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Technical evaluation of additive manufacturing technologies for in-situ fabrication with lunar regolith

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Abstract

In-Situ Fabrication and Repair can significantly reduce the construction cost of a permanent Moon base by using additive manufacturing (AM) and exploiting local resources instead of bringing all the required materials from Earth. In this article, we evaluate alternative additive manufacturing technologies for building a lunar base and maintaining it across its lifecycle. We compare alternative 3D-printing techniques, already tested for manufacturing with simulants of lunar regolith, using energy, Earth-deliverables consumption, and compressive strength of the produced samples as figures of merit. Based on our analysis, we conclude that Cement Contour Crafting and Stereo-lithography AM techniques are the most promising solutions for the construction of outdoor lunar infrastructure and small precise parts and instruments, respectively.

Keywords: additive manufacturing, 3D-printing, ISFR, ISRU, Moon exploration, lunar regolith

1. Introduction

A new Moon race is being pursued by the national space agencies and commercial aerospace companies to set foot on the Moon and build there a permanent and sustainable human presence (NASA, 2021a). The need to build a crewed outpost on the lunar surface entails the necessity of delivering large amounts of cargo from Earth to construct all the required infrastructure for habitation, transportation, energy supply, and life support (Benaroya, 2010). The high costs associated with launching all the corresponding mass to the lunar surface make in-situ resource utilization (ISRU) (Lim et al., 2017) an attractive alternative to be considered for on-site construction activities. One of the possible approaches for on-site construction on the Moon, using local resources, is additive manufacturing (AM) with lunar dust (Happel, 1993). In recent years several AM technologies capable of producing solid parts from lunar regolith were considered, utilizing lunar regolith simulants (Engelschiøn et al., 2020; Isachenkov et al., 2022; Sun et al., 2017a; Zocca et al., 2020) for tests (Isachenkov et al., 2021a). The present paper aims to support the decision-making of the researchers and engineers, working in the field of in-situ fabrication and repair (ISFR), helping them select the most promising additive manufacturing approaches for

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both the construction of large-scale civil infrastructure and to produce precise ceramic parts from lunar regolith.

Over the last few years, several review papers were published on the topic of in-situ resource utilization on the Moon. Lim et al. (Lim et al., 2017) reported on advancements, opportunities, and challenges of R&D in the field of in-situ fabrication on the Moon. Authors of (Sacco and Moon, 2019) discussed the wider topic of additive manufacturing for space, also considering additive manufacturing on the Moon as one of the most important aspects of ISRU. In the work (Isachenkov et al., 2021a) authors systematized cases of additive manufacturing with lunar regolith simulants and formulated the basic requirements and approaches for adapting additive manufacturing methods to lunar surface conditions. Authors of another recent review (Ulubeyli, 2022) focused on discussion on additive manufacturing technologies, applicable for lunar shelter construction.

In this paper, we aim to quantify performance and evaluate tradeoffs in the introduction of AM technology in lunar settlement developments; and to downselect the most promising approaches for the large-scale outdoor construction and in-door precise parts manufacturing from lunar regolith, based on a parametric system-level mathematical model.

The remainder of this paper is structured as follows. Section 2 provides additional background on the use of additive manufacturing using lunar regolith. Section 3 illustrates the approach followed to conduct the analysis in this paper. Section 4 shows the results of our analysis, illustrating key tradeoffs. Section 5 illustrates the limitations of our approach and avenues of future work we envision in the field. Section 6 concludes our analysis, addressing our intended research objectives.

2. Background

NASA OIG's November 2021 report (NASA, 2021a) estimates the launch cost of the Orion crewed vehicle to the Moon at $4.1 BUSD (Figure 1). Considering the 27-ton payload capacity of Space Launch System (SLS) Block 1 to the lunar surface, one can calculate that cost of launching mass to the Moon using SLS would be around $80 kUSD/kg.

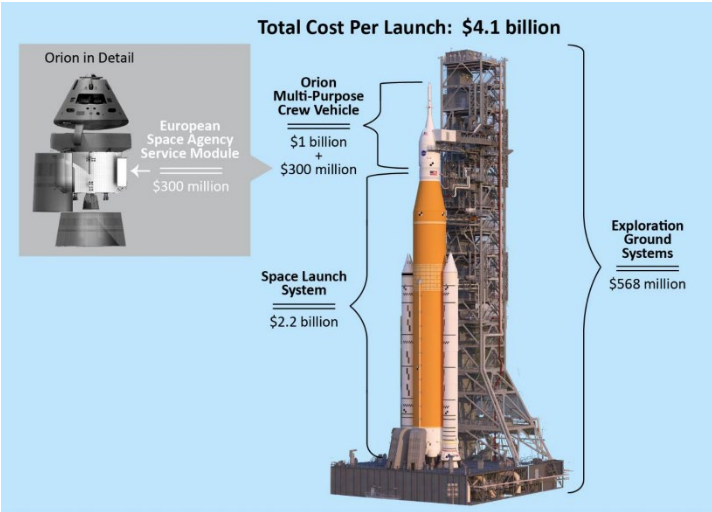

Figure 1 Total cost per launch of space launch system for Artemis program missions (NASA, 2021a) ***(Credit: NASA)***

According to estimates made by (Cesaretti et al., 2014), the radiation shielding needed for a 40 m^3 pressurized living volume would weigh about 250 tons, which would then cost $20 BUSD to deliver from Earth. Such considerations bring attention to the concepts of ISRU and correspondingly to the vision of In-Situ Fabrication & Repair (ISFR) as promising options for making the human presence on the Moon affordable and sustainable. Those concepts include extracting oxygen and metals from lunar rock (Sanders and Larson, 2011), mining lunar ice (Li et al., 2018) for drinking water and rocket fuel, and AM using lunar regolith (Isachenkov et al., 2021a)(Figure 2).

