A	N/A
Aluminum Processing	682 kg	N/A	N/A	N/A
Vanadium Processing	455 kg	N/A	N/A	N/A
Print 1	1	N/A	97.50%	2.50%
Radiation Lining	2	97.5%	N/A	N/A
Print 2	1	N/A	N/A	N/A
Finished Product	0	N/A	N/A	N/A

Case 3 represents what would happen if the printer were to break after printing the inner cylinder and applying the first lining. In this case, the Forge cannot produce any finished products and since it follows just-in-time manufacturing principles, the entire system suffers. Due to there not being storage for more than a single cylinder's worth of resources at a time on the Forge, all three mines have a change of -98.37% in resources produced as excess material is unable to be processed beyond the first two cylinders.

The Forge would be able to produce a single printed cylinder using the first delivery of resources and would begin to process the second delivery as the first cylinder is printed. However, as the printer breaks after the first cylinder, the resources from the second delivery are no longer able to be used to print the outer cylinder. This also leads to a 1931.24% increase in the Print Stage 1 %Idle time. As there is no storage for excess materials on the Forge, all deliveries would need to be halted until the machine is fixed.

4.5 Interpretations

After analysis of all three test cases, I can say that Case 3 would be the most devastating for the Forge. It results in zero finished product and approximately a 98% decrease for all Forge processes until the printer is fixed. This is a catastrophic failure of the Forge and should be avoided entirely if possible. Case 1 represents a more manageable scenario; the Forge would be able to produce some final products but at a reduced amount in equity to the reduced input of resources. Case 2 is the easiest to manage, as it has a minimal impact of the production of final products, however the implications of the wasted linings is not something to dismiss entirely in the grand scheme of the supply chain. It could have an effect on the financial operations of the Forge and could lead to re-evaluation of the consistency in regard to the 72-hour supply chain.

Table 4.5 Full Results for all cases and change values compared to control case

Process	Control	Ilmenite 0.5x	Change c-V1	% Change	Radiation Lining 3x	Change c-V2	% Change2	Stage 2 Forge Break	Change c-V3	% Change3
Ilmenite Mine Output	2,774,880	1,324,650	-1,450,230	-52.26%	2,774,880	0	0.00%	45,243	-2,729,637	-98.37%
Ilmenite Mine %Blocked	99.00%	0.00%		-99.00%	99.10%	0	0.10%	99.10%	0	0.10%
Anorthite Mine Output	4,166,010	1,998,330	-2,167,680	-52.03%	4,166,010	0	0.00%	67,924	-4,098,086	-98.37%
Anorthite Mine %Blocked	99.10%	99.40%		0.30%	99.00%	0	-0.10%	99.10%	0	0.00%
Vanadium Mine Output	28,250	13,570	-14,680	-51.96%	28,250	0	0.00%	461	-27,789	-98.37%
Vanadium Mine %Blocked	95.90%	97.60%		1.70%	95.90%	0	0.00%	95.80%	0	-0.10%
Shuttle Packer Output	6,970,360	3,337,130	-3,633,230	-52.12%	6,970,360	0	0.00%	113,628	-6,856,732	-98.37%
Shuttle Packer %Idle	0.10%	0.00%		N/A	0.10%	0	0.00%	0.00%	0	N/A
Shuttle Packer %Process	0.00%	0.00%		N/A	0.00%	0	0.00%	0.00%	0	N/A
Forge Unloader Output	6,857,030	3,286,280	-3,570,750	-52.07%	6,857,030	0	0.00%	111,780	-6,745,250	-98.37%
Forge Unloader %Idle	100.00%	100.00%		N/A	100.00%	0	0.00%	49.20%	-1	-50.80%
Forge Unloader %Process	0.00%	0.00%		N/A	0.00%	0	0.00%	50.80%	1	N/A
Titanium Processing Output	614,196	294,278	-319,919	-52.09%	614,196	0	0.00%	10,238	-603,958	-98.33%
Aluminum Processing Output	40,946	19,619	-21,328	-52.09%	40,946	0	0.00%	682	-40,264	-98.33%
Vanadium Processing Output	27,298	13,079	-14,219	-52.09%	27,298	0	0.00%	455	-26,843	-98.33%
Print Stage 1 Output	120	56	-64	-53.33%	120	0	0.00%	1	-119	-99.17%
Print Stage 1 %Idle	4.80%	55.20%	50.40%	1050.00%	4.80%	0.00%	0.00%	97.50%	1	1931.25%
Print Stage 1 %Process	95.20%	44.80%	-50.40%	-52.94%	95.20%	0.00%	0.00%	2.50%	-1	-97.37%
Radiation Lining Output	61	29	-32	-52.46%	61	0	0.00%	2	-59	-96.72%
Radiation Lining %Blocked	97.50%	97.50%	0.00%	0.00%	98.30%	0.80%	0.82%	97.50%	0	0.00%
Finished Product	60	28	-32	-53.33%	60	0	0.00%	0	-60	-100.00%
Stage 2 Print Ready Queue	0	0		N/A	0	0	0.00%	1	1	N/A

Chapter 5 - Discussion & Conclusion

5.1 Potential Changes to the Forge

The current design of the Forge has no considerations for storage of resources beyond the exact amount necessary for a single cylinder at a time. This leads to a majority of the system being backed up while waiting for later processes to finish. Accounting for storage itself also requires a few key considerations: first being size, as the Forge is already going to be a large structure in of itself. It has to have room for the printing area in addition to the processing machines. This size is further increased when taking energy requirements into account: this would include both the batteries for energy storage, as well as solar panel arrays for power generation. If there were to be advances in the miniaturization of nuclear energy generation for space purposes, that may help in reducing the size of the Forge.

