KAZAKHSTAN INTERNATIONAL LINGUISTIC COLLEGE

Students majoring in Software

PROJECT AIDEN

Autonomous Integrated Deep-space Ecological Network

Abstract

The conceptual design for a self-sustaining orbiting colony in the Kuiper Belt is presented in this report.

For a population of about 124,500 people, the project combines engineering, biological, and environmental systems to provide stable housing, closed-loop life support, and sustained productivity.

Spatial planning, agricultural systems, temperature control, air and water regeneration, and biological ecosystems built for long-term operation in harsh outer Solar System environments are all evaluated in this study.

Redundancy and energy efficiency are optimized, and all computations are predicated on moderate comfort levels.

Team: ECLIPSE STRIKE

League: Senior

Competition: AEROO / ASSC 2025

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1. Introduction: Problem Statement and Project Goals

The Kuiper Belt is one of the most distant and poorly explored regions of the Solar System, located beyond Neptune's orbit. Despite extreme conditions — low temperatures, limited sunlight, and high radiation exposure — this region offers unique advantages for deep space exploration, including abundant frozen volatiles (water ice, ammonia, methane), mineral resources, and the potential to establish autonomous orbital platforms far from Earth, reducing the risks associated with colonizing nearby planets or asteroids.

Problem Statement: Establishing a permanent colony in the Kuiper Belt requires a fully autonomous life-support system capable of sustaining human life without regular supplies from Earth. Key challenges include limited resources, extreme environmental conditions, and complete isolation from familiar infrastructure.

Project Objectives:

- Create a self-sustaining orbital colony capable of supporting up to 124,500 inhabitants over 80 years of autonomous existence. This figure takes into account population growth and natural mortality based on an initial population of 100,000.
- Develop an integrated system combining biological and technological modules for air, water, and food regeneration.
- Ensure structural and environmental stability, thermal regulation, and psychological comfort in a rotating toroidal habitat with 0.9 g artificial gravity.
- Establish a scalable infrastructure for future expansion and resource extraction missions.

Key Project Objectives:

- Implementation of a closed-loop life support system for water, air, and food, including advanced vertical farms and photobioreactors.
- Development of energy systems based on advanced D-T thermonuclear reactors with backup microreactors and efficient heat dissipation.
- Develop autonomous robotic systems for extracting resources from nearby icy Kuiper Belt objects.
- Integrate social, cultural, and educational systems to support the long-term well-being of the community.

Project Significance: Establishing an autonomous colony in the Kuiper Belt will be an important milestone in deep-space colonization. It will allow testing of closed ecological systems capable of withstanding extreme conditions and create a platform for resource extraction and preparation for colonizing more distant objects in the Solar System.[2]

2.Colony Location and Structural Form

Astronomical Location: The orbital colony is situated in the Kuiper Belt, near Pluto's orbital zone, at an average heliocentric distance of 39.5 astronomical units (AU). The chosen orbit is an elliptical trajectory with an eccentricity of 0.2, ensuring a stable position relative to nearby trans-Neptunian objects and minimizing collision risks. This site provides a balance between scientific accessibility, availability of resources, and orbital safety. The surrounding region contains a high concentration of icy and metallic bodies rich in water ice, methane, ammonia, and silicate minerals, which could serve as potential resources for life support, construction, and energy production. The colony's location allows for efficient use of autonomous mining drones, which traverse short inter-orbital distances (~0.1 AU) to extract and transport raw materials [4].

Despite the low solar illumination at this distance (less than 0.1% of Earth's), the colony uses advanced nuclear fusion reactors combined with highly efficient solar concentrators to provide a stable and backup energy supply. The proximity to Pluto also offers exceptional opportunities for scientific observation and planetary research, allowing for continuous study of the Kuiper Belt dynamics, the chemical composition of icy bodies, and the long-term evolution of the Solar System.

Structural Form and Configuration: The colony features a toroidal (ring-shaped) modular design, optimized for both structural integrity and biological comfort. The primary structure is a rotating torus with a diameter of 4 kilometers and an inner radius of 1.2 kilometers, attached to a central axial core approximately 6 kilometers long. The torus rotates at 1.3 revolutions per minute, producing 0.9 g of artificial gravity in the residential areas, sufficient to preserve human health and physiological adaptation over decades.