Figure 2 Artist's impression of moon base construction with extensive use of ISRU © Xtend design

ISRU may become a cornerstone for sustainable crewed Moon exploration, providing astronauts with all needed infrastructure while improving the lunar outpost's redundancy by making possible the in-situ repair of exploration equipment and dramatically reducing the weight to be carried to the lunar surface by perusing local materials (Anand et al., 2012). However, the cost-benefit trade-off of the regolith-based AM technologies strongly depends on the manufacturing technology selected and its intended application use.

Lunar regolith is relatively well studied compared to other extra-terrestrial soils. This dust-like natural material, covering the lunar surface (Heiken et al., 1991), has been generated by space weathering for millions and billions of years. These space-weathering phenomena include thermal cycling, meteorite impacts, solar wind, and cosmic radiation (Pieters et al., 2000).

Lunar regolith has wide particle size distribution– individual particles of lunar regolith range in size from micrometers to hundreds of millimeters, with mean values of 45 - 100 µm (Greenberg et al., 2007). The shape of the regolith particles is different from Earth minerals, as the lunar soil was never exposed to erosion factors like wind and rain, leading to an irregular, angular shape with sharp edges (Rickman et al., 2012). Samples of lunar regolith delivered with the Apollo, Luna, and Chang'e 5 missions from different areas of our natural satellite, including both lunar highlands and lunar mare, were extensively studied by the scientific community. It was found that lunar soils are mostly composed of the same minerals, as the Earth's crust (Heymann, 1978). It was determined that the lunar highland's regolith is dominated by plagioclase (anorthosite) (Labotka et al., 1980; Taylor et al., 2010), with crystal basalt being the second greatest constituent and only trace amounts of olivine and ilmenite. Lunar mare regolith is mostly composed of pyroxene basalts, with significant amounts of plagioclase, olivine, and ilmenite (Jerde et al., 1994; Papike et al., 1982). There are some important differences in the mineral composition of lunar regolith from the composition of terrestrial soils. Since their formation, lunar soils were exposed to the constant flow of solar wind particles, mostly high energetic protons. This proton sputtering of the lunar minerals led to the formation of iron nano-particles on the borders of FeO grains in lunar minerals (Tang et al., 2012). Another interesting peculiarity of lunar rock composition is the vast abundance of the glass phase. Since the Moon's surface is regularly bombarded by hypervelocity micrometeorites, the kinetic energy of impacts melts lunar dust to a specific glass-like phase, known as agglutinate (Chao et al., 1970).

The availability of lunar regolith samples on Earth from the Luna and Apollo missions makes it possible to create high-fidelity simulants (Engelschiøn et al., 2020; Isachenkov et al., 2022; Ray et al., 2010; Sun et al., 2017b) with chemical, mineral, and mechanical properties close to the real lunar soils. However, the geography of obtained samples is limited. It is not possible to predict the precise soil composition of a candidate landing zone for a future permanent lunar base, which most probably would be located near the lunar south pole, where cold traps containing water ice can be found alongside the crater rims, almost constantly lit with sunlight (Kruijff, 2000). AM technologies for the Moon rely on Earth-derived consumables such as binders or inert gases, which cannot be taken from the Moon and used to improve the properties of 3D printed materials. In the future, we want to minimize the consumption of Earth-derived materials either by improving our 3D printing technologies or by applying locally produced binders.

The present work will consider the AM technologies, which were various lunar regolith simulant materials. All of the described AM approaches were thoroughly discussed and analyzed in several research articles and literature reviews (Isachenkov et al., 2021a; Lim et al., 2017; Sacco and Moon, 2019).

Additive manufacturing is an effective and versatile way of producing objects of a wide range of sizes – from micrometers to tens of meters. AM is a promising alternative to traditional techniques (CNC machining, casting, pressing, etc), especially in the field of crewed space exploration of the Moon, where the capability of manufacturing objects with virtually any shape on-demand may serve as an essential backbone of lunar outpost's sustainability. The ability to 3d-print infrastructure objects, everyday items, and spare parts from in-situ mined lunar regolith is particularly tempting, as it helps drastically decrease the amount of construction material to be launched from Earth. AM techniques, capable of printing with lunar regolith, are based on different physical principles and can be subdivided into a few categories: Powder Bed Fusion techniques include Selective solar light sintering (SSLS) (Meurisse et al., 2018), Selective laser melting (SLM) (Fateri and Gebhardt, 2015), and Selective microwave sintering (SMWS) (Taylor and Meek, 2005). The second group of AM technologies is extrusion-based methods, which are Cement Contour Crafting (CCC)(Scott Howe et al., 2013), Inkjeeting (IJ) (Jakus et al., 2017), and Binderjetting (BJ) (Ceccanti et al., 2010). Finally, the third type of AM capable of printing with lunar regolith is the stereolithography-based methods, which are Digital light processing (DLP) (Liu et al., 2019)(Isachenkov et al., 2021b) and Laser stereolithography (SLA) (Isachenkov et al., 2022) (figure 3).

