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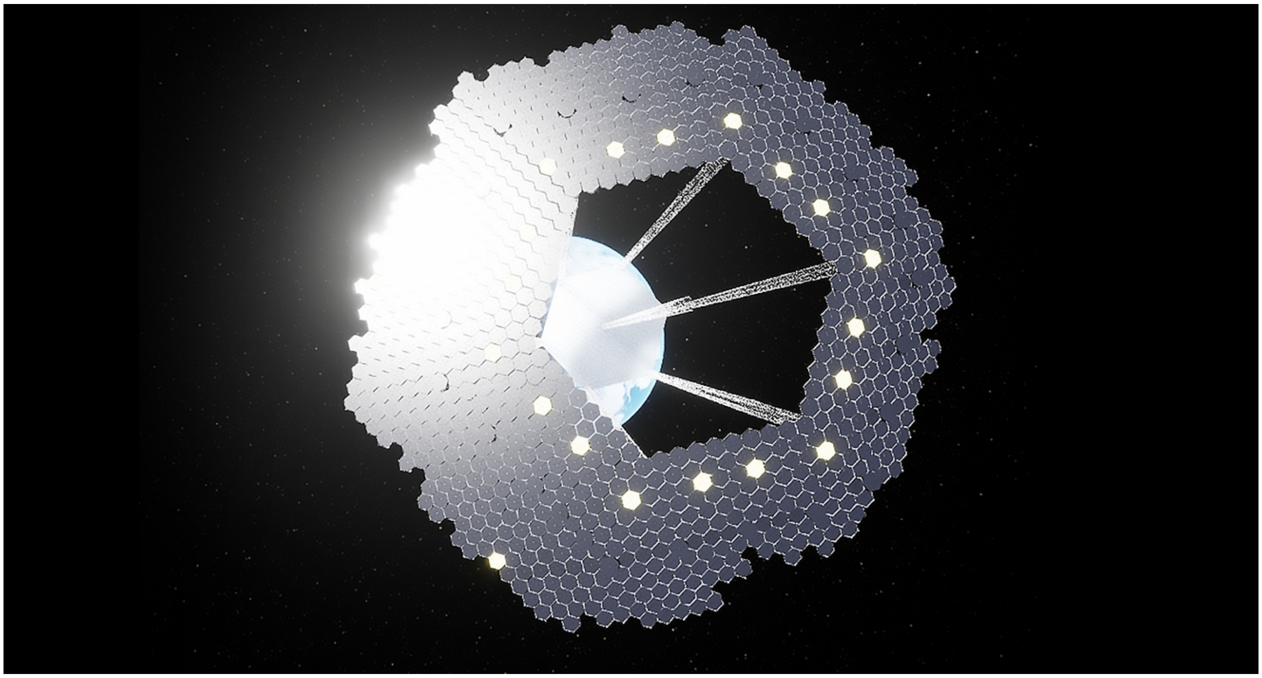
Skybeam: In-Orbit Assembly for Space-Based Solar Power with European technologies

ESA OSIP Study: Contract 4000136664/21/NL/GLC/ov
Executive Summary



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Abstract

Advanced green energy generation concepts like space-based solar power (SBSP) have extensively been studied in the past and interest in these concepts has increased recently. To prepare for future decision making on SBSP, ESA has initiated a preparatory initiative called SOLARIS. In November 2022, funding for this initiative was approved at the ESA Council at Ministerial Level.

Previous studies have shown that implementing space-based solar power (SBSP) is challenging due to the demand for tremendously large infrastructures that require numerous launches with large masses. In- Orbit Assembly using robotic systems in weightlessness is expected to be required, and various enabling technologies being developed could be used, including those under the PER ASPERA programme, a collaboration between ESA, National Agencies, the EU, and Industry, as well as ESA technology developments. These technologies include the HOTDOCK modular interconnect, MOSAR walking manipulator, and the ESA MIRROR Multi-Arm Robot (MAR).

To advance the concept of In-Orbit Fabrication and Assembly for SBSP, the Skybeam project, an effort funded by the ESA Open Space Innovation Platform (OSIP) and precursor to SOLARIS, conducted a literature survey of 27 SBSP concepts and identified a suitable reference architecture for the project. The survey included a comprehensive comparison of the architecture overview, conceptual functional breakdowns, existing assembly approach, concept parameters, system budgets, and level of available information for each concept. Based on this survey, the team selected SPS-ALPHA as the most appropriate baseline architecture for the project.

The team has proposed modifications to the SPS-ALPHA concept and the technologies of interest to converge on an assembly concept compatible with both. To gain insight into the assembly concept of operations and establish construction duration parametrically, the team has carried out a simulation of the assembly process. This simulation framework is used in order to gain insight into the concept of operations of the assembly process, and can be used to simulate the assembly of space systems as large as SPS-ALPHA in the future.

Keywords: Space-Based Solar Power, In-Orbit Assembly, SPS-ALPHA, HOTDOCK, MOSAR, ESA MIRROR

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1. Introduction

1.1 Background

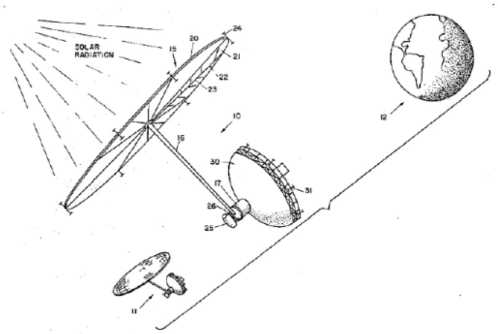


Figure 1: Peter Glaser SBSP Concept 1968 [6]

The global energy demand continues to grow inadvertently year after year and the environmental impact of conventional fossil fuel power plants is becoming increasingly worrying and evidently unsustainable. In 2021 alone, the global energy demand increased by more than 6% [1]. With this increased energy, demand comes a proportional increase of greenhouse gas pollution and ultimately an inexcusable contribution to climate change. It is paramount that the reliance on these hydrocarbon- based fuels is severed and a clean renewable energy source is realised, capable of reaching the Net zero 2050 goal.

Large-scale terrestrial solar plants offer a partial approach yet are evidently not the optimal solution for a truly green energy future. Solar radiation transmitted to the Earth's surface lacks density and so requires problematically large solar collection plants to meet the required energy demand. With this comes an extreme demand on materials and associated infrastructure. In addition, these terrestrial solar plants are subject to diurnal cycles and atmospheric losses resulting in either null energy production periods or reduced energy production periods.

The idea of Space Based Solar Power (SBSP) proposes a promising mitigation to the drawbacks of terrestrial solar power plants. SBSP systems conceptually bathe in direct sunlight indefinitely without any interface of the earth atmosphere or day/night cycles. This allows constant energy collection and clean power generation.

1.2. Objectives

The Skybeam project has several key objectives aimed at advancing the understanding and feasibility of Space-Based Solar Power (SBSP). The first objective is to *conduct a comprehensive survey of various SBSP concepts*, examining their respective architectures, functionalities, and assembly approaches. This supports the second objective, which is to *down-select and identify a suitable reference architecture for assessing in-orbit assembly*. The focus for this will be the SPS-ALPHA concept, chosen for its potential compatibility with European technologies.

The third objective is *technological adaptation*, which entails assessing the requirements and feasibility for incorporating European technologies into the selected architecture. These technologies include some of those under the ESA/EU initiative PER ASPERA. Complementing this, the fourth objective is to *create a simulation framework that can offer insights into the In-Orbit Assembly concept of operations*. The simulation models individual robotic tasks to estimate the total time needed for In-Orbit Assembly..

Finally, a fifth objective involves *logistics and cost modelling*. The aim is to simulate and evaluate the logistical considerations of constructing and operating a large-scale SBSP system, and a high-levelCapex/Opex model for cost evaluations.

1.3 Scope and Purpose

The overall scope and purpose of the project are to conduct an in-depth analysis and assessment focused on the assembly process of Space-Based Solar Power (SBSP) systems. This involves researching existing SBSP concepts and selecting a reference architecture for further investigation. The selected architecture will be assessed for adaptability to European technologies and studied through various simulation models to understand assembly timelines, logistics, and associated costs. While the project aims to provide a comprehensive view of the assembly aspect, it does not extend to creating an entirely new SBSP concept, studying detailed elements beyond the assembly process, or evaluating the functionality of the SBSP satellite or its ground segment.

1.4 Structure of the Paper

This paper begins with an Introduction that sets the context, presenting the background, objectives, scope, purpose, and the overall structure of the paper (this section). This is followed by a Literature Review that explores the historical development of SBSP, as well as relevant initiatives by ESA such as SOLARIS and PER ASPERA. The paper then progresses into the Survey Methodology used to compare various SBSP concepts and the subsequent Selection of the Reference

Architecture, SPS-ALPHA, including its adaptability to European technologies.

The main body of the paper delves into the technical aspects of In-Orbit Fabrication and Assembly, laying out the enabling technologies such as HOTDOCK, MOSAR, and ESA MIRROR. It describes the proposed assembly concept and the simulation framework designed for this study. System Modelling covers the simulation approaches, including robotic assembly, logistics, and costing models. The Simulation Results section presents the findings of these simulations, leading to a Discussion that analyses key findings, implications for future projects, and limitations of the study. The paper culminates in a Conclusion and Recommendations section, summarising the work and suggesting directions for future research.