Each structural module has a dedicated function:

- **Residential rings**: ten pressurized sectors with 10,000 residents each.
- **Bio-domes and vertical farming decks**: multi-level agricultural systems supporting food and oxygen production.
- **Energy core**: containing the D–T fusion reactor, radiators, and auxiliary microreactors.
- **Air and water regeneration modules**: closed-loop environmental control units.

The toroidal design offers several advantages:

Radiation protection: dense outer hull layers and distributed shielding provide uniform control of radiation exposure.

Structural efficiency: centrifugal gravity allows internal space to be divided into functional decks with predictable load distribution.

Thermal management: rotation and modular compartments promote passive heat exchange and temperature maintenance.

Scalability: modular segments allow future expansion or reconfiguration without disrupting core operations.

Psychological comfort: continuous curvature and panoramic living areas reduce spatial claustrophobia and enhance social interaction.

3. Colony Architecture and Engineering Methods

The orbital colony in the Kuiper Belt is designed as a **toroidal megastructure** with an outer ring 4 km in diameter and a central axis 6 km long. The initial capacity is 100,000 residents, with projected growth to 124,500 over 80 years (29,220 days). The general structural layout of the station is shown in **Figure 1** (*see Appendices1*).

The design includes **residential modules**, **industrial and technical sectors**, **agricultural areas**, **scientific complexes**, and **transport systems**, providing artificial gravity of approximately 0.9 g through rotation at ~1.3 rpm.

Construction materials consist of **aluminum–titanium composites**, **graphene-reinforced panels**, and **resources extracted from Kuiper Belt objects**, assembled using **orbital 3D printing** and

autonomous robotics. Protection against **micrometeoroids** and **radiation** is ensured through the use of **Whipple layers**, **regolith composites**, and **thermal microchannel panels**.

Life support systems maintain **sustainable closed cycles** of water, air, and food. The daily water requirement is 2.5 L per person, amounting to approximately 9.09×10^9 L over 80 years, with losses of about 3% (~280,981 m^3) due to filtration inefficiencies, leaks, chemical reactions, and accidents. **Greywater recycling** at a rate of about 320.6 m^3/day allows approximately 311 m^3 to be returned to use daily, effectively maintaining the water cycle.

Air regeneration is achieved through a **hybrid system** combining electrolysis, photobioreactors, CO_2 scrubbers, and Sabatier reactors, producing roughly 68,475 m^3 of O_2 per day (~97.8 t/day). This system occupies 1–1.5 km^2 and consumes 15–25 MW of continuous power, with an additional 20–50% required for lighting, circulation, and climate control.

Food production takes place in **ten-story vertical farms** covering a total area of 1.137 km^2, providing approximately 113.7 billion kcal per year for 124,500 inhabitants. Crops include wheat, soy, potatoes, quinoa, leafy greens, and fruiting vegetables. Water losses per square meter range from 730 to 1,826 L per year, totaling 0.83–2.08 billion L annually, or 66.4–166.1 billion L over 80 years. **LED lighting** at 100 W/m^2 for 16 hours per day requires approximately 584.4 kWh/m^2 per year, resulting in about 664 GWh/year or 53.14 TWh over 80 years. The visual features are indicated in **Figure 4** *(see Appendices 4)* [7]

4. Life Support Systems

The colony's life support system integrates air and water regeneration, thermal regulation, biological ecosystems, and light ecology, ensuring autonomous operation for 29,220 days (80 years) for a population growing from 100,000 to 124,500 people. The diurnal cycle follows a 24-hour Earth-equivalent timezone.

4.1 Air and Water Regeneration

Water requirements are 2.5 liters per person per day, totaling 9,093,225,000 liters over 80 years. Considering filtration losses, leaks, chemical reactions, and operational contingencies (~3%), the total water demand reaches approximately 9,366,022 m^3. Greywater recycling manages about 320.6 m^3/day, with 311 m^3/day effectively treated and total losses of around 280,981 m^3 over the entire lifespan of the colony. Electricity consumption for water treatment is about 2,000 kWh/day, corresponding to a continuous load of roughly 80 kW. Air regeneration is implemented using a hybrid system combining water electrolysis, photobioreactors, CO_2 scrubbers, and Sabatier reactors. The colony's oxygen demand (~68,475 m^3/day $\approx$ 97.8 t/day) is met through a combination of biological and mechanical systems occupying approximately 1–1.5 km^2. Energy requirements for oxygen production range from 15 to 25 MW, with an additional 20–50% needed for circulation, climate control, and lighting.