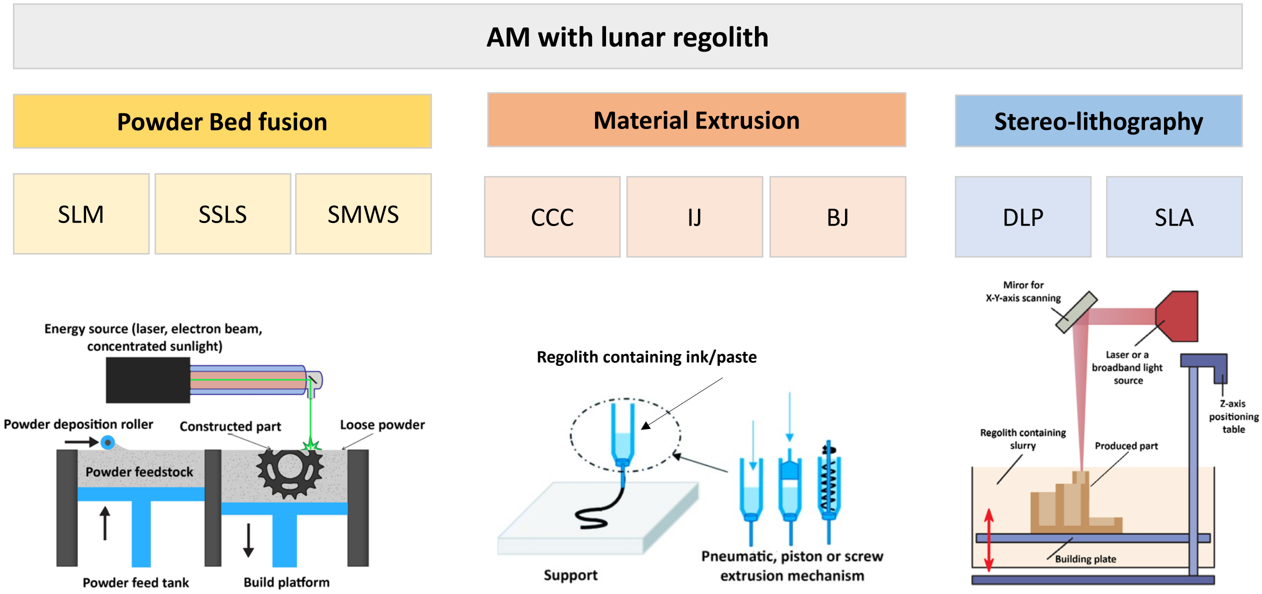

Figure 3 Classification of AM techniques, capable of 3d-printing with lunar regolith

All these methods were tested with high fidelity lunar regolith simulants, thus shown to be technically feasible to use. Each technology has certain drawbacks and advantages, which govern the possible areas of application of the AM method. The major flaws of the AM technologies requiring improvement are high demand for consumables (mostly binders) delivered from the Earth, low mechanical strength and high anisotropy of printed parts, the high energy demand of printing, and pre/post-processing equipment, and inadequate low-gravity performance. Also, it is important to mention the selenographical restrictions– whereas the efficiency of material extrusion-based AM methods is mostly independent of source lunar soil composition, powder bed fusion and stereolithography-based techniques' performance may strongly vary, depending on lunar regolith composition. For example, in the work (Isachenkov et al., 2022), it was shown that slurries containing anorthosite-rich lunar highland simulant can be UV-cured to a greater depth than basalt-rich lunar mare simulant-based slurries, thus resulting in different efficiency of 3d-printing via stereolithography-based techniques. A study (Meurisse et al., 2017) reveals that the mineral composition of lunar regolith strongly affects the mechanical properties of sintered parts, which should be taken into consideration for the development of all sintering-based AM approaches.

As the research in this field of studies boldly continues, we have more data to analyze, gathered by several research teams around the globe, utilizing different AM approaches with various lunar regolith simulants. To speed up these efforts, it is essential to analyze and compare results achieved up-to-date.

3. Approach

As the analyzed AM techniques are based on the different physical principles, their FoMs differ significantly, which complicates the decision-making for the R&D in this area. The main idea here is to balance competing FoMs, so the best possible trade-off can be found. One of the possible approaches to solving a multiple criteria decision-making problem (Jahan and Edwards, 2016) (and specifically a multi-objective optimization problem) is the Pareto efficiency method. The Pareto front includes all Pareto optimal solutions for a given set of FoMs (Crawley et al., 2016). Figure 4 illustrates the approach followed in our work.

