IAC-18.D3.3.7x42605

URBAN: conceiving a lunar base using 3D printing technologies

A.Sgambati[a]*,M. Berg[a] ,F.Rossi[a],A. Daurskikh[b] , B. Imhof[c], R. Davenport[c] ,P.Weiss [d], M.Peer [d], T.Gobert [d], A. Makaya [e]

[a] *OHB System AG, Bremen, Germany* antonella.sgambati@ohb.de, marco.berg@ohb.de; francesca.rossi@ohb.de
[b] *Sonaca Space GmbH, Germany*, anna.daurskikh@sonaca-space.com
[c] *LIQUIFER Systems Group GmbH, Austria,*barbara.imhof@liquifer.com, bob.davenport@liquifer.com
[d] *Comex, France,* p.weiss@comex.fr, m.peer@comex.fr, t.gobert@comex.fr
[e] *European Space Agency, The Netherlands* advenit.makaya@esa.int
* Corresponding Author

Abstract

One of the most critical points in space exploration beyond Low Earth Orbit is the provision of systems that ensure the long-term survival of both crew and technological assets in the harsh space environment. The utilization of the Moon seems to be the next logical step in implementing the global strategy for humans to explore the solar system. The key to any sustainable presence in space is the ability to manufacture necessary structures, spares, in situ and on demand reducing the cost, volume, and up-mass constraints that could prohibit launching everything needed for long-duration or long distance missions from Earth. Additive Manufacturing (AM) has the potential to provide a number of sustainability advantages. The establishment of an AM process in support of a Moon base will be strongly correlated to the self-sustainability of the process itself and the possibility in re-using the recycled materials for different purposes. The ESA General Study project URBAN evaluates the feasibility and implementation effort required in establishing the possible use of AM in easing the construction, expansion and maintenance of a lunar base.

The study is implemented through two parallel tasks:
1) Comprehensive survey of the elements/hardware required in a permanent and sustainable manned lunar base, based on a hierarchical investigation from permanent infrastructures to the “on demand” items.
2) Specific survey of additive manufacturing technologies addressing a broad range of applications that can be useful from a lunar base perspective. The assessment includes the state of the art of 3D printing related to several materials such as metals, polymers, ceramics, food ingredients and living tissues.

From these two surveys a database related to required hardware and available technologies has been created. A systemic analysis will be described, to define the most suitable printing technologies for hardware manufacturing. Derived from the selected 3D printing technologies, a roadmap for Moon applications will be presented, including the recommendations for “print on the Moon” versus “bring to the Moon”.

Keywords: Lunar Base, additive manufacturing, process sustainability, material processing

Acronyms/Abbreviations
Additive Manufacturing (AM),
Big Area Additive Manufacturing (BAAM),
Continuous Filament Fabrication (CFF),
Contour Crafting (CC),
Carbon fiber reinforced polymer (CFRP)
Ultrasonic Additive Manufacturing (UAM)
Electron-Beam freeform Fabrication (EBF)
European Space Agency (ESA),
Fused Filament Fabrication (FFF),
In Situ Resources Utilization (ISRU),
International Space Station (ISS),
Low Earth Orbit (LEO),
Preliminary Activity Review (PAR),
In-Space Manufacturing (ISM),
Technology Readiness Level (TRL)

1. Introduction

Several studies have been addressing the building of a lunar base either under ESA or other space agencies initiative. These studies are looking at conceptual designs, often of one specific element while most of the requirements are not adequately or not at all taken into consideration. The *Conceiving a Lunar Base Using 3D Printing Technologies* study, under ESA General Study Program, aims to establish the possible uses of Additive Manufacturing in a lunar base perspective. It assesses the use of additive manufacturing for a broad range of possible applications and evaluates the feasibility and implementation effort required in establishing the use of AM technology in easing the construction, expansion and maintenance of a lunar base.