2 Literature Review

2.1 Historical Context of Space-Based Solar Power (SBSP)

The concept of Space-Based Solar Power (SBSP) has gained significant attention as a sustainable energy source, especially in the context of the increasing urgency to combat climate change. The idea was initially proposed by Dr. Peter Glaser in 1968, envisioning satellites in geosynchronous orbit (GEO) that could collect solar energy through photovoltaic panels and transmit it back to Earth in the form of electromagnetic radiation, such as light or microwaves. Glaser's objective was to tackle the increasing costs of traditional energy sources and their adverse impact on the environment, long before climate change became a globally recognised issue. Space solar power systems present a strategic advantage over terrestrial renewable energy sources due to their nearly continuous energy flux, a benefit attributed to the absence of atmospheric absorption and consistent exposure to sunlight. Advancements in technology, particularly improvements in solar panel, electronic efficiencies, ad a trend of reduction in launch costs have made the concept more feasible today than ever before.

Despite these advancements, social and political challenges, including public perception and resistance from conventional energy providers, continue to serve as roadblocks to large-scale implementation of SBSP.

2.2 ESA Initiatives: SOLARIS, PER ASPERA and MIRROR

SOLARIS, PER ASPERA, and MIRROR are European initiatives focused on advancing space technologies with wide-ranging applications.

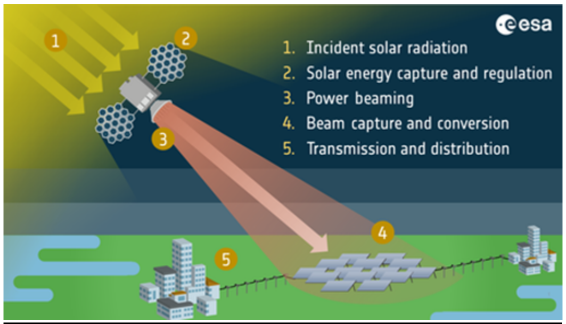


Figure 2: SOLARIS Initiative focus areas [Source: ESA]

SOLARIS: SOLARIS is a ground-breaking initiative led by the European Space Agency that focuses on Space-Based Solar Power (SBSP) as a viable energy source for Europe. Its primary goals are technological advancements in high-efficiency solar cells, wireless power transmission, and in-orbit assembly techniques. These innovations not only have the potential to serve as a baseload power source, akin to nuclear or hydroelectric power, but also to revolutionise other areas like wireless energy transfer and advanced photovoltaic systems on Earth.

Beyond the technological scope, SOLARIS aims to tackle regulatory challenges, navigating the complexities of international space policy. The array of activities also plans comprehensive assessments to scrutinise health risks, energy efficiency, and atmospheric interactions. Environmental impact analyses are slated to ensure the technology contributes positively to Earth’s environment from inception to decommissioning.

Economically and politically, SOLARIS could act as a cornerstone for Europe in achieving cleaner energy goals and reaching Net Zero targets. It has the potential to engender commercial partnerships and give Europe a competitive edge in a nascent, yet potentially transformative, field.

PER ASPERA: Funded by the European Union through the Horizon 2020 Programme and with support of ESA, PER ASPERA is an ambitious initiative designed to propel Europe into a leadership position in the global space robotics industry. The programme is organised around Operational Grants (OGs) focusing on specific challenges in space robotics. These grants fund projects such as MOSAR, which has developed ground demonstrators for modular and reconfigurable satellites, and SIROM and its related development by Space Applications Services HOTDOCK, which focus on creating a standardised interface for robotic manipulation in space missions.

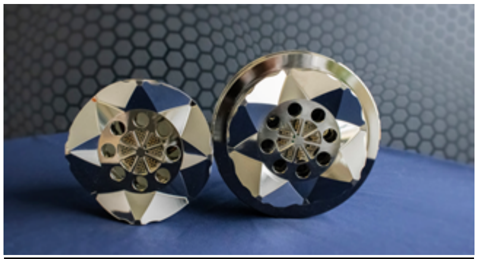


Figure 3: HOTDOCK [Source: Space Applications Services]

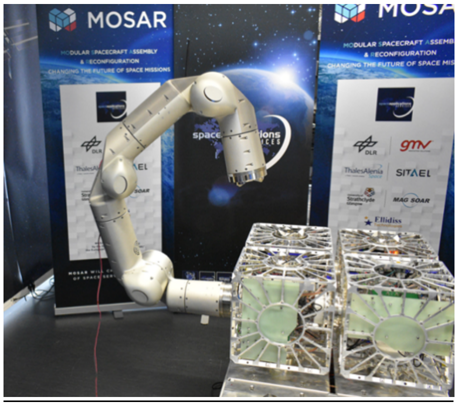


Figure 4: MOSAR [Source: Space Applications Services]

PRO-ACT, another operational grant, is geared towards implementing and demonstrating collaborative planning among multiple robots in a lunar construction setting. Other projects within PER ASPERA, like EROSS, PULSAR, and ADE, cover a wide range of topics including orbital support services, high-precision assembly in space, and long-range planetary exploration. The programme seeks to be holistic, addressing not just technological innovation but also regulatory frameworks and commercial aspects, securing European competitiveness in the strategic field of space robotics.

MIRROR: The MIRROR project is focused on the development of a Multi-Arm Robot (MAR) for assembling large structures in orbit. Having achieved a Technology Readiness Level (TRL) of 4, the initiative has a fully developed a breadboard to demonstrate the concept and capabilities of the MAR. This includes a comprehensive ground-based test environment featuring a dummy spacecraft structure, mission control centre, and gravity compensation system.

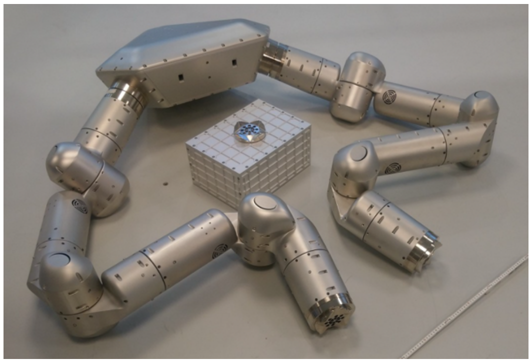


Figure 5: MIRROR [Source: Space Applications Services]

A key innovation in MIRROR is the use of standard interconnects that serve as multi-functional points for mechanical, data, and power transfer between modules. This not only facilitates modular assembly but also enables the robots to perform various tasks by moving across the spacecraft structures. The project assumes future large structures like spacecraft and telescopes will be modular and equipped with these standard interconnects, allowing for more efficient and flexible assembly and maintenance in space.

As SOLARIS continues to materialise, we anticipate incorporating pioneering technologies from multiple European initiatives into the programme, that can be used to implement the future of sustainable energy. Leveraging advancements from the PER ASPERA programme, we aim to utilise state-of-the-art robotic systems for modular assembly and in-orbit manipulations. Additionally, we integrate key technologies from the MIRROR project to streamline the assembly of large, intricate structures in space using Multi-Arm Robots (MAR).

3. Survey Methodology for SBSP Concepts

1.1 Criteria for Survey

The survey undertaken was orchestrated with a structured methodology to ensure an exhaustive and impartial comparison of various Space-Based Solar Power (SBSP) concepts that have been developed or proposed over the years. Our aim was to down-select a reference architecture that could be optimised for subsequent work packages (WPs) in the overarching project.

The first phase of our survey approach involved the meticulous collection of information from a wide range of credible sources. Over 150 documents, reports, and research papers were reviewed, which spanned an array of institutions and publications [7-15]. These included:

- National Space Society – Space Solar Power Library
- Satellite Power System Concept Development and Evaluation Program (A collection of reports by DoE and NASA from 1977-1981)
- Reference Documents from recent European Space Agency Invitations to Tender related to SBSP
- NASA Technical Reports Server (NTRS)
- Both institutional and industry research papers

Following data collection, we established a dedicated database to centralise the extracted information. This database served as the cornerstone of our analysis, enabling us to create unique tables that distilled each concept's characteristics into manageable and comparable metrics. A summarisation table was generated to collate architectural overviews, functional breakdowns, assembly approaches, concept parameters, system budgets, and architecture details for each SBSP concept under review.

1.2 Description of surveyed concepts

The surveyed concepts exhibited a wide range of characteristics. Power output among these concepts varies dramatically, from as low as 1 MW in the Solar Power Beaming Concept to as high as 75 GW in the Lew Fraas Orbiting Mirrors.

This scaling is also reflected in the systems' mass, which ranges from a lightweight 1 tonne for each SolarBird SPS satellite to a hefty 51,000 tonnes for the NASA Reference Concept 1. The mass is often correlated to the system's power output and indicates the varying complexities involved in their construction and deployment.

In terms of frequency for microwave power transmission (MPT), most concepts adhere to the 2.45 GHz or 5.8 GHz bands, an exception being the AeroSpace Corp Laser Concept, which uses a 1µm laser for power transmission.

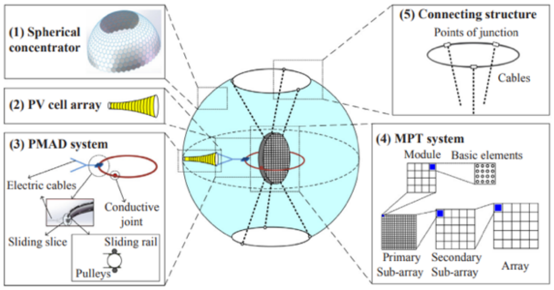


Figure 6: OMEGA-SSPS [15]

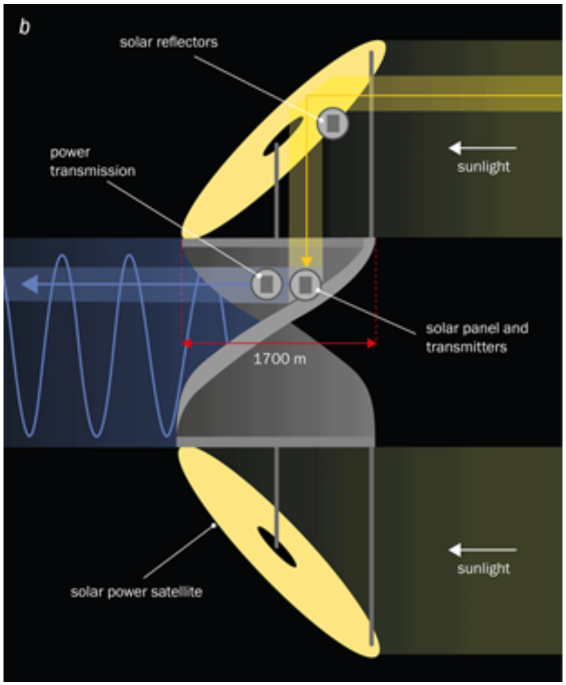


Figure 7: CASSIOPeiA Concept [Source: https://www.internationalelectric.com/]

A noteworthy feature across multiple systems is the emphasis on modularity, often signified by their MAR compatibility. Modularity is vital for facilitating repairs, allowing for upgrades, and potentially lowering launch costs. This is especially important given the transition from older systems requiring astronaut assembly, such as the NASA Reference Concept 1 and Boeing 1979, to newer models that lean towards robotic assembly.