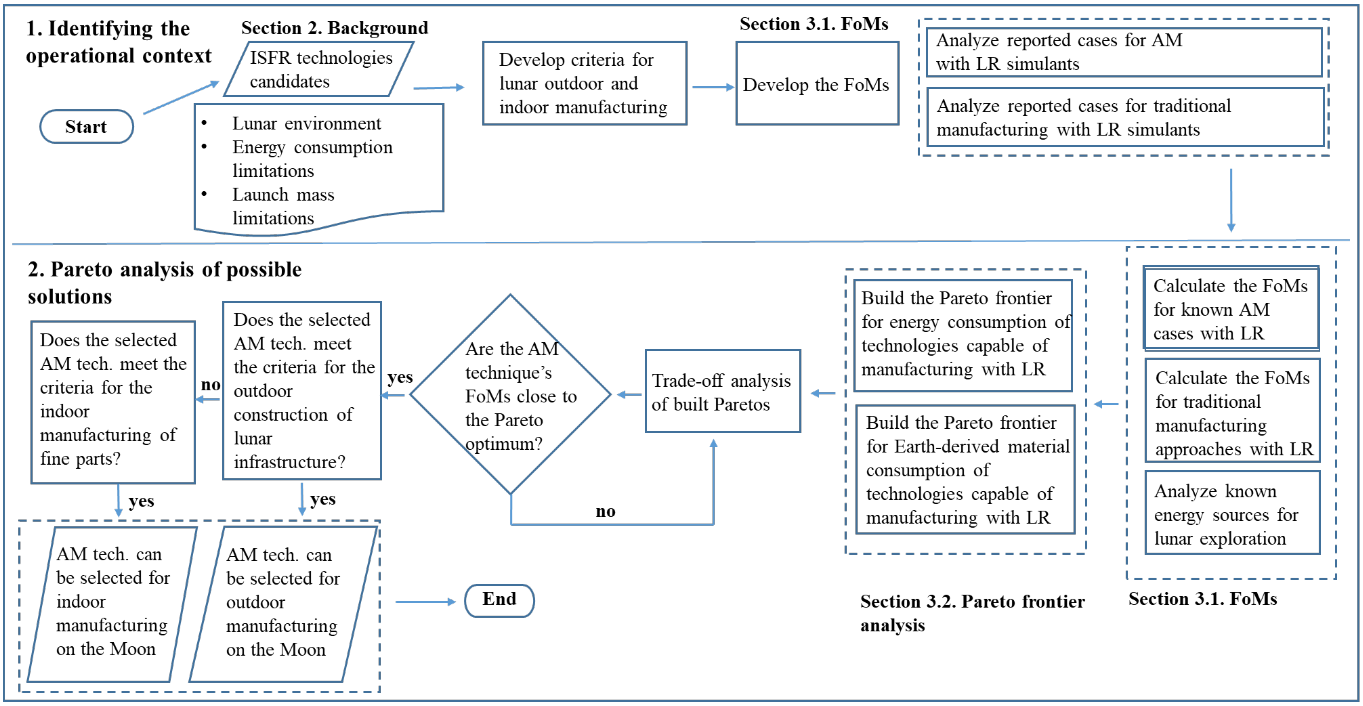

Figure 4 Framework of evaluation of AM technologies for use in ISFR on the Moon

In Part 1 ("Identifying the operational context") we first identify candidate technologies for ISFR and define the operational constraints of our use case. Specifically, we consider the specifics of the lunar environment (e.g. regolith material properties), energy consumption limitations, and launch mass limitations. We then develop engineering criteria for lunar outdoor and indoor manufacturing and consequently derive a set of figures of merit (FoMs) to analyze AM technologies in the operational context of Moon ISFR. We use the proposed figures of merit to evaluate both the traditional and additive approaches of manufacturing with lunar regolith. In Part 2 ("Pareto analysis of possible solutions") we aggregate the results of our analysis into a multicriteria approach to identify Pareto efficient solutions for ISFR and ask the question of whether dominant AM technologies exist, and if so under which operational conditions. To achieve this goal, we compare FoMs with each other to identify trade-offs. We derive the corresponding Pareto frontier of efficient manufacturing methods. This ultimately allows us to downselect the most promising candidates for outdoor and indoor additive manufacturing technologies with lunar regolith on the Moon. It should be noticed that the present technical evaluation and any drawn conclusions are based on studies carried out with lunar regolith simulants and within terrestrial conditions.

4. Results

4.1. Figures of Merit

Future lunar exploration efforts will require surface infrastructure (Rousek et al., 2012; Scott Howe et al., 2013) such as habitat shielding, landing pads, and pathways, as well as a variety of complex machinery (for recon, excavation, mining, and transportation), spare parts, instruments. It will also require items on demand (Liu et al., 2019), which would be practical to manufacture on-site, utilizing indigenous resources. Infrastructure needs can be decomposed by size into two main categories: large-scale outdoor infrastructure (Melodie et al., 2021) (habitat modules' shielding, pathways, launchpads) and small-scale parts (ceramic instruments, spare parts, on-demand items) to be manufactured indoors (Isachenkov et al., 2021a). The AM technologies required to manufacture these two categories of parts are fundamentally different in terms of structural properties, manufacturing tolerances, as well as other performance and cost requirements, for them to be effective substitutes for parts that are manufactured on the Earth and then delivered to the Moon surface. While low energy and material consumption are essential for AM techniques for large-scale production in an outdoor lunar environment (Ceccanti et al., 2010), they are less important for small-scale indoor production lines (Isachenkov et al., 2021b). For the latter, the key requirements include the precision of printing and the resulting structural properties in terms of stiffness and strength.

As AM technologies can be based on completely different physical principles (such as extrusion, direct sintering/melting, and indirect sintering), there is no universal AM technique that fulfills all the requirements of a future lunar settlement. It follows that an optimal AM strategy for the Moon considers a combination of AM methods that are tailored for the portfolio of required applications at different volumes and sizes. To derive this portfolio, we first have to evaluate the AM techniques for their key distinguishing characteristics. We encode those characteristics into a set of parametric figures of merit (FoMs). Table 1 shows the FoMs we consider in the present work.

Table 1 Figures of merit (FoMs) for evaluating AM techniques

Figures of merit	Units	Description
Material compressive strength	σ, [MPa]	Reflects overall strength of material against compression.
Specific energy consumption	E_V, [kWh/m^3]	The total energy required for manufacturing a unit volume (1 m^3) of material with the specific technology application.
Earth-derived consumables mass	m_E, [kg per 100 kg]	Consumption of materials brought from Earth per 100 kg of printed material.

Material compressive strength is a characteristic that allows one to assess the resistance to external (physical) and internal (thermal compression) pressure and the material's overall physical strength. This FoM is variable regarding many parameters used during the printing process. The resulting σ value depends on the composition of source material: percentage of solid regolith in pre-mixture (especially for extrusion/jetting technologies), a type of binder substance, as well as on conditions of sintering/melting process (for those technologies, where this stage takes place): temperature, duration, and atmosphere. The diversity of these parameters causes the immense potential for compressive strength improvement and optimization for specific tasks even within one applied AM technology.

It should be noticed that the mechanical behavior of the materials is governed by several properties, including not only the compressive strength, which we use as an FoM in the present research but also tensile strength, flexural strength, ductility, hardness, stiffness, fatigue strength, corrosion resistance, thermal conductivity, etc. Moreover, the geometry of the individual AM-produced layers, hatching pattern, in-fill percentage, and other 3d-printing parameters can also alter the mechanical properties of the manufactured lunar regolith parts. We could not include all of these properties in the list of FoMs, because of the lack of data points— most of the reported cases of AM with lunar regolith included only the compressive tests of produced samples as the main evaluation criteria for their mechanical strength (Khoshnevis and Zhang, 2012; Sitta and Lavagna, 2018; Taylor et al., 2018). Some of the reports can not be included in our FoM diagrams, because they lack even the compressive strength measurements (Balla et al., 2012; Khoshnevis and Zhang, 2015). It is also important to mention that using compressive strength as a FoM of AM with lunar regolith, we should assume that produced material is isotropic. As the research in the field continues, it will be vital to compare samples, manufactured by different AM approaches, in terms of mechanical properties other than compressive strength.