4.2 Thermal Regulation and Heat Dissipation

Temperature control is achieved through integrated thermal circuits and radiators, coupled with life-support and agricultural systems. The design maintains comfortable internal conditions despite extreme external cold, leveraging heat exchange loops and automated regulation for both habitational and industrial zones.

4.3 Biological Ecosystem and Microbiology

Microorganisms carry out waste decomposition, nitrogen fixation, and pathogen control, supporting vertical farms and the water cycle. Redundant biological pathways increase system resilience, while bioreactors and plant cultivation create an integrated, self-sustaining ecosystem.[3]

4.4 Photosynthesis and Light Ecology

Artificial lighting mimics natural photoperiods and spectral requirements, optimized for the growth of plants and microalgae. Ten-level vertical farms cover approximately 1.137 km² and produce around 113.7 billion kcal per year for 124,500 people. Water losses during cultivation range from 0.83 to 2.08 billion liters per year, totaling 66–166 billion liters over 80 years. LED lighting at 100 W/m² for 16 hours a day consumes about 664 GWh per year, totaling 53.14 TWh over the colony's lifespan. Light distribution is managed through optical fiber networks to ensure uniform intensity throughout multi-level agricultural areas. Crops include cereals (wheat, rye, barley), tubers (potatoes, sweet potatoes), legumes (soybeans), pseudocereals (quinoa, amaranth), leafy greens (kale, spinach), and fruiting vegetables (tomatoes, peppers, cucumbers) to meet nutritional and psychological needs.[1]

5. Energy System

The colony's energy system combines helium-3 fusion reactors and solar concentrators as primary energy sources, with auxiliary small reactors, batteries, and supercapacitors providing backup. Energy is distributed via superconducting and cryogenic lines to minimize transmission losses. The system supports all critical functions, including life support, water recycling, hybrid oxygen generation (electrolysis combined with photobioreactors, CO_2 scrubbers, and Sabatier reactors), vertical farm lighting, climate control, and auxiliary systems.

For a population starting at 100,000 and projected to grow to approximately 124,500 over 80 years (29,220 days), water requirements are substantial. Daily drinking water needs are 2.5 L per person, with system losses due to filtration, evaporation, chemical processes, and maintenance averaging ~3%. Total water consumption over the station's autonomous lifespan reaches approximately 9.37 million m³, with greywater processing recovering nearly 97% of this volume, resulting in ~281,000 m³ of irrecoverable loss over 80 years. Energy consumption for water processing is estimated at 2,000 kWh/day, corresponding to ~80 kW continuous load.

Air regeneration relies on a hybrid life-support system producing ~68,475 m³ O_2 per day (~97.8 t/day) for 124,500 inhabitants. Depending on the proportion of biological versus electrolytic oxygen production, the system footprint varies between 0.6 and 1.8 km², while continuous electrical demand ranges from 15 to 25 MW, increasing by 20–50% when accounting for lighting, circulation, and climate control.

Food production is based on high-efficiency vertical farming. Meeting annual caloric requirements of approximately 1.14×10^{11} kcal for 124,500 individuals requires ~1.14 km² of multi-tiered hydroponic systems (10 levels). Water losses in the farm range from 0.83 to 2.08 billion liters per year, depending on irrigation efficiency. Energy consumption for LED lighting (100 W/m², 16 h/day) totals ~664 GWh/year, or ~53.1 TWh over 80 years, with lower and upper bounds from 332 GWh to 1,328 GWh/year depending on lighting intensity.[5]

These estimates are summarized **in Table 1** -which outlines the main power sources, energy storage systems, life-support units, and auxiliary subsystems, along with their respective functions and energy requirements to maintain continuous and stable operation of the colony.