Some unique concepts were identified such as SSPS-OMEGA which employs a spherical shell made of semi-transparent and semi-reflecting concentrators, while SolarBird SPS adopts a cluster of small satellites for a different approach to scaling. Tin Can takes it a step further by proposing lunar fabrication, which could be a resource-saving technique. Lew Fraas Orbiting Mirrors distinguish themselves by using direct reflection to terrestrial farms, bypassing the energy conversion steps necessary in other models.

Lastly, MAR compatibility is a key criteria established for all concepts, as it makes the particular concepts relevant for the study where assembly with these robots is investigated. If a particular concept, although viable, does no necessitate assembly, it is not relevant to the study.

1.2 Method of Comparison

Our evaluation centred around the following key system parameters:

- Photovoltaic (PV) Efficiencies
- Mass
- Power Delivery
- Specific Power

These metrics were selected based on their capacity to provide a comprehensive understanding of each concept's potential efficiency and viability.

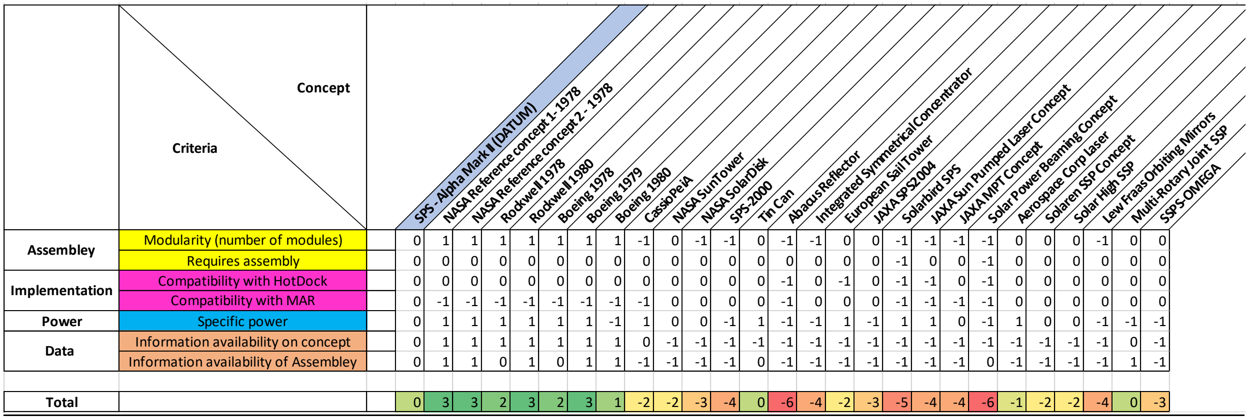
We performed a comprehensive analysis of the summarisation table and underlying data, focusing on trend recognition and correlation analysis. Trade-offs `were evaluated to optimise the selection of a baseline architecture. Our findings revealed significant technological advancements that could be retrofitted into older SBSP systems, making them potentially more efficient and economically viable.

In Skybeam, the primary objective of the survey was to identify the Space-Based Solar Power (SBSP) system that aligns most closely with the project goals, rather than simply finding the best-performing system. To achieve this, we employed a Pugh Matrix, a decision-making tool that enables comparative evaluation of different concepts based on specific criteria.

The Pugh Matrix was developed using chosen criteria that are pivotal for system viability and project compatibility. These criteria include:

- **Modularity**: Evaluating the design's adaptability and complexity, with a preference for more modular and numerous components (as the project will study the assembly process).
- **Assembly Requirements**: Assessing if the concept requires complex assembly in space or is self-deploying, ensuring that selected options allow for in-depth assembly analysis.
- **Specific Power**: Assessing the power output per unit mass to eliminate poor performers and identify feasible concepts.
- **Compatibility with HotDock and MAR**: Determining if the system can integrate or adapt to modular interconnects like HotDock and Multi-Arm Robots (MAR).
- **Information Availability**: Prioritising systems with sufficient information for comprehensive analysis in future work packages, both for the concept and its assembly process.

The evaluation was carried out collaboratively by experts in Systems Engineering and Robotics, specifically those well-versed in HOTDOCK and MAR technologies.



	Concept Criteria		SPS - Alpha Mark II (DATUM)	NASA Reference concept 1 - 1978	NASA Reference concept 2 - 1978	Rockwell 1978	Rockwell 1980	Boeing 1978	Boeing 1979	Boeing 1980	CassioPeiA	NASA SunTower	NASA SolarDisk	SPS-2000	Tin Can	Abacus Reflector	Integrated Symmetrical Concentrator	European Sail Tower	JAXA SPS2004	Solarbird SPS	JAXA Sun Pumped Laser Concept	JAXA MPT Concept	Solar Power Beaming Concept	Aerospace Corp laser	Solaren SSP Concept	Solar High SSP	Lew Fraas Orbiting Mirrors	Multi-Rotary Joint SSP	SSPS-OMEGA
Assembley	Modularity (number of modules)		0	1	1	1	1	1	1	1	-1	0	-1	-1	0	-1	-1	0	0	-1	-1	-1	-1	0	0	0	-1	0	0
	Requires assembly		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	-1	0	0	0	0	0	0
Implementation	Compatibility with HotDock		0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	-1	0	-1	-1	0	-1	0	0	0	0	0	0
	Compatibility with MAR		0	-1	-1	-1	-1	-1	-1	-1	-1	0	0	0	0	-1	0	0	0	-1	-1	-1	-1	0	0	0	0	0	0
Power	Specific power		0	1	1	1	1	1	1	-1	1	0	0	-1	1	-1	-1	1	-1	1	1	0	-1	1	0	0	-1	-1	-1
Data	Information availability on concept		0	1	1	1	1	1	1	1	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	0	-1
	Information availability of Assembley		0	1	1	0	1	0	1	1	-1	-1	-1	-1	0	-1	-1	-1	-1	-1	-1	-1	0	-1	-1	-1	-1	1	-1
Total			0	3	3	2	3	2	3	1	-2	-2	-3	-4	0	-6	-4	-2	-3	-5	-4	-4	-6	-1	-2	-2	-4	0	-3

Figure 8: Pugh Matrix for reference concept selection

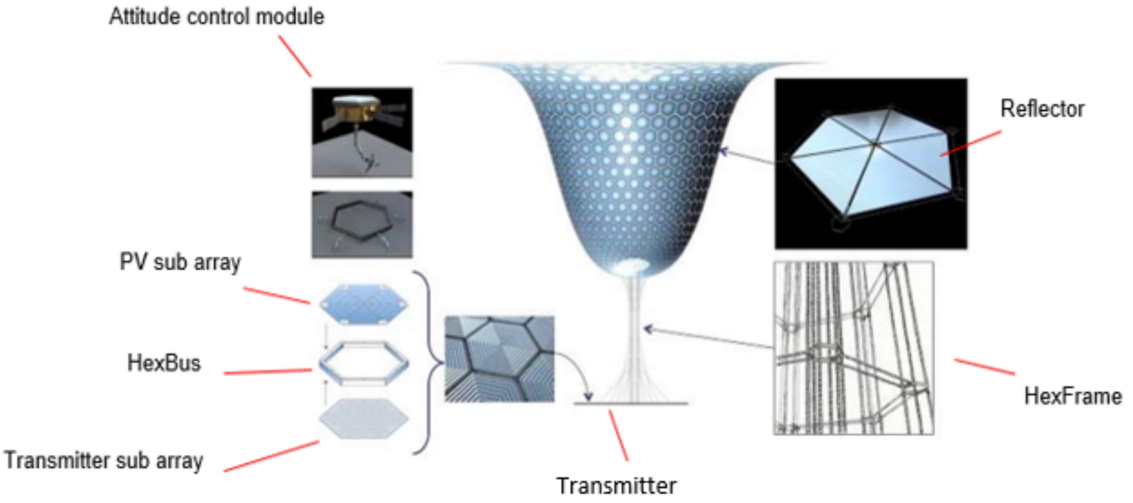


Figure 9: SPS-ALPHA system composition [7]

4. Selection of Reference Architecture

In the evaluation of various Space-Based Solar Power (SBSP) concepts, the multi-criteria assessment employing a Pugh matrix revealed a range of viable architectures, including the NASA / DoE concepts, SPS-ALPHA Mark II, Multi-Rotary Joint SSP, Tin Can, Aerospace Corp Laser concept, and CassioPeiA. While NASA / DoE systems initially scored the highest, they were largely similar and relatively complex, necessitating substantial launch mass for modest gains in power output. On the other hand, SPS-ALPHA Mark II emerged as a highly modular, efficient, and flexible solution. Its 3D structure is designed to be assembled using MARE robots, which share high similarities with Space Applications Services' Multi Arm Robot (MAR), thus promising compatibility with minimal adaptation. While its power generation capabilities are robust, it does not require as significant a mass to be launched into orbit, making it potentially more feasible for future development. Concepts like the Multi-Rotary Joint SSP and Tin Can, although interesting, raised concerns either due to the risk of mechanical failure or due to insufficient documentation. Aerospace Corp Laser concept stood out for its low mass and high power delivery, but a lack of detailed information rendered it less appealing. CassioPeiA, with its unique helical design and no moving parts, also offered an attractive alternative but fell short in terms of available definition of modules allowing assessing compatibility with MAR, and availability of comprehensive documentation. Given these assessments, SPS-ALPHA Mark I [7] was selected as the baseline architecture for its modularity, power efficiency, and expected compatibility with existing robotic assembly technologies.