Specific energy consumption is the value of total energy required to conduct the complete printing process of the unit of volume (1 m^3) with the chosen AM manufacturing technology. This is a complex value obtained by calculating the energy consumption of each stage taking place in the technological process. Depending on the type of technology, stages may be raw material mixing, extruder heating, raw material distribution, sintering/melting stage, moving the active parts of the printer, thermal annealing, etc.

Earth-derived consumables mass is the total mass of raw material auxiliary components that are consumed during the printing process and cannot be mined right away at the lunar surface (which is normalized to 100 kg of printed material produced). These consumables may be different binder materials (both organic and inorganic) used in printing, or gases used in the printing process or for the annealing stage. The lower this FoM value, the more autonomous and less dependent on the Earth-derived resources is the AM technology.

The last two FoMs determine the final cost of using the technology on the Moon and characterize the scale of AM technologies implementation. Table 2 lists the AM technologies that have been tested for manufacturing objects with lunar regolith simulants. Printing speed and resolution of corresponding AM techniques are also reported for completeness of the information.

TABLE 2: Comparison of state-of-the-art cases of AM with lunar regolith.
*Specific Energy consumption is calculated according to assumptions made in (Isachenkov et al., 2021a)

AM technology	*Specific energy consumption, kWh/m^3	Consumables (kg per 100 kg)	Compressive strength, MPa	Print speed, m/min	Printing resolution, mm	Authors, publication year
CCC	4.5	38	48	12.7	3.2	B. Khoshnevis et al., 2012 (Khoshnevis and Zhang, 2012)
BJ	7.5	28	18.5	9	0.5	G. Cesaretti et al., 2014 (Cesaretti et al., 2014)
IJ	510	33	18	0.3	0.5	S. Taylor et al., 2018 (Taylor et al., 2018)
SSLS	15	0	2.5	2.8	20	M. Fateri et al., 2019 (Fateri et al., 2019)
SMWS	615	0	N/A	N/A	15	V. Srivastava et al., 2016 (Srivastava et al., 2016)
SSS	800	0	N/A	N/A	4	B. Khoshnevis et al., 2015 (Khoshnevis and Zhang, 2015)
SLM	4200	0	34.1	3	0.2	L. Sitta et al., 2018 (Sitta and Lavagna, 2018)
LENS	2140	5	N/A	1.2	1.65	V. Balla et al., 2012 (Balla et al., 2012)

DLP	820	25	428	N/A	0.025	M. Liu et al., 2019 (Liu et al., 2019)

Additional key aspects to consider when evaluating AM technologies for in-situ manufacturing purposes pertain to the energy source used within the process. Specifically, the energy source shall reliably supply the required power ensuring seamless operations, as well as being minimally dependent on Earth-derived feedstocks. These two conditions limit the number of viable options for solar or nuclear energy sources. In this paper, the power-to-weight ratio is used as an FoM to benchmark the different sources. It is defined as the ratio between the total power (in W) of the energy plant and its total mass (in kg). The power-to-mass ratio has been estimated for energy sources flight-proven and potentially available in short term. Table 3 summarizes the key characteristics and the FoMs for the different sources considered.

TABLE 3: Comparison of in-service and prospective energy sources for AM with lunar regolith.

Project/technology name	**Type of energy plant**	**Total power (for tested prototypes), W**	**Total mass (for tested prototypes), kg**	**Power per mass, W/kg**	**Lifetime**	**Reference**
Flexible thin-film solar cells	ISS Roll-out Solar Array (ROSA)	23000	340	67	≥ 10-15 years	(Spence et al., 2018)
Triple junction solar cells	Solar panel (used on Juno spacecraft)	14000	340	41	~ 15 years	(Dawson et al., 2012)
Perovskite solar cells	Solar panel (in project, tested)	N/A	N/A	~1000	~ 2 months	(Reb et al., 2020)
Organic solar cells	Solar panel (in project, tested)	N/A	N/A	350	~ 6 months	(Cardinaletti et al., 2018)
ISS heritage solar panels	Solar panels	32000	1088	29	~ 30 years	(Gietl et al., 2000)
Kilopower	Nuclear reactor (next-generation, in project)	from 1000 to 10000 (scalable)	from 430 to 1530 (scalable)	2.3-6.7	≥ 10 years	(Gibson et al., 2017)
TOPAZ-II	Nuclear reactor	6000	900	6.7	~ 1 year	(Voss, 1994)
RAPID-L	Nuclear reactor	200000	7600	26.3	~ 10 years	(KAWASAKI, 2003)
Zeus/ NUCLON	Nuclear reactor	470000	17600	26.7	~ 10 years	(Sputnik, 2021)

The sunlight is an excellent energy source for space applications. Different types of solar panels have been developed specifically for use in space (NASA, 2021b). They are characterized by high PCE values, ranging from 18-20% for silicon panels to 39-42% for multi-junction solar cells. The main challenge in using solar panels in long-duration moon missions relates to the extreme temperature fluctuations on the lunar surface (from -170°C at night to +125°C in the daytime). That would affect the performance of the solar panels by shortening their lifetime and lowering their efficiency over time.

Nuclear power units have been developed since the beginning of space exploration (Voss, 1994). Nuclear reactors can provide a continuous and almost constant energy supply. Although the development of space-grade nuclear reactors slowed down in the 1980s, several new projects for next-generation space nuclear power generators are in progress now, including Kilopower (NASA (Gibson et al., 2017)) and NUCLON (Roscosmos (Sputnik, 2021)).

Depending on the concept of operations (ConOps) of the mission and the scale of AM technologies implementation, different sets of power sources may be considered.

At the first stage of Moon exploration, the ROSA-type solar panels might represent a viable solution to meet the initial requirements targeted to low-energy consumption AM techniques, while better performing power generators (Nair et al., 2020) can be chosen in later stages of lunar surface exploration.