Table 1 - Key Resource and Energy Requirements for Long-Term Colony Operation

System Component	Function / Notes	Power / Energy
Helium-3 Fusion Reactors	Main energy source	Continuous high power
Solar Concentrators	Supplementary energy	Daytime peak supply
Small Reactors	Backup / emergency	On-demand
Batteries	Storage	Load smoothing
Supercapacitors	Short-term storage	Rapid load handling
Electrolysis (O_2)	Life support	611 MWh/day ≈ 25.5 MW continuous; hybrid 15–25 MW
LED Lighting (Vertical Farm)	Food production	100 W/m² × 16 h/day ≈ 664 GWh/year for 1.137 km²; 53.1 TWh over 80 years
Auxiliary Systems	Pumps, heating/cooling, control	+20–50% to base power

6. Operational Plan and Performance Metrics

This plan outlines the daily operations, task distribution, performance monitoring, and success criteria for a space colony. It ensures efficient use of resources, sustainable life support, and reliable automation.

6.1. Daily Operations

Task Distribution:

- **Crew and modules are assigned roles:** habitat maintenance, hydroponics, air/water systems, monitoring, and research.
- Tasks rotate to balance workload and prevent burnout.

Module Functions:

- **Life Support:** water, air, temperature, and waste management
- **Agriculture:** crop cultivation and harvest
- **Maintenance:** repairs, system checks, and preventive work
- **Monitoring & Automation:** sensor checks, data logging, and autonomous adjustments.

Look at the main features in **Figure 2** *(see Appendices 2)* [6]

6.2. Performance Metrics

To evaluate the operational stability and sustainability of the Kuiper Belt colony, a set of quantitative and qualitative performance metrics has been established. These indicators define the minimum acceptable standards for habitation comfort, agricultural productivity, life-support efficiency, and system reliability over the projected 80-year autonomous period. The principal metrics and their target values are summarized in **Table 2**.[6]

Table 2 - Performance Indicators of Life-Support and Habitat Systems

Metric	Target / Standard
Space per person	Adequate for living, working, and recreation
Crop yield	Sufficient to meet caloric and nutritional needs
Water regeneration efficiency	≥97% recovery from grey water
Air regeneration efficiency	Oxygen and CO_2 balance maintained continuously
System uptime	≥99% availability for critical life support systems

6.3. Maintenance & Monitoring

Maintenance Plans:

- Scheduled inspections, cleaning, and preventive replacements;
- Emergency repair protocols for critical failures.

Monitoring:

- Continuous sensor data collection on temperature, humidity, gas composition, and water quality;
- Automated alerts for parameter deviations.

Automation:

- Systems self-regulate based on sensor inputs;
- Redundant systems ensure fail-safe operation.[8]

6.4. Criteria for Successful Operation

1. **Sustainability:** Resources recycled efficiently to support population growth.
2. **Reliability:** Critical systems maintain continuous operation with minimal downtime.
3. **Safety:** Environmental parameters remain within safe limits.
4. **Efficiency:** Tasks distributed to maximize productivity and minimize energy/resource waste.
5. **Scalability:** System can accommodate gradual population growth (~0.5% per year) over decades.

7. Risks, Limitations, and Mitigation Strategies

The creation and long-term operation of a large-scale space colony are associated with numerous risks, inherent limitations, and strategies for their mitigation. Potential threats to the colony include exposure to ionizing radiation, accidental incidents, equipment failures, and psychological stress among crew members. Ionizing radiation represents a chronic hazard that can affect both human health and the integrity of electronic and structural systems. Accidents or system malfunctions can disrupt life-support systems, food production, or energy supply, while prolonged isolation and confined conditions create psychological risks that can reduce performance and operational reliability.

Project constraints are determined by physical, technological, and economic factors. The total mass of the station, available budget, and technological capabilities limit the scale and redundancy of critical systems. For instance, designing water and air recycling systems must take into account the balance between efficiency, energy consumption, and space requirements, while areas designated for vertical farming are limited by available floor space and lighting capacity. Likewise, energy generation and storage systems must meet the needs of life support, agricultural, and industrial modules without exceeding technological or resource constraints.