4.1 Overview of SPS-ALPHA

SPS-ALPHA MK-I presents a novel, biologically-inspired design aimed at solving the complex challenges associated with generating solar power in space and transmitting it back to Earth. Built on modular principles, the system comprises eight distinct modules that together provide comprehensive functionalities, such as power generation, power management, and station keeping, among others.

At the heart of the system is the HexBus module, a structural small satellite that serves as the foundational building block. Weighing 25 kg and with a hexagonal shape, the HexBus enables wireless communication between the various elements of the SPS-ALPHA system. These HexBus modules are connected by Interconnects, small nanosats with a mass of approximately 1 kg, which also offer the potential for vibration isolation.

One of the key structural components is the HexFrame Structural Module (HSM). Acting as deployable beams, the HSMs assemble with HexBuses to form the overall structure of the SPS-ALPHA, which includes elements such as the Solar Reflector Assembly (SRA) and the Primary Array Assembly (PAA). The HSM is highly versatile, enabling multiple possible configurations including deployable truss structures, pre-stressed structures, and inflatable/rigidized structures.

Energy generation is managed by the Solar Power Generation (SPG) module, which utilises high-efficiency multi-bandgap Photovoltaic (PV) cells for power conversion. This module is fundamental for providing the electrical energy that is ultimately beamed back to Earth. The Wireless Power Transmission (WPT) module is instrumental in this regard, converting electricity into coherent RF (microwaves) that are transmitted to Earth-based rectennas through Microwave Power Transmission (MPT).

In the area of propulsion and station-keeping, the Propulsion and Attitude Control (PAC) module features an electric propulsion unit, expected to be a Hall Effect thruster, along with other subsystems such as avionics and thermal control systems.

The Modular Autonomous Robotic Effector (MARE) stands out as the central feature for the automated assembly and maintenance of the SPS-ALPHA system. This module can be reconfigured to adapt to various functionalities, including construction operations and reflector and thruster placements.

4 Adaptations for European Technologies

Considering the primary focus of this study, the architecture has been adapted to the use of European technologies.

4.1 Multi-Arm Robot (MAR)

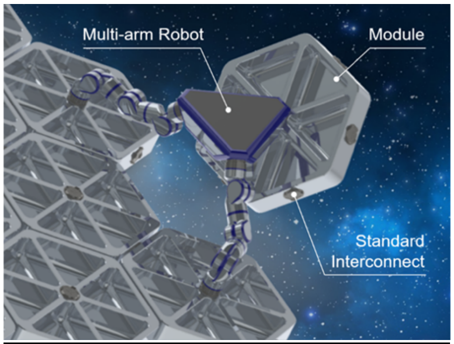


Figure 10: Multi-Arm Robot assembling a satellite on-orbit

The Modular HexBot Assembly (MHA) is replaced by a European system of similar functionality, the Multi-Arm Robot (MAR) developed by Space Applications Services.

MAR will work in a similar manner to the MHA in terms of functionality with the key difference being that of the systems implementing the functionality. MAR is composed of 2 MOSAR-like (see section 4.2) robotic arms and a central connecting torso. Each robotic arm will consist of a sophisticated arrangement of structural elements, joints and 2 SI's each connected to either end of the effector. The structure includes an arrangement of symmetrical assemblies and motorized joints combining to offer the required degrees of freedom necessary for the requested movement.

As opposed to the MHA, the central torso is a truncated tetrahedral volume, which connects the entire MAR system. The torso is equipped with 3 SI's including 2 static (passive) and one actuated (active) mechanisms enabling the MAR to connect with any module possessing a similar SI, a crucial requirement for the assembly of SPS-ALPHA. Equipped with a vision system, power source (PV cells) and avionics, MAR features a truly redundant, modular and highly versatile structure, offering a variety of manipulation and multi-robot cooperation possibilities.

The MAR has been initially introduced in the ESA TRP MIRROR project. In MIRROR, this robot aims at installing hexagonal elements and payloads in order to build a large orbital structure, and in particular, a telescope larger than the James Webb Space Telescope, as depicted in the above figure.

Since the Space-Based Solar Power station concept presented in this document features hexagonal elements, similarly to the MIRROR concept, a robot not dissimilar to the MIRROR's MAR can be used for performing the assembly operations.

Here, the elements are 4m hexagons (side to side). That would mean a scaling up of the MIRROR robot by a factor of 3.3. Thus, the robotic manipulator would measure 6 meters when fully deployed and the torso would be contained in a 4mx4mx0.85m volume.

For dexterity purposes related to the size of the manipulators needed in the context of MIRROR, a human-like arm configuration with non-spherical wrists has been selected. The existing kinematic configuration is baselined for this project, but since the manipulator would be 6 meters long here, other viable kinematic configurations could be envisaged in order to optimize the stowed configuration during launch. Hence, multi-offset configurations (similar to the Canadarm) or symmetric human like arm ones (similar to ERA) are also considered depending on the required launched configuration.

Three types of MARE modules exist in SPS-ALPHA: 1) servicing, construction & mobility; 2) reflector pointing; and 3) thruster pointing. Of these, the first type is the primary contributor during the assembly stage. MARE modules are designed to work both independently and cooperatively. They have standard interfaces for connecting with other system modules and rely on primary power from the HexBus module when fully assembled.

In the updated concept, the modules' cooperative nature enables complex tasks, such as transporting larger hexagonal tiles after pre-assembly. Preliminary assumptions suggest that two MAR robots can carry seven pre-assembled HexBus modules.

4.2 MOSAR-Walking Manipulator (WM) Robotic Arm

The MARE robotic modules (not to be confused with MAR) of SPS ALPHA are effectively replaced by MOSAR-like robotic arms at the following assemblies: SRA, PACA (in addition to its use in the MAR arms).

MOSAR-WM is a 7 joint symmetrical relocatable manipulator robot. Equipped with HOTDOCK standard interconnects at its tips (acting as end-effector), MOSAR-WM is able to relocate itself over the spacecraft equipped with SIs and is able to manipulate spacecraft modules and/or payloads featuring SIs. MOSAR- WM is fully compatible with the proposed architecture adaptation of SPS-ALPHA reliant on HOTDOCKs. This manipulator is based on a human like arm configuration with asymmetric joints and measures 6m long (adaptable to the need of the mission) and weighs 110kg (probably more in practice). Its joints consist of a set of components (frameless BLDC motor, magnetic brake, strain wave gear, preloaded bearings, motor and output position sensors, torque sensor, thermal elements, electronics + needed redundancy) that can be sized with respect to (wrt) a specific mission. Designed to support launch loads and offering wide range of motion, MOSAR-WM is perfectly suited to replace MARE to implement reflector steering functionality in the adapted SPS-ALPHA system.

4.3 HOTDOCK

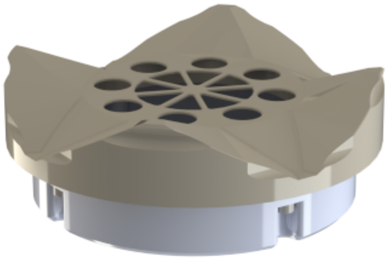


Figure 11 - Render image of Passive HOTDOCK

The HOTDOCK is an androgynous mating interconnect developed by Space Applications Services. This is an all in one interface capable of supporting mechanical loads, electrical power, data and heat transfer within a single coupling interconnect. Enabled by its versatile design the HOTDOCK can fulfil a broad spectrum of purposes including but not limited to the following:

- Distribute and control power between electrical subsystems (28V...100V / 40A)
- Transmit data at high rates bi-directionally between processing units (TTEthernet)
- Transfer thermal loads via direct conduction or fluid coolant transfer (20W...50W)

The product line is highly scalable and may be sized to satisfy a variety of mission needs, a key consideration for a system the size of SPS-ALPHA. Further prevailing its suitability, is its potential ability to be launched in a coupled state reducing in space assembly and also the availability of a radiation- hardened variant, a necessity for the geostationary environment. The sheer number of interconnects required for a km-scale SBSP system introduces potential mass overrun if not carefully monitored. Therefore, the availability of both active and passive HOTDOCK variants further justifies their suitability. Active HOTDOCKs contain actuation systems, whilst passive do not and thus may offer significant mass savings if implemented extensively where possible.

Additionally, it is proposed to modify HOTDOCK as follows:

- Interfacing to a compliance mechanism: this mechanism would allow to cope with stresses induced by the assembly of the large structure, where mechanical loops are closed, which are widespread in this system. In parallel to standard mechanism, the implementation of deformable mechanism is likely required. This compliance mechanism is assumed to be part of the HexBuses and the Deployable HexFrames, where the HOTDOCK is attached to.
- Release mechanism: this mechanism allows latching and unlatching the interconnects thanks to robotic operations. Thus, one can think about install external accesses to the interconnect that drives directly the interconnect mechanism when actuated by an external tool of action. At high level, when the robot successfully positioned its subassembly or element, one of its arm with a dedicated tool equipped at it tips, could be used to actuate the

needed number of mechanisms to attach the payload to the global assembly. Given the substantial number of HOTDOCKs, their aggregate mass and potential risks of failure, this would allow removing the embedded actuation and control systems currently present in the HOTDOCK design.