Furthermore, when accounting for the storage of the metals in their post processing, the decision for how it should be stored will also increase the size of the Forge. Ideally, the processed metals would continue in their normal production process of being extruded into the titanium alloy wire but would then be stored in their spooled wire form. This leads to further considerations in regard to the movement and management of such a large quantity of titanium alloy wire.

Lastly, when accounting for storage of excess radiation/puncture linings, the same considerations for storage capacity are also present. The more linings the Forge has at once, the greater the storage space required. There would also need to be considerations for how to move linings in and out of storage.

Another separate point of interest would be the number of delivery shuttles. Currently, the simulation accounts for only two delivery shuttles, this results in a rather large wait time between shuttle packings, leading to backups in the resource mines. An increase in delivery shuttles along the route could be considered as a solution, however, there would need to be simulations run to determine the proper number of shuttles necessary to maximize effectiveness without introducing more points of conflict.

In theory, the Forge could also be modified to produce smaller structures or even entirely different shapes. However, as with existing manufacturing systems, adding deviation or changes to a standardized process would require more research into the potential for changeover costs and potential changeover downtime. It would also require a more intricate printer system in order to produce non-cylindrical objects as the current printer head would only move in a single direction while printing onto a rotating substrate.

5.2 Conclusions & Further Research

The science behind the concept of the Empyrean Forge is solid. The supply chain it represents has been tested and a few flaws have been exposed, as is the intention with first-draft concepts. When evaluating the supply chain model I created, I can say that it works well in theory and within the parameters defined in this research. This model is inherently in need of refinement, as is the nature of science, but this working model illustrates the possibility of moving manufacturing for large scale space structures off Earth and into orbit using current technology. This would negate some of the strict design requirements currently imposed on large scale structures launched from Earth into space, as these objects would no longer need to endure the harsh rocket launch environment.

Outside of the current scope of research, however, are the solutions to those flaws: the intention of this draft was only to lay the foundation for a solution to in-situ manufacturing.

Furthermore, more research would need to be done on the chemical reactions and their application in zero gravity environments.

Another recommendation would be to study the layer deposition of an additively manufactured Ti-6Al-4V structure and whether this alloy of titanium would be appropriate for this process. Additionally, more research could be done to determine the safety and usability of the final product as parts of starships as said research could be an evaluation of the puncture resistance and radiation shielding provided by the greater combined structure.

An additional research recommendation would be to investigate other metals and metal alloys for use in the forge in place of the titanium alloy. There would need to be considerations for the refinement processes necessary to obtain the elemental forms of the metal from raw materials and whether the machinery on the Forge is capable of such refinement for alternative metals. This research would also need to consider the challenges that a tool changeover would face when operating in the space environment as well. I would recommend incorporating a machine learning algorithm (MLA) that could catalog the capabilities of all onboard refinement processes and machinery. This MLA could possibly calculate the most optimal alternative alloys using currently equipped machinery on the Forge.

A final recommendation would be research into use cases for such structures beyond a simple starship body. The ability to make large scale structures in space could be just an opening into much larger space stations or in space habitats. However, as the shape of these new structures deviates from the original cylindrical design demonstrated in this research, the more points of failure that are introduced into the printing process.

5.3 Summary

During the course of this research, I investigated the requirements to make a cylindrical starship body made of Ti-6Al-4V and the supply chain needed to produce such a structure in space using in space resources. The supply chain was simulated and then tested to determine its weaknesses. These weaknesses were then explained, and potential fixes were theorized. In the end, the Empyrean forge has shown that is has the potential to be a viable alternative to traditional earth-based manufacturing of large-scale space structures, as well as potentially reducing resources and launches from Earth.

This research created a model for the future of in-space manufacturing. While this model is tailored to a very specific set of inputs, it could be further expanded upon to encapsulate even more requirements or to create entirely different structures with only a few modifications. The case studies were used to determine the viability of the model when compared to current Terran manufacturing systems and conditions. The Empyrean Forge would allow space exploration to "live" off the land beyond Earth so to speak. While this research does seem close to science fiction, it is actually quite possible using current technology.

The Empyrean Forge as a system could be used to further expand human permanence in space by creating a system of manufacturing and supply not reliant on the expensive and slow launch schedules from Earth. This research is a first step towards the future of mankind in space, but it is only that, a first step. It provides the groundwork for future in space additive manufacturing systems that use in-situ resources. It is not all inclusive, as I would like to see more research into the materials science and viability of the chosen titanium alloy for additive manufacturing systems as well as more research into entirely different material types. Considering alternative metals for production could cause the need for a changeover in refinery machines, much like a current manufacturing center performing a changeover for a different product run. In the end, this research almost certainly will need to be refined and tested over and over again, as is the nature of the scientific method. However, by being able to make space exploration less reliant on Earth, this research also shows promise into cleaner manufacturing for Earth as well. If resources are able to be obtained and processed in space, the need for mining here on Earth could be lessened. This foundational research is just a metal, waiting to be forged into a tool to better serve its wielders for the good of space exploration.

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