Mitigation strategies aim to reduce the likelihood and consequences of failures. System redundancy is implemented for critical components such as water filtration units, air regeneration reactors, and power distribution networks. Emergency protocols, including reserves of water and oxygen, provide temporary autonomy in case of a malfunction. Crew training focuses on operational competence, emergency response, and psychological resilience to maintain effective management under stressful conditions. Advanced monitoring and automation further improve reliability by enabling early detection of anomalies and rapid corrective actions. Overall, the integration of technological safeguards, operational protocols, and personnel preparedness ensures that identified risks remain within manageable limits, while project constraints are addressed through careful system design, redundancy, and resource optimization.

8. Hierarchy of Governance on the Space Station

The space station, hosting over 124,000 residents, is governed through a hierarchical system that ensures efficient administration, resource management, and operational control. The station is divided into six sectors, each with local self-governance but ultimately reporting to a central triangular administration. Authority is distributed across five levels, from ordinary citizens to the highest strategic leadership. Citizens, including workers, specialists, engineers, researchers, and colonists, form the base, with active participants eligible for sectoral roles and committee positions.

Sector coordinators and councils manage local energy, logistics, security, medical services, and resource allocation, reporting to district administrations. Three districts, each comprising two sectors, are overseen by district managers and councils, which coordinate inter-sector projects and liaise with the central Triangular Council. The council consists of three branches: the Council of Reason (science and development), the Order of Guardians (security and discipline), and the Arbitration Branch (law and justice). At the top is the Triarch, comprising leaders from each branch, responsible for strategic decision-making, crisis command, and overall governance, supported by a nominal station head. This pyramidal structure ensures clear delegation of authority, efficient coordination, and sustainable operation of the station. The main structure of the hierarchy is indicated in **Figure 3** *(see appendices 3)*

9. Conclusion and Recommendations

This study confirms that a fully autonomous space colony capable of supporting over 100,000 inhabitants is technically achievable. The proposed design ensures continuous operation over several decades while maintaining a stable 24-hour cycle for the population. By integrating water recycling, hybrid air regeneration, and high-efficiency vertical farming, the colony can sustain its inhabitants with minimal resource losses and without external resupply. Water systems are designed to recover the majority of consumed water, while air regeneration combines electrolysis, photobioreactors, CO_2 scrubbers, and chemical conversion to maintain a stable atmosphere.

Food production relies on multi-tier vertical farms that efficiently convert limited floor area into sufficient caloric intake, complemented by hydroponic and greenhouse cultivation. These systems are designed to minimize water losses and energy consumption while providing a diverse and nutritionally balanced diet. LED lighting and controlled environmental conditions optimize crop growth, ensuring year-round production and scalability for population growth.

The overall architecture demonstrates that combining modular living spaces with integrated agricultural and life-support systems allows efficient use of space, resilience against failures, and adaptability to changing demands. Redundant and hybrid systems enhance reliability, while automation and monitoring ensure operational stability over long periods. This approach creates a regenerative ecosystem that can maintain resource balance and support human life sustainably over decades.

For future development, emphasis should be placed on system redundancy, real-time monitoring, and crew training for emergency situations. Expansion of agricultural and life-support modules should be modular and scalable, following population growth while preserving system stability. Energy efficiency can be further improved through optimized lighting strategies, renewable energy integration, and advanced resource recycling. Continued research on nutrient cycling, waste processing, and biosphere dynamics will enhance sustainability and operational resilience. By integrating habitat, agriculture, and life-support systems into a cohesive and adaptive framework, long-term self-sufficiency and resilience of the colony can be achieved, supporting human habitation far from Earth.