4.2. Pareto frontier analysis

To build the first Pareto frontier, we plotted the ultimate compressive strength of the additively produced samples against the mass of Earth-derived materials needed to manufacture the samples with different AM approaches (figure 4). For comparison purposes, some data points obtained with traditional manufacturing approaches (cement press-forming, thermal sintering etc), listed in (Caprio et al., 2020) were also included in the graph. The blue dotted line represents the ultimate compressive strength, reported for cast regolith. The red dotted line represents the ultimate compressive strength reported for regolith-based cement (Happel, 1993).

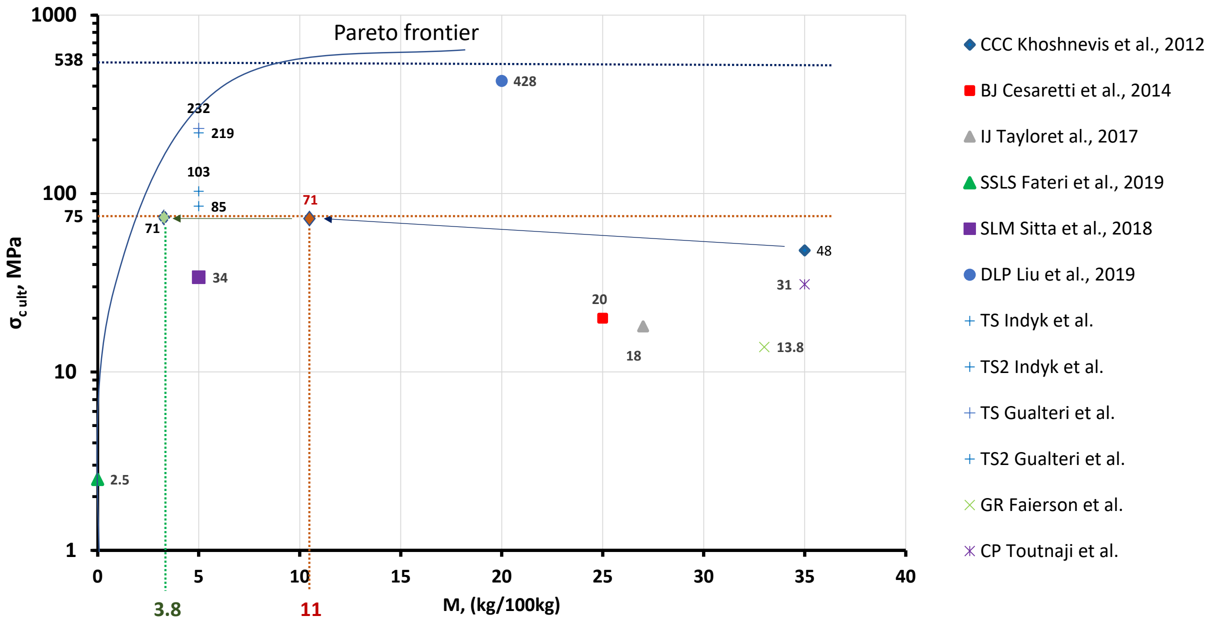

Figure 5 Earth-derived material consumption of additive and traditional manufacturing technologies, utilizing lunar regolith as source material (TS- thermal sintering, GR- geothermal reaction, CP- cement production). Data points with red and green central sections represent the expected characteristics of CCC at the mid-term and long-term stages, correspondingly

Figure 5 shows that methods that require lower consumables result in poor compressive strength of the samples. Such strength is, however, still enough for building low-loaded civil engineering structures, considering low lunar gravity (1/6 G). According to the plot, the SSLS and SLM approaches are found to be the most efficient in terms of Earth-derived material consumption, while the extrusion-based methods (IJ, BJ, and CCC) perform worst, demanding 25-35 kg of earth-derived consumables. However, when we analyze the specific energy consumption (Figure 5 the SLM technique performs the worst, as it is based on the direct laser sintering of the regolith, which is a very energy-demanding process (Figure 6).