1.1 Study objectives and challenges

The establishment of a permanent human presence on the Moon is one of the major goals currently under consideration for human spaceflight in the next decades. Such a base will provide among others, (Figure 1):

- In-situ surface exploration to determine material composition and lunar chronology
- Remote seismic exploration of lunar interior to determine physical structure
- Assessment of lunar surface / near surface resources for human exploitation
- Testing of technologies for human exploration of the Solar System

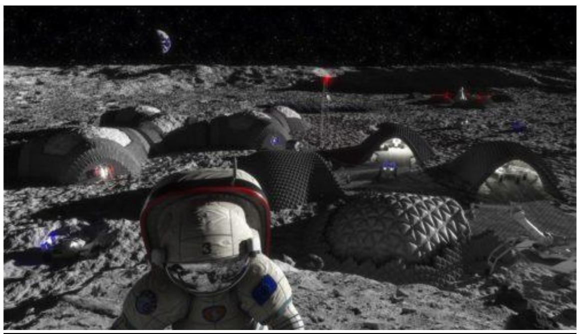

Fig. 1. Conceptual view of an operational category lunar base showing habitat, hangar, operational pads and a telescope (Credit: RegoLight consortium).

One of the major challenges facing such a lunar base is the need for a constant supply of consumables including not only food/water/oxygen for the crew but also provision of module elements, power generation, module interior fittings, laboratory resources, medical facilities etc. All of these needs require a major logistics implementation when they have to be transported from Earth. The ISS construction and operation provides a good example of why human habitation in space requires continuous enormous logistics support from Earth. ISS is a permanent base in Low-Earth orbit supporting the needs of up to 6 crewmembers and a host of scientific experiments. But building the ISS required about 40 US Space Shuttle and Russian Proton/Soyuz flights [1] leading to a structure with a mass of about 400,000 kg. Further, to keep the ISS operating between 2014 and 2017 required no less than 37 supply missions by Cygnus, Progress, ATV, HTV and SpaceX Dragon vehicles. [2]

Such logistics support when extrapolated to a Lunar base construction and operation are clearly both too costly and physically prohibitive!

One of the main goals of the URBAN study is to assess the possibility of reducing this Earth dependency by making maximum use of both existing lunar surface materials and recycling of end-of life or broken equipment as raw material for 3D printing. A fully operational base will have access to an enormous quantity of both regolith and waste material. To understand which items can potentially be 3D printed, it is first necessary to establish a database of all the hardware requirements for a Moon base. Then each hardware item can be assessed both for its criticality and for 3D print potential in the lunar environment. Therefore, two different surveys have been performed in parallel, with the objectives detailed below. The surveys included a questionnaire sent to industry professionals.

1.1.1 Hardware survey objectives

The main objective of the hardware survey is to identify different permanent infrastructure, machinery and various on demand and temporary items that are needed to build, operate and sustain a lunar base. The approach (refer to Fig.2) has been structured in a hierarchical logic, starting with the identification of the mandatory infrastructure, which will enable the human settlement on the Moon. Then, after the human presence has been established, the survey investigated temporary and on-demand elements, which are mostly driven by the human needs and the support to the sustainability of the overall lunar base.

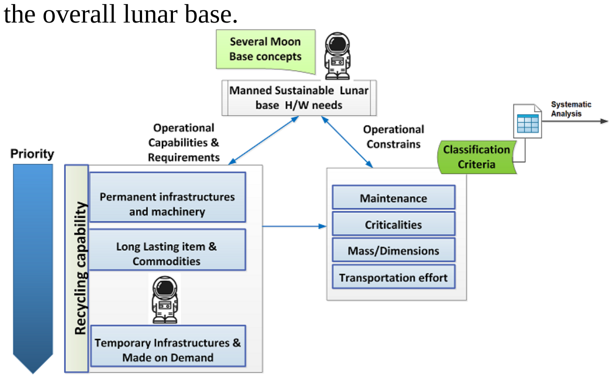

Figure 2: Approach for the Hardware classification

1.1.2 AM technology survey objectives

In parallel, a survey related to all currently existing AM technologies that appear to be relevant for a lunar base or any other space enviroment has been performed to collect information on the capabilities, environmental conditions, power requirements and post-processing needs. Sustainability aspects, such as unused material recycling, printed part recycling, waste recycling and down/upcycling are especially emphasized. Figure 3 illustrates the approach for the classification according to a set of criteria.