- Escape mechanism (EP Patent EP3,825,237): this mechanism allows retracting the form fit of HOTDOCK such that a module fully surrounded can be removed. This mechanism could be actuated using the same way as for the release mechanism. The use of an escape mechanism would be of particular benefit if implemented in the PPTA of SPS-ALPHA. Here each PAA is completely surrounded, incorporated into an assembly of approximately 63,936 PAA. The use of the escape mechanism here would allow for a PAA located within to be simply isolated and removed / replaced should a significant defect occur. This removal will therefore have no impact or impingement on neighbouring PAA ensuring the optimum power producing capability of the system even when undergoing maintaionance events.

Preliminarily, it is assumed that HOTDOCK may not need to be rescaled and is consistent with sizes in the order of magnitude of those proposed for SPS-ALPHA. Future structural analyses would need to be performed.

The mass of HOTDOCK with all the mechanisms would reach 1.5kg for the active version of HOTDOCK (not used in this concept). For the present concept, and with the release mechanism explained above, allowing to remove the active components, 500 g can be achieved for a so called “semi-active” version. A passive version with a mass of 200g is also used in the modified SPS-ALPHA concept.

4.4 Architecture modifications

Five methods for the translation of MAR across the system were explored. Walking operations using HOTDOCKs were initially considered but found preliminarily too time-consuming and unfeasible for large structures like the CTSA where the robots would need to walk for kilometers along the structure to perform assembly tasks. Other options like deployable torsos, free-floating methods, and transportation spacecraft were deemed either technically nonviable or too risky. The final choice involved combining walking operations with a rail translation mechanism made of Carbon Fibre Reinforced Polymer (CFRP). This proposed mechanism balances feasibility and speed, although adding an estimated additional mass of 2330.5 t for the Full Scale system and 32.5 t for the Pilot Plant system.

The HexBus module will remain the same size but is modified to include 24 HOTDOCKs to provide maximum flexibility for module mating. The HOTDOCKs will be strategically located on both the upper and lower faces, as well as on the side faces of each HexBus.

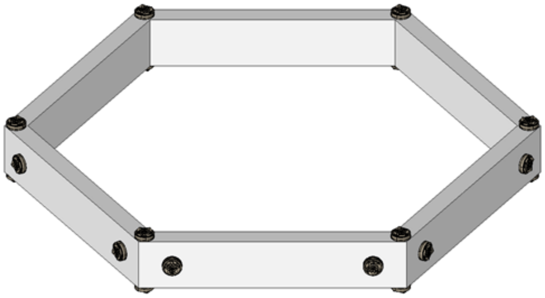


Figure 12: HexBus with pre-intergrated HOTDOCK interconnects

HexFrames will now include HOTDOCK modules at either end of its stowage canister, thereby standardising the interconnect and aiding in the assembly process.

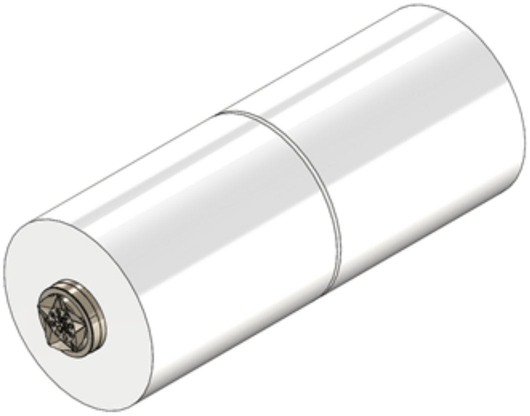


Figure 13: Deployable HexFrame with pre-integrated HOTDOCK shown in stowed configuration

The CTSA will consist of assemblies newly defined, using components from the existing SPS-ALPHA concept: Integrated HexBus (IH), Integrated HexBus Ring (IHR), and Integrated HexBus Ring Column (IHRC).

A new concept of Cargo Bays and Docking Ports based on HexBuses is proposed. Known as Harbours, these will facilitate module storage and docking of Orbit Transfer Vehicles (OTVs). The PPTA will be the initial section where these facilities will be placed, and their locations will change as the system grows.

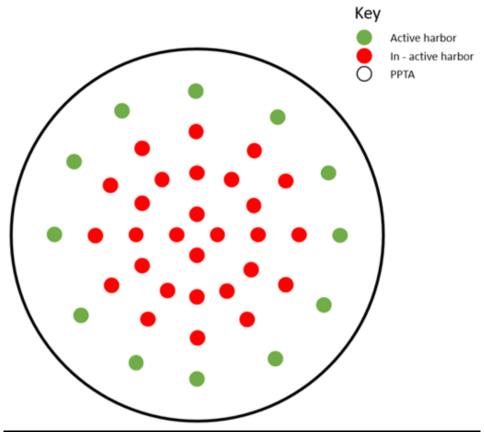


Figure 14: Diagram showing movement of harbours radially as the PPTA system grows

The steering of reflectors will be done via modular Push-me/Pull-you robotic arms, initially referred to as MAREs. For the sake of architectural adaptation, the MARE will be replaced with related European technology, MOSAR-WM.

Due to the lack of dimensional data for its components, dimensions from the SPS-ALPHA MK-II are used as an approximation for MK-I. MK-II's single Solar Reflector Assembly (SRA) has a known area of about 1900 m^3, leading to an estimated width of 54 m for the SRA. This data is then used to estimate that MK-I would require around 2060 SRAs, even though the original document [7] specified 4305 reflectors for MK-I. The discrepancy suggests that the MK-I SRAs were likely smaller than MK-II's, but for the purpose of the study, it's assumed that 2060 SRAs of 54 m diameter each are required for MK-I.

6. System Modelling

SysML has been employed to document the overall concept for simulation, covering both a pilot plant and the full-scale system. The model is crafted to represent the hierarchical composition of these systems at a component level, and it uses product tree diagrams to delineate this hierarchy, noting the quantity of each module required for every sub-assembly.

Architectural diagrams further refined the SysML model. These were designed to define the interface relationships between high-level assemblies. The model described the intricate system of HOTDOCK modules that act as connectors between various key structural elements like the PSA, CTSA, and PPTA.

The SysML model also delves into the modularisation of assemblies like the Reflector Array and the Solar Reflector Assembly (SRA), detailing how the modules interface with each other through HOTDOCKs. For instance, the PSA has been represented as a series of concentric stepped rings, each containing a single ring of SRA.

For greater granularity, the model also identified unique sections within assemblies, such as the inner, central, and outer sections of the PSA. These are detailed at a component level, highlighting unique interfaces both internally and externally.

Diagrams of the model showcased the varying lengths of these columns in both the pilot and full-scale models.

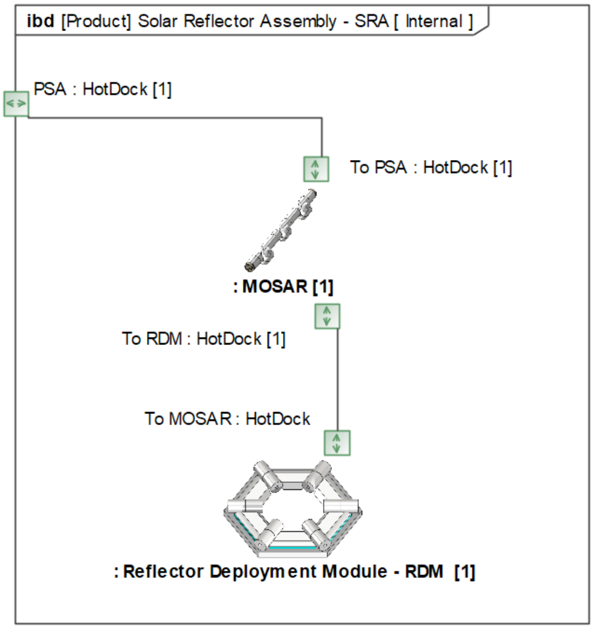


Figure 15: MBSE Diagram showing physical architecture of the SPS-ALPHA-Mark-I modified SRA

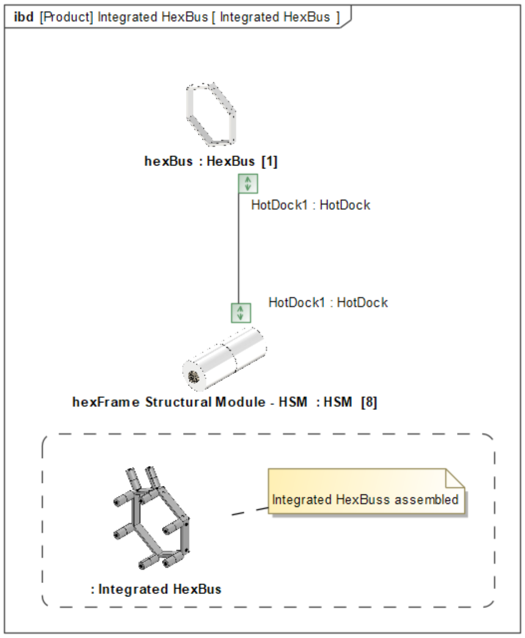
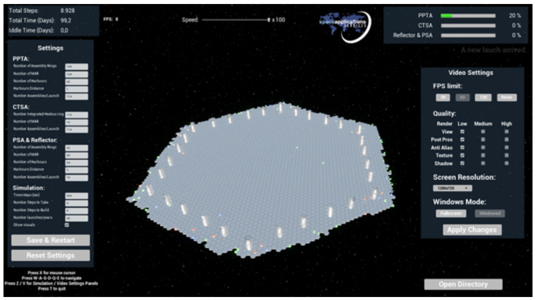


Figure 16: MBSE Diagram showing the physical architecture of a modified integrated HexBus assembly

The macroscopic and microscopic views of the system architecture are documented in the model, mapping out interfaces between assemblies and individual modules, providing a robust foundation for simulation and further development.