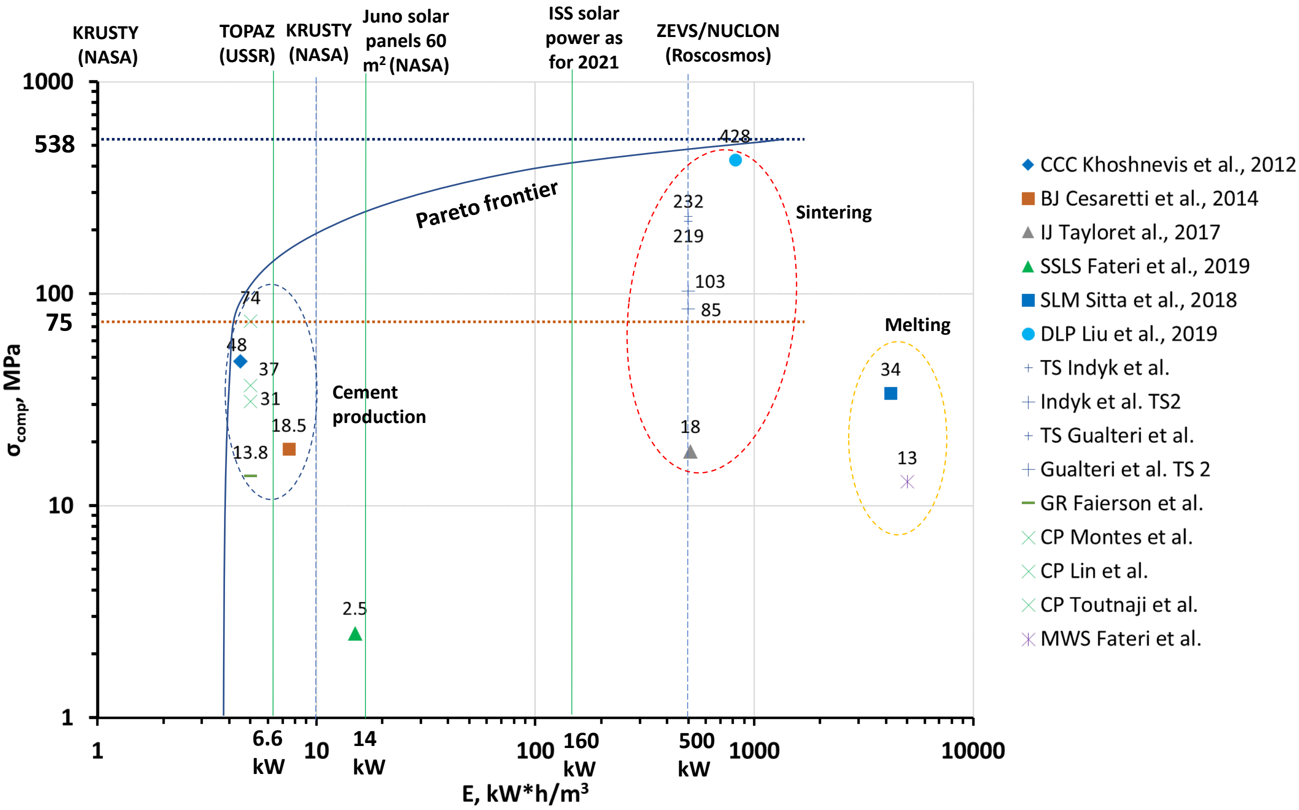

Figure 6 Energy consumption of additive and traditional manufacturing technologies, utilizing lunar regolith as source material (TS- thermal sintering, GR- geothermal reaction, CP- cement production, MWS- microwave sintering)

Based on this assessment, for the outdoor construction use case, material extrusion methods such as the CCC shall be considered. They require more earth-derived material but consume less energy. As the binder for the CCC consists of water and magnesium salts, it can be produced in situ from the lunar ice and refined regolith, which can eventually make CCC drastically more effective (it is shown in the figure with arrows going from CCC's initial data point). The BJ and IJ techniques are slightly more efficient than CCC, in terms of mass consumption, but as they utilize organic binder as an ad-mixture, it will be harder to adapt these methods for the ISRU-produced binders. Despite being quite resource-demanding, the stereolithography approach can produce parts with the highest compressive strength among the AM methods that have been analyzed. Thus, it can be efficiently used for small-scale precise ceramic parts production, where high mass consumption won't be a big deal.

For evaluating possible earth-derived consumables mass reduction, we can assume that the utilization of locally-mined water ice (Li et al., 2018) will help reduce earth-derived mass consumption by ~70% (11 kg/100kg), as the cement binder is primarily water-based. From the far perspective, magnesia can be mined from the local sources or interchanged with another type of ISRU-produced binder (sulfur, phosphoric acid, etc. (Buchner et al., 2018; Meyers and Toutanji, 2007; Pilehvar et al., 2019)), further decreasing the mass consumption to ~90% (3.8 kg/100kg), leaving only ~10% for earth-derived/ wasted binder. For the SLA, the reduction of earth-derived mass is much harder to achieve, as this technique utilizes complex organic substances, such as photocurable resin, photoinitiator, dispersant, etc. It will be a complex task to synthesize these organic components in the lunar conditions, with the lack of chemical machinery on the Moon. However, they can be potentially recycled after the printing cycle if the solvent debinding (Christensen et al., 2019; Oh et al., 2020), instead of a standard thermal one would be implemented.

Developing such a technique for the lunar conditions would be hard so we can expect a decrease in earth-derived materials consumption for the SLA only in the longer term. Considering the complexity of technology, we can assume that only ~50% (12.5 kg) of the binder can be effectively recycled.

To evaluate the theoretical limit of compressive strength for the additively manufactured regolith parts, we can take the ultimate strength for the casted and concrete lunar regolith, 538 MPa, and 75 MPa, respectively (Happel, 1993). As we can observe, the SLA technique performance (428 MPa) is the closest to the theoretical limit of compressive strength for the lunar regolith ceramic. It should be noted that in the paper (Altun et al., 2021), the authors reported that they were able to achieve only 5.4 MPa of ultimate compressive strength for DLP-manufactured lunar regolith ceramics. This extremely low value of $\sigma_{ult,c}$ reported by Altun et al. may be explained by inappropriate milling parameters– authors milled EAC-1 regolith simulant down to a mean particle size of only 8 μm, which may be too coarse for ceramic manufacturing via DLP. In support of this hypothesis, obtained samples have also demonstrated an extremely low relative density of 55.9%, which indicates high residual porosity between unevenly spaced coarse particles.

We assume that with further optimization of pre-processing, printing, and sintering stages, the mechanical strength of SLA-produced parts can get even closer to the 538 MPa. For example, the introduction of powder surface modification at the stage of slurry preparation can increase the flexural strength of lunar regolith ceramics by 22.5% compared to the one, prepare from unmodified slurry (Chen et al., 2022). Authors haven't reported on the compressive strength of the samples, but we can assume that it has also increased due to the more homogeneous distribution of lunar regolith simulant particles during sintering. Also, the introduction of fiber reinforcement could drastically increase the mechanical performance of SLA-printed regolith ceramics parts. It was shown (Yunus et al., 2017) that fiber-reinforcement of ceramics could lead to up to a 200% increase in flexural strength, through the crack-bridging mechanism. Considering that we can achieve 95% (511 MPa) of the maximum ultimate compressive strength value, reported for casted regolith, optimization of SLA-printing can help increase σ by 20% from the state-of-the-art result.

For the non-ceramic technologies, CCC is the closest one (48 MPa) to the theoretical limit for the ultimate compressive strength for the regolith-based concrete (Happel, 1993). For the CCC we can also expect that optimization of pre-processing and printing operations may help to increase the compressive strength up to 95 % (71 MPa) of the theoretical limit for the traditional concrete technology, achieving a 48 % increase in compressive strength of CCC-manufactured parts.