10. References

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11.Members section

Captain - Simonov Danil

1. Batalova Aruzhan
2. Utegenov Imanali
3. Rashidova Milara
4. Turganbay Aisultan

Appendices 1

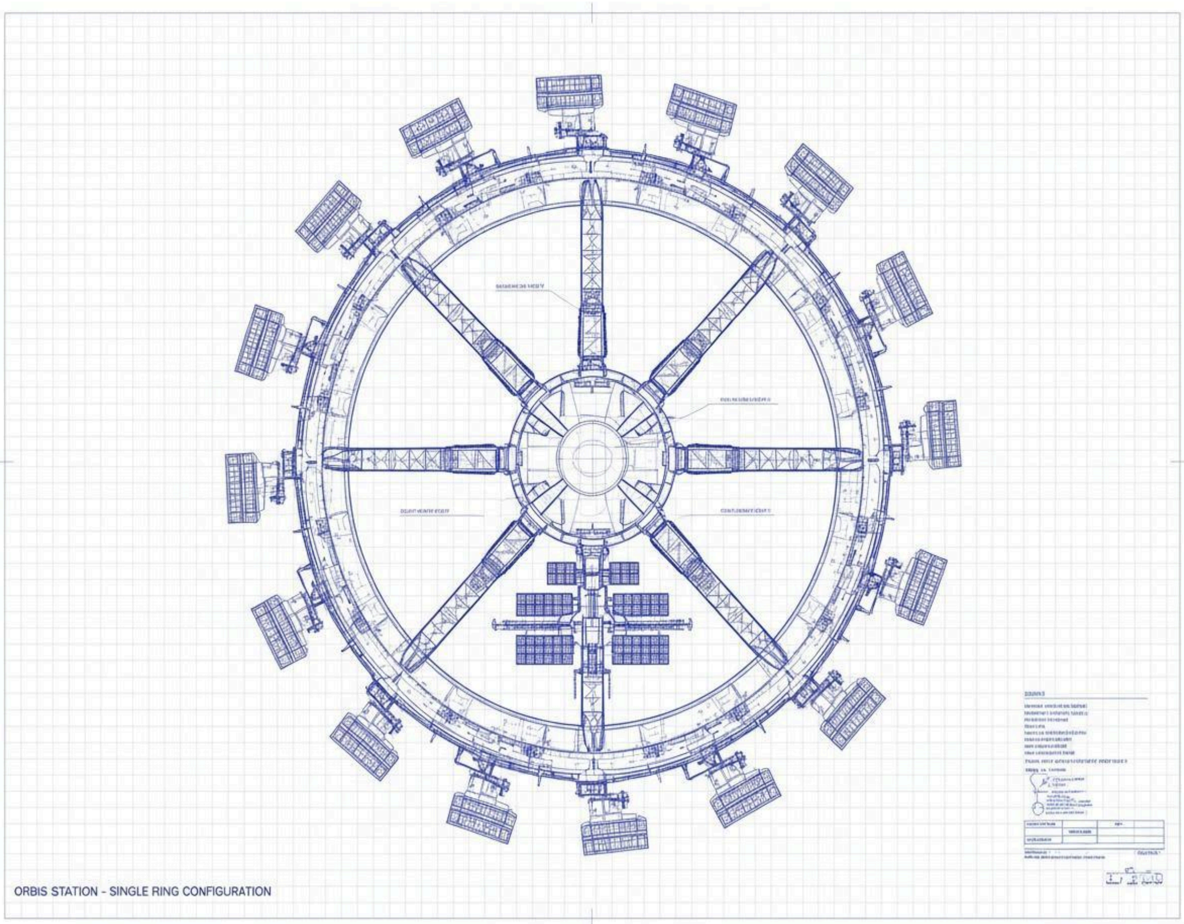

Figure 1

Appendices 2

https://docs.google.com/document/d/1pqFyCf5XUnrCo3GY35Xd7vkahWcKFtmVGNh7KPfYPvM/edit?usp=drivesdk