6.1 Robotic Assembly Simulation


Total Steps: 8.928
Total Time (Days): 99,2
Iddle Time (Days): 0,0

FPS: 8

Speed: x100

PPTA 20 %
CTSA 0 %
Reflector & PSA 0 %

A new lauch arrived.

Press X for mouse cursor
Press W-A-S-D-Q-E to navigate
Press Z / V for Simulation / Video Settings Panels
Press T to quit

Figure 17: Robotic assembly simulation GUI

The Skybeam software aims to simulate the construction of the SPS-ALPHA Mark-I system.The main goal is to approximate the time needed for the entire assembly, while a secondary goal is to visualize each phase in real time. The software is highly detailed and user-friendly, featuring adjustable settings and camera controls. It includes various parameters such as the number of robots, launch schedules, and module management. Different elements within the simulation like MAR, docking bays, and various components are designed for a highly visual experience. For example, MARs are color-coded for different tasks, and their movement is restricted to pre-built assemblies.

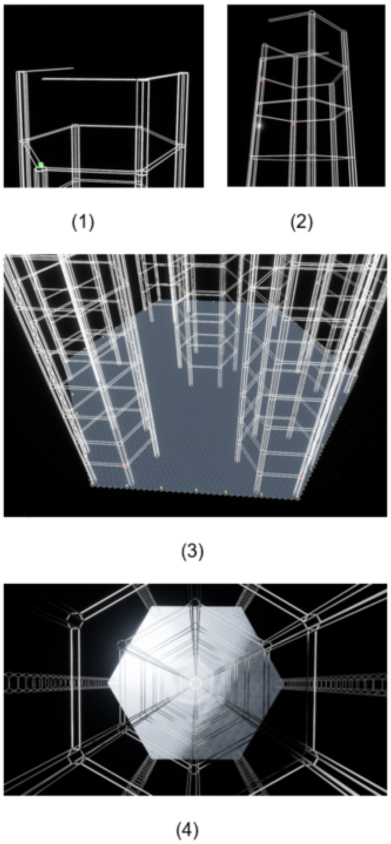


Figure 18: Assembly sequence of CTSA

The software uses Unreal Engine 5, which provides a range of features ideal for this complex simulation. It includes features like Nanite for virtualized geometry, Lumen for global illumination, and a virtual shadow map system for realistic lighting. Programming is done using a combination of blueprints and C++ classes, allowing quick iterations and advanced customisations. Users can interact with the simulation via a Graphical User Interface (GUI) that shows real-time progress, and settings can be adjusted for custom simulations.

Once a simulation is complete, a results file is generated, summarizing key metrics such as the time needed for construction, idle times, and the number of modules used. These results can be accessed via the GUI and are saved in a CSV format for further analysis.

MARs are responsible for constructing the system in a specific sequence. They start with the core structure

(PPTA), move to CTSA, and then assemble reflectors and PSAs. The construction process is divided into stages and is coordinated to avoid overcrowding of robots. Builders and Helpers are types of MARs, with Builders placing modules and Helpers assisting in the final steps. Their activities are overseen by a master controller. If a robot gets stuck, it is replaced to maintain progress.
\
Docking bays, where modules are stored, are arranged in rings around the construction and move closer to the structure as it is built. They are critical for MARs to retrieve building materials. The simulation currently lacks a priority system and inventory management for docking bays. Routes for MARs are optimized using an A* algorithm, though the algorithm isn't completely robust, it is deemed sufficient for the preliminary assessments in the present project.

A short Public Relations video of the assembly process can be viewed in [17].

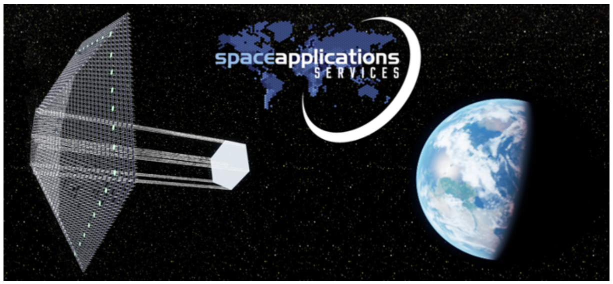


Figure 19: SPS-ALPHA Mark-I after the robotic assembly simulation has been completed

6.2 Logistics Assessment

An assessment has been made for the packing of modules in SpaceX's Starship and Ariane 64. This assessment primarily highlights the Starship's significant payload advantages over other options like Ariane 64. The increased fairing envelope and payload mass capacity of Starship, especially when on-orbit refuelling is considered, allow for much higher packing efficiency and fewer required payload launches to deliver hardware for SPS-ALPHA.

It was found that for PAAs, for example, Starship can accommodate 114 units per launch, an almost fourfold increase over Ariane 64 which can accommodate only 28.

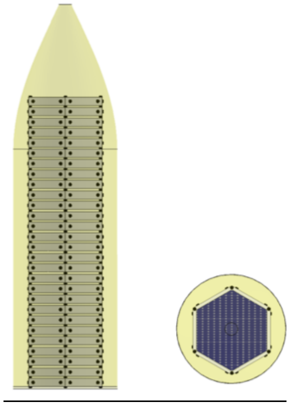


Figure 20: PAA example of packing analysis in Ariane 64 fairing envelope

Similarly, for Solar Reflector Assemblies (SRA), Starship can carry 75 in a single launch, approximately three times the Ariane 64's capacity. MARs also see enhanced efficiency, with 45 torsos or 346 arms fitting into a single payload.

For non pre-integrated components like HexBus and HexFrame used in CTSA and PSA, Starship can accommodate a total of 114 HexBus and 1600 HexFrame modules, limited only by its mass constraint and not by volume. This too represents a significant improvement over Ariane 64.

The overall takeaway is that Starship's unique capabilities, including on-orbit refuelling, significantly reduce the number of launches required to deploy the SPS-ALPHA system, making it a more economically viable and logistically simpler option. Although the analysis is not fully optimised, even a rough comparison makes it obvious that Starship has distinctive advantages for this high-volume, high-mass mission profile.

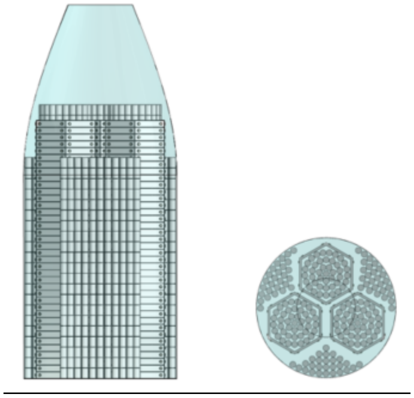


Figure 21: PAA and HexBus, example of combined launch analysis in Starship fairing envelope.

The approach for assessing hardware delivery timelines focused on each unique launch scenario. The model accounts for various types of hardware payloads each having distinct unloading times due to varying mass, volume and geometries. These unique payloads are delivered through a series of events, termed as missions, that follow a pre-defined trajectory from Starbase to other locations like Low Earth Orbit (LEO) and Geostationary Orbit (GEO).

The key parameter that differentiates each mission is the payload and its associated unloading time. Each trajectory has specific time durations for its segments, for instance, Starbase to LEO takes 0.25 days, LEO to GEO takes 6 days and so on. The model calculates the unloading times under a worst-case scenario, using a single robot for unpacking the payload, to provide a baseline for process optimisation. For example, a PAA launch that includes 114 PAA modules takes 3.8 days to unload, while a MAR Torso launch with 45 torso elements requires just 1.5 days.

The model's granular insights are then extrapolated into a high-level mission timeline using a combination of SpaceNet and Excel. This timeline incorporates all the low-level events, such as launch dates, trajectory durations, and docking times, providing a comprehensive view of the entire hardware delivery process. The end goal is to offer a coherent and accurate timeline that can be used for effective hardware delivery, thus aiding in the strategic planning and optimisation of space missions.

6.3 Capex/Opex Costing Assessment

The costing Skybeam assembly was made using a model developed in MS Excel, designed to accommodate various operational scales and sourcing scenarios. It accounts for technical specifics, simulation outcomes, and existing historical data to generate a cost profile in EUROs for the fiscal year 2023.

At its core, the model explored four different operational scenarios: a pilot plant with Earth-sourced modules, a full-scale operation also reliant on Earth-sourced materials, and two full-scale variations which consider using either Earth-sourced or Moon-sourced raw materials. These scenarios serve as the foundation for calculating both capital and operational expenditures, commonly abbreviated as CAPEX and OPEX.

A number of inputs are fed into the model, such as mass breakdowns, module lifetimes, and simulation results—which include variables like the number of robots required for assembly, assembly time, and material consumption over time.

Capital expenditures (CAPEX) cover the costs of development and launch, while operational expenditures (OPEX) account for the running costs including maintenance and refurbishment, calculated based on an annual average factor of 2.67%. Additionally, pre-development costs are calculated as roughly 20% of one-of-a-kind (OAK) costs with an additional 15% earmarked for testing and qualification. Acceptance testing further adds about 5% to OAK costs.

Crawford's theory is applied to predict cost reductions that can be achieved in mass production. The learning factor applied is 0.7 (for a higher number, lower price of the products is, for large productions). In terms of staffing, the model assumes that a pilot plant would require 50 staff members, while full-scale operations would necessitate a team of 350.

The model does not incorporate the costs associated with ground infrastructure, assuming these to be Government-Furnished Equipment (GFE).