Further increase of compressive and flexural strength of additively manufactured lunar regolith parts can be achieved through the use of short fiber reinforcements (Yunus et al., 2018), which can be either earth-derived (silica, alumina, basalt, carbon fibers) or locally produced regolith glass fibers (Becker et al., 2019; Happel, 1993). We haven't found any published research on the fiber-reinforced 3d-printed regolith parts, so a lot of R&D would require developing such technology. To evaluate the improvement of the mechanical properties of fiber-reinforced regolith parts, we can use values of strength increase for the well-studied alumina and silica-based 3d-printed ceramics. The most significant improvement we can expect is in the flexural strength, as the fibers are much less brittle, when bent, as the fibers help bridge the cracks in the ceramic matrix.

The second Pareto frontier (Figure 6) that we have plotted is the ultimate compressive strength of the additively produced samples against the specific energy consumption of specific AM approaches. Here we have also plotted the energy output of different sources, both existing and perspective.

Three clusters of data points can be seen in figure 6: the cement/binder-based technologies, which are low-temperature, thus low energy-demanding techniques, the sintering-based additive and casting technologies, and the techniques based on melting, which consume the most amount of energy per produced volume of regolith part. Based on the energy consumption of Pareto-frontier, we suggest using the technique, which is the least energy-consuming yet results in sufficient printed parts' strength. According to the data available, the best candidate for such an application is Cement Contour Crafting, which can print relatively strong (48 MPa) large structures with rather low energy consumption (few kW/m^3). This method is closer to the Pareto frontier of specific energy consumption than the BJ technique, which is based on a similar principle. Thus, it is a more promising method. To efficiently utilize cement/binder-based AM techniques for the construction of lunar infrastructure, it would be important to solve the problem of binders' outgassing in a vacuum. This issue was discussed in several studies (Cesaretti et al., 2014; Pilehvar et al., 2021), where it was shown that this phenomenon could be countered by changing binder composition and printing parameters. For example, it was proposed to use sulfur (Grugel and Toutanji, 2008; Toutanji et al., 2012) and urea (Pilehvar et al., 2019), which have a higher boiling point than water, as a binder for cement production. It was also proposed to use pressurized volumes to cover the building area to couple the problem of binder outgassing– authors of (Cesaretti et al., 2014) have calculated that about 30 kg of water is required to fill a dome of about 2000m^3 volume at room temperature and pressure of 20 mbar. In the study (Cullingford and Keller, 1992) it was shown that despite vacuum exposure producing a faster release of free water from the concrete samples, it has not worsened the compressive strength of produced concrete.

The Solar Light Selective Sintering is also close to the Pareto-frontier, as it consumes almost no external energy than the sunlight, used for direct sintering of regolith. However, produced samples pose too low mechanical strength to use this method as a versatile outdoor manufacturing technique.

Concerning the precise printing method for indoor manufacturing, stereolithography-based DLP printing shows the best trade-off between the mechanical strength of the parts and the specific energy consumption. Despite the that SLA/DLP printing demands more energy than methods that don't utilize subsequent sintering, this technique produces parts with the highest mechanical properties, which is crucial for manufacturing on-demand items, instruments, and spare parts. It should be also noticed that as the SLA/DLP process is proposed for in-door use at the lunar base, with sintering to be carried out in an air atmosphere, this technology won't face any problems of binder outgassing in a vacuum.

5. Conclusion

In this paper, we have defined a set of FoMs (i.e., material compressive strength, specific energy consumption, Earth-derived consumables mass) to quantitatively evaluate the performance of the AM techniques that utilize the lunar regolith as a primary feedstock. Both outdoor and indoor Moon-based manufacturing scenarios have been considered. As a result of the trade space exploration and trade-off analysis, two AM technologies have been downselected. Figures 5 and 6 summarized the performance of the considered AM technologies and present the Pareto fronts. The trade space analysis highlighted three clusters corresponding to three different AM underlying technologies: melting, sintering, and material extrusion. Two of those clusters exhibit Pareto optimal points and relate to two distinct applications.

For large-scale civil engineering, such as road-paving, launchpad, and habitat shielding, the cement contour crafting (CCC) technique is the most promising AM approach. It can leverage locally mined water and inorganic binders (lowering earth-derived mass consumption from 35 kg/100 kg to just 3.8 kg/100 kg, according to our estimates). Furthermore, CCC can produce parts with 48 MPa compressive strength, consuming only 5 kWh/m^3, which is extremely important for the production of large-scale infrastructure on the Moon.

For the small-scale in-door manufacturing approach, the analysis suggested the use stereolithography (SLA) AM technique. However, further development of such a technique, including using less earth-derived consumables and less energy for the sintering procedure is required. At the time of writing this paper, only the Digital Light Processing type of SLA approach was tested with lunar regolith simulants. Produced ceramic parts exhibited a compressive strength of 428 MPa (which is matched only by direct sintering of press-formed regolith), making SLA the preferred method for manufacturing tough ceramic parts. Mass and energy consumption of SLA, which are too high for large-scale production in the limited resource environment (20 kg/ 100 kg and 800 kWh/m^3) can be decreased by fine-tuning pre-processing and sintering regimes, resulting in production slurries with higher content of regolith and less binder. This method can also benefit from the advanced hybrid sintering procedures (e.g., furnace heating together with microwave sintering), as they would help achieve more density of produced part, thus higher strength.

As the AM of lunar regolith is a relatively new direction in the field of ISRU studies, we had only a few data points available to build the Pareto frontier, limiting its thoroughness. Some of the used estimates are rather rough, including estimations of the energy consumption during the pre-and post-processing stages of the lunar regolith-based AM. Also, it is important to remember that reported and analyzed studies were carried out with lunar regolith simulants and mostly within terrestrial conditions, thus it would be extremely important to proof-test selected AM techniques on the Moon before their actual routine operation.

For a more exhaustive comparison of the various AM techniques, it would be useful to include also financial estimates. Especially it would be useful to compare the mass of pre/post-processing equipment accompanying each of the 3d-printers, working on different physical principles, better informing the decision-making process of selecting the AM technology for the lunar exploration.

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