Figure 2

Appendices 3

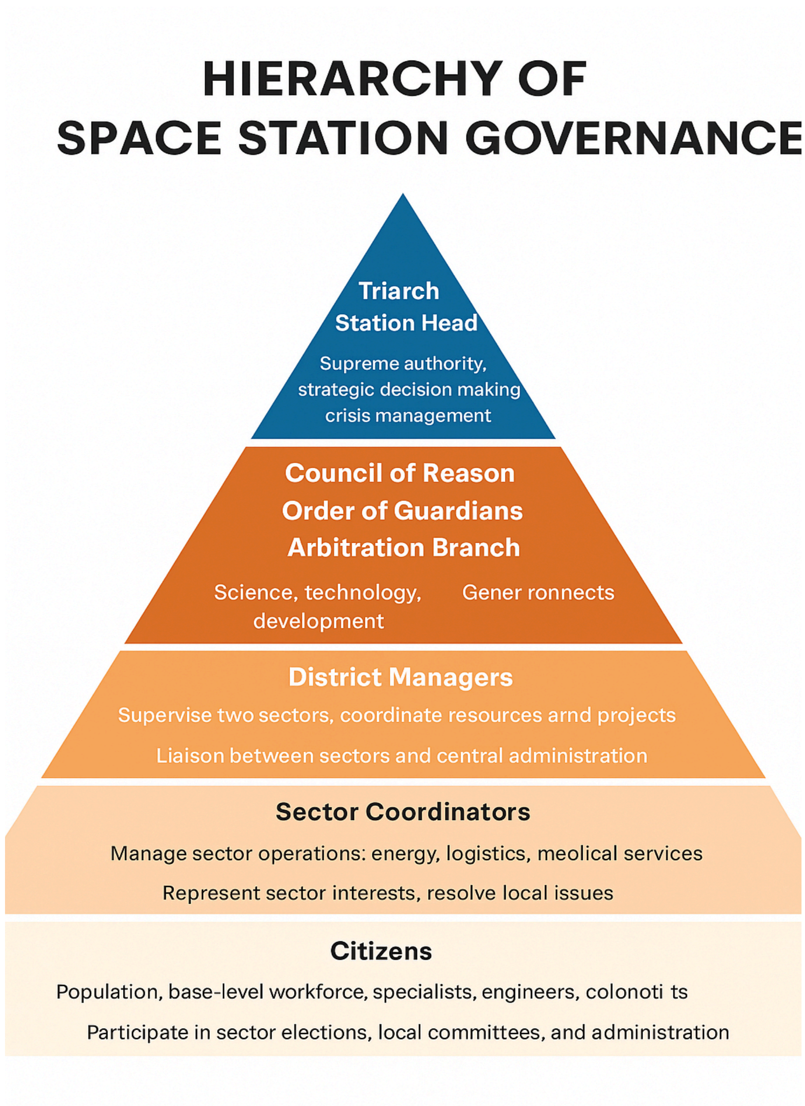

Figure 3

Appendices 4

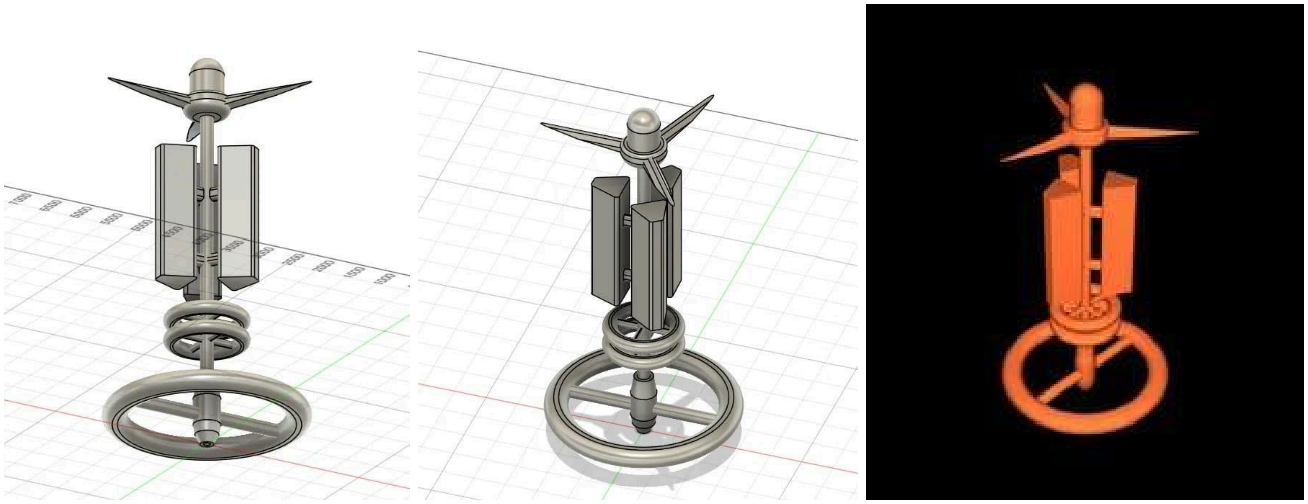

Figure 4