7. Simulation Results

7.1 Timeline estimates

An assessment of the timeline is made for the unloading different types of launches these scenarios, where different payloads—ranging from Propulsion and Attitude Control Assembly (PACA) to Solar Reflector Assembly (SRA)—are considered. Each payload type has a unique set of attributes such as mass and volume, and different unloading times.

The study modelled various types of launches, from PAA to MOSAR-WM 2 DoF, each with their unique requirements for unloading time. For example, a PAA launch, which consists of 114 modules, requires 3.8 days to unload, while a Combined HexBus and HexFrame launch, which is more complex, requires a considerably longer 57.13 days for unloading.

The following is a rundown of the various types of launches modelled in a SpaceX starship launcher.

- PAA Launch: Contains 114 PAA modules and requires 3.8 days for unloading.
- MAR Torso Launch: Comprises 45 MAR Torso elements and needs 1.5 days for unloading.
- MAR Arm Launch: Includes a total of 346 MAR ARM's and takes approximately 11.53 days for unloading.

- PACA Lower Launch: Holds 200 Lower PACA elements and needs 6.67 days for unloading.
- PACA Upper Launch: Contains 27 upper PACA elements, requiring just 0.9 days for unloading.
- Combined HexBus and HexFrame Launch: Consists of 114 HexBuses and 1600 HexFrames, taking a significant 57.13 days for unloading.
- HexBus Only Launch: Contains 114 HexBus modules, requiring 3.8 days for unloading.
- SRA Launch: Includes 75 Solar Reflector Assemblies (SRAs) and needs 2.5 days for unloading.
- MOSAR-WM 2 DoF Launch: Has 1038 MOSAR-WM modules and requires an extensive 34.6 days for unloading.

The timelines are built upon key locations like Starbase, Low Earth Orbit, and Geostationary Orbit, with varying durations for reaching each point.

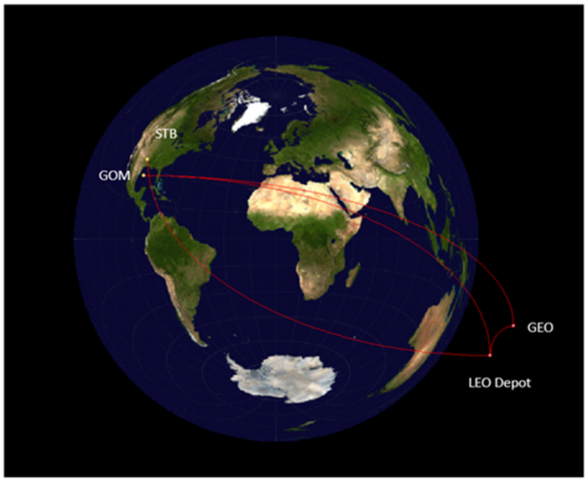


Figure 22: Screenshot taken from SpaceNet Logistics model showing the nodes and trajectories used.

The considered trajectories for these are: Starbase –LEO (0.25 days), LEO – GEO (6 days), and GEO-GOM (8 days).

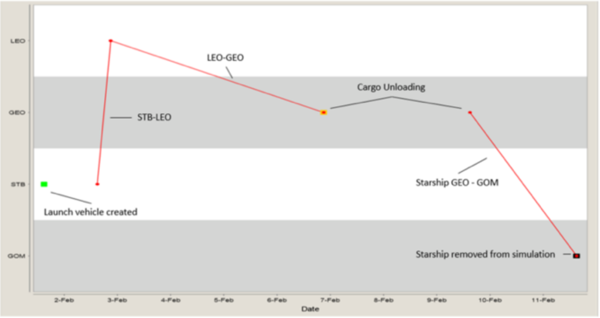


Figure 23: Screenshot from SpaceNet showing notional mission timeline for launches modeled for the logistical analysis

Unloading times are calculated under the pessimistic assumption of using a single robot to unload each module. This provides a worst-case scenario, not taking into account parallel unloading that could shorten these times. The model also accounted for the trajectory durations between different orbits and docking times.

The timelines were exported to Excel to establish a high-level hardware delivery schedule, which includes launch dates, trajectory durations, and docking dates. This comprehensive approach allows for a more accurate prediction of the hardware delivery process, although optimization, particularly in unloading times, remains an area for future study.

7.1 Assembly Process Simulation

The simulation for determining optimal parameters for on-board operations in the Skybeam assembly project explored 36 distinct cases. These cases are set up to evaluate three key variables: the number of MARs, the number of docking bays or harbours, and the frequency of payload launches per month (note, this number does not include the number of launches for refueling of Starship, only payload launches). The output metrics include the total duration of assembly in both days and years, as well as an estimate of the idle time for the MARs. The simulation results were further visualised through 3D surface plots to examine the effect of the input variables more clearly.

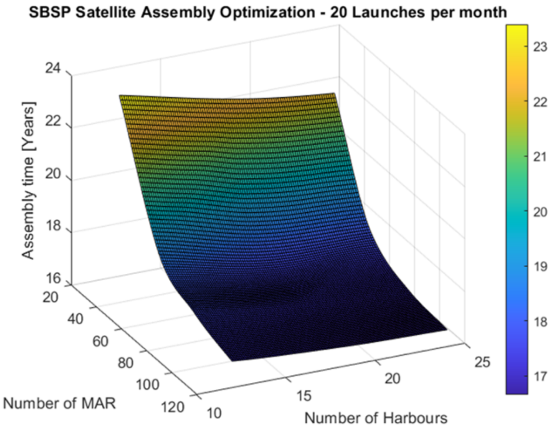


Figure 24: Assembly duration surface plot for a launch frequency of 20 launches per month

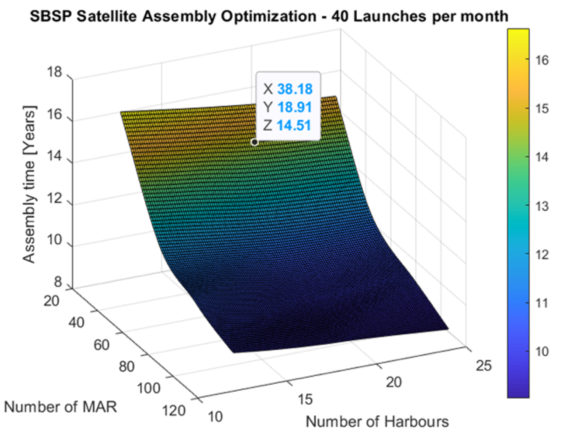


Figure 25: Surface plot for 40 Launches per month showing that for approximately 39 MAR and 19 Harbours an assembly duration of 9.5 years is estimated

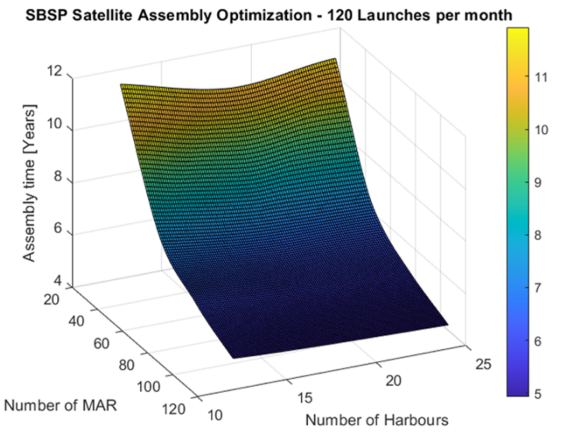


Figure 26: Assembly duration surface plot for a launch frequency of 20 launches per month

In scenarios with 20 payload launches per month, the simulation suggests that increasing the number of MARs and harbours leads to a decrease in the total assembly time. This is a predictable outcome and indicates that more resources, storage areas and docking ports expedite the assembly process. The total assembly durations for these scenarios ranged from approximately 16.66 to 23.4 years. However, increasing the number of harbours alone did not lead to a significant reduction in total assembly duration.

With 40 payload launches per month, the data similarly indicates a strong positive correlation between the increasing numbers of MARs and harbours, and a decrease in the assembly time. The assembly durations ranged from 9.03 to 16.64 years. A similar strong improvement is observed with the number of MARs, and a moderate improvement with the number of harbours.

In the high-frequency case of 120 payload launches per month, the data reinforced the trend that increasing both the number of MARs and harbours leads to quicker assembly. However, simply increasing the number of harbours without a corresponding increase in MARs offered very limited benefits. In this case a specific range within 15-20 harbours could potentially be optimal under the simulation conditions, supported by a noticeable dip in assembly times when the number of MARs is lower.

This is suspected to be the result of an optimum balance between number of MAR and number of harbours. For low numbers of MAR and low number of harbours (<15), assembly time will be inherently long as although launch frequency is high, having a low number of harbours will limit the benefit observed from using a high launch frequency. Conversely, when using a high number of harbours (>20) in combination with a low number of MAR a long assembly duration is also observed. It is hypothesised that this is due to long travel durations required by MAR in this scenario. For example, as the number of harbours is large they will be spread out further from each other. Due to the low number of MAR there may be an increase in idle time where MAR and translating across the system to retrieve modules from harbours rather than performing building operations.

This is supported by the residing of this dip observed in the surface plot of figure 27 as the number of MAR increases. Eventually as MAR continue to increase this dip is seen to disappear forming a smooth sloping plane.

The simulations concluded that, for the simulation assumptions made, to optimise the Skybeam assembly process, greater benefits may be achieved in the reduction in system assembly time by increasing the number of MARs while the increase of docking bays or harbours may offer more limited benefits (note that 1 harbour is composed by multiple modules allowing docking of spacecraft and storage of modules).

7.3 Cost Evaluation

The model includes various cost elements such as predevelopment, equipment, testing, maintenance, refurbishment, and both Earth and Lunar launch costs. Ground infrastructure, assumed to be Government-Furnished Equipment (GFE), is notably left out of the costing model.

Pre-development costs are calculated using equipment mass and Cost Estimating Relationships (CERs). Each use-case involves extensive testing and qualification of unique items, which are then integrated into single or multiple systems to evaluate various aspects like deployment and communication.

In terms of mass production, the rate of equipment production is adjusted to align with the launch rate, and all equipment must be prepared at least a month before the scheduled launch. The model assumes that manufacturing and launch frequencies are the primary schedule drivers. Manufacturing can be scaled up, but launch services act as a bottleneck, necessitating 2-3 payload launches per week.

All costs are presented in Euros, and the analysis is based on the fiscal year 2023.

For the majority of payload launches, the payload does not exceed 21t and so may be launched directly to GEO [16]. However, for each scenario a number of payload launches exceed the 21t payload limit for direct GEO injection. Instead, these launches require a refuel in order to launch a payload up to 100t to GEO. Although this refuel step adds additional complexity to logistical operations, [16] states the intentions for this to become a reality for Starship launched payloads. Therefore, refueling ahs been considerd in the cost analysis for each scenario. The table below summarizes the number of launches for each scenario with / without refuel needs:

Table 1: Number of launches with refuel and without refuel to GEO

Scenario	Number of launches without refuel	Number of launches with refuel
Scenario 1	24	6
Scenario 2	3425	40
Scenario 3	3391	42
Scenario 4	3399	34

The assumed cost per launch of a Starship launch is 10 MEUR per launch.is 10 MEUR (be it for payload launches the refueling launch needed when the individual Starship payload is heavier than 21 tonnes).

The cost of production of metal on the Moon with an FFC plant and a power station (ESA European Charging Station for the Moon) is calculated at 500 EUR/kg, with a cost of delivery from the Moon to GEO of 1000 EUR/kg [18].

Note: In the following costs, the lower end of the scenario and launch cost represents the hypothetical scenario in which the modules density is ignored (i.e. the modules can be made as compact as needed to use the full mass capacity of the launcher). The higher end of the cost represents the Skybeam scenario, in which a preliminary study of the volumetric load of the modules was made against the Starship capacity, which is believed to be the more realistic scenario.

Scenario 1 - The results for Scenario 1 show that setting up a Pilot Plant system with pre-fabricated modules brought from Earth would require a total cost of 4.9-5.34 billion Euros (BEUR). This amount includes 4.8 BEUR for initial capital expenditure (CapEx), 0.1-0.54 BEUR for launch costs from Earth, and 0.7 BEUR for operational expenditure (OpEx).

Scenario 2 The cost estimation for Scenario 2, which involves setting up a Full Scale Solar-Based Power System (SBSP) using pre-fabricated modules from Earth, indicates a total cost of 32.7-97.4 billion Euros (BEUR). This total is broken down as follows: 28.5 BEUR for initial capital expenditure (CapEx), 4.1-68.9 BEUR for launch costs from Earth, and 4.1 BEUR for operational expenditure (OpEx).

Scenario 3 explores the cost of setting up a full-scale Solar-Based Power System (SBSP) using a combination of raw materials from Earth and in-orbit manufacturing for the Central Thermal Solar Array (CTSA).

It is noted that The truss (CSTA) includes 7476 (~1.9% of total of the System) Hexbus modules and 9968 (~54% of total of the System) Hex frame structures making up about 717.7 tons.

The total estimated cost for this approach is 45.2-109.2 billion Euros (BEUR). The breakdown is as follows: 41.0 BEUR for initial capital expenditure (CapEx), 4.2-68.2 BEUR for launch costs from Earth, and 4.6 BEUR for operational expenditure (OpEx).

Scenario 4 explores the cost of setting up a full-scale SBSP using a combination of modules sent from Earth and raw materials from the Moon. The raw material for in-orbit manufacturing for the CTSA will be produced on the Moon by an ISRU process assumed to be FFC Cambridge, with yet-to-be-defined enhancements for producing a suitable metal alloy useable for this purpose with the process.

The total estimated cost for this approach is 46-109.2 billion Euros (BEUR). The breakdown is as follows: 41.0 BEUR for initial capital expenditure (CapEx), 4.0-67.2 BEUR for launch costs from Earth, and 4.1 BEUR for operational expenditure (OpEx).

It must be noted that the result of this scenario as is does not lead to savings, and the total cost would be higher than Scenario 2, the baseline Full Scale Scenario. This is attributed to the low expected launch costs of Starship.

A sensitivity analysis is made to establish what can be the breakeven point that could be achieved with respect to scenario 2. That is the point at which ISRU would become an attractive proposition. This point is reached if more Hexbus modules and more Hex frame structures i.e.when in addition to the CTSA, additional Hexbus modules and Hexframe structures are built with raw material from the Moon.

This amounts to a total of 90222 (i.e. ~23% of total of the System) Hexbus modules and 11791 (~63.9%% of total of the system) Hexframe structures. In this case the total cost is 97.4 BEUR.

This is only for the Skybeam scenario, in which a preliminary study of the volumetric load of the modules was made against the Starship capacity.

If the totality of Hexbus and Hexframes were built with Lunar material, the cost would be 51.6 BEUR, for the same volumetric assessment scenario, a considerable reduction of the cost over the 97.4 BEUR of Scenario 2..

8. Conclusion and Recommendations

8.1 Summary

The assembly simulation explored 36 different cases to investigate the impact of three critical variables: the number of MARs the number of docking bays or harbours, and the frequency of monthly payload launches. The outcomes indicated that an increase in the number of MARs and harbours generally resulted in a reduction in total assembly time as expected. For instance, at 20 payload launches per month, the assembly duration ranged from around 16.66 to 23.4 years. This range dropped to 9.03 to 16.64 years with 40 payload launches per month. Furthermore for the specific assumptions made, in a high-frequency scenario of 120 payload launches per month, the number of harbours optimally falls within the 15-20 range, especially when the number of MARs is lower, an optimal balance between the number of MARs and harbours seems to be crucial for time-efficiency, particularly at higher launch frequencies , although this potential optimisation point may benefit from confirmation in further studies. . The findings suggest that allocating more resources to MARs could offer greater efficiency gains than simply increasing the number of harbours.

In Scenario 1, a pilot plant with Earth-manufactured modules, the total cost ranges from 4.9 to 5.34 BEUR. Scenario 2, the baseline full-scale setup using Earth-based modules, estimates a range of 32.7 to 97.4 BEUR.

When considering the integration of in-orbit manufacturing in Scenario 3, the total cost estimates range from 45.2 to 109.2 BEUR. However, moving to Scenario 4, which considers sourcing raw materials from the Moon, does not provide cost savings compared to the Earth-based baseline scenario, amounting to a total of 46 to 109.2 BEUR. Sensitivity analysis suggests that there could be a breakeven point at which sourcing from the Moon becomes economically viable. This point is reached when about 23% of Hexbus modules and nearly 64% of Hexframe structures are built using lunar materials, resulting in a total cost of 97.4 BEUR. This figure significantly drops to 51.6 BEUR if all Hexbus and Hexframes are lunar-made. If a different launcher from Starship would be used this breakeven point would be reached much earlier.

Lunar sourcing under the initial hypothesis of building only the CTSA, appears economically in-viable unless a significant additional percentage of the structure is built from lunar materials. Even then, due to the low expected launch costs of Starship, the lunar scenario becomes competitive at high lunar material utilisation rates.

It has been identified that there is a strong influence of the packing density in the costs of the launches, as according to the module accommodation study, the density of the modules may be relatively low and may not occupy the full mass capacity of the launcher.

8.2 Recommendations for Future Work

- The algorithms responsible for determining pathways could be improved to minimise instances of blockages.
- While the costing was made for Starship launches, only an accommodation assessment was conducted for Ariane 64, future work could involve more in-depth costing analysis for this and other launch systems.
- The simulation framework and MBSE can be extended to study new European concepts, providing a broader scope of assessment.
- The current evaluation of Starship costs relies on preliminary figures. Future work will necessitate more robust, definitive data.
- To better understand the cost model's vulnerability to various assumptions and variables, multiple sensitivity analyses should be undertaken.
- Future work could couple the current simulation frameworks with more in-depth studies that consider thermal aspects, Attitude and Orbit Control Systems (AOCS) factors, environmental impacts, and multiple other wider-scope considerations.

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Acronyms & Abbreviations

Acronym	Description
AOCS	Attitude and Orbit Control System
BEUR	Billion Euro
CAPEX	Capital Expenditure
CFRP	Carbon Fibre Reinforced Polymer
CTSA	Connecting Truss Structure Assembly
ESA	European Space Agency
EU	European Union
GEO	Geostationary
GUI	Graphical User Interface
GW	Giga Watt
HSM	Hexframe Structural Module
IH	Integrated HexBus
IHR	Integrated HexBus Ring
IHRC	Integrated HexBus Ring Column
LEO	Low Earth Orbit
MAR	Multi Arm Robot
MARE	Multi Arm Robotic Effectors
MBSE	Model Based System Engineering
MEUR	Million Euro
MHA	Modular HexBot Assembly
MPT	Microwave Power Transmission
MPT	Microwave Power Transmission
MW	Mega Watt
NTRS	Nasa Technical Reports Server
OAK	One of a Kind
OG	Operational Grant
OPEX	Operational Expenditure
OSIP	Open Space Innovation Platform

PAA	Primary Array Assembly
PAC	Propulsion and Attitude Control
PACA	Propulsion and Attitude Control Assembly
PPTA	Primary Power Transmitter Array
PSA	Primary Structure Assembly
PV	Photovoltaic

RF	Radio Frequency
SBSP	Space Based Solar Power
SPG	Solar Power Generation
SRA	Solar Reflector Assembly
TRL	Technology Readiness Level
WPT	Wireless Power Transmission