Based on the results of the two surveys, a step-by-step analysis of the possibilities to use 3D printing technologies for obtaining the identified items will be performed in the next phase. The study will be concluded with a Roadmap description for the promising identified technologies able to support the programmatic development of the lunar base.

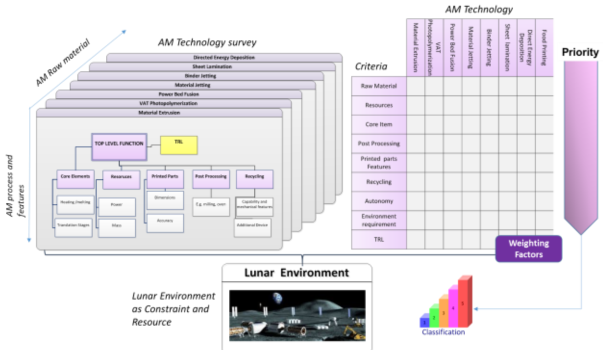

Figure 3: Approach for the AM technologies classification

2. URBAN approach and methods

Setting up a lunar base will most likely follow a 3-step approach (as shown in the Figure 4).

Step 1: Survivability. A minimum crew will establish a permanent presence on the lunar surface. They will be highly dependent on structural elements such as modules and life-support resources from Earth, both prior to a human presence (automated pre-crew modules), and post-crew landing. Some 3D printing of structural elements may be possible in this stage although it will be very limited. The elements required in this phase will be essential items such as habitat module(s), power generation and communications facilities, logistics module, and rovers.

Step 2: Sustainability. Once the basic elements are in place the Moon base can grow rapidly to also include a scientific laboratory, greenhouse module, construction vehicles, hangars and a manufacturing module including basic 3D printing facilities. In this phase 3D printing may play a significant role in using for example lunar regolith among other materials to manufacture structural elements for new modules. Also 3D printing will be used for critical hardware containing parts that either have a limited lifetime or degrade in the lunar environment.

*Step 3: Operational***.** This step represents the fully operational Moon base. In addition to all the elements of Step 1 and Step 2, the base will now include additional in-situ manufacturing capabilities including a range of 3D printing capabilities, maintenance modules, extensive scientific research facilities for astronomy, materials research, lunar research, laboratories etc. The Moon base will be as autonomous as possible by using lunar resources for manufacturing purposes, extraction of oxygen, water, and volatiles. A significant role will be played by the re-cycling of waste as basic material for 3D printing a range of hardware items. Re-cycling of organic waste and water will be significant for food production. Also 3D printing of food will be possible.

3. Lunar manned outpost hardware survey and requirements

3.1 Hardware classification

The hardware survey objective was divided into the following four groups, based on their usage and development stages as shown in Figure 4.

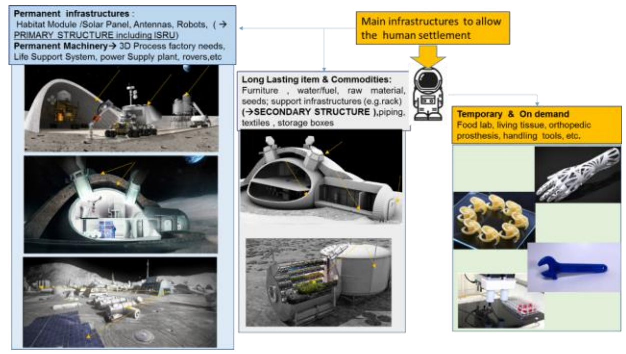

Figure 4: Different lunar base development stages and associated hardware needs

- Group 1: Permanent Infrastructure and maintenance.

The first group refers to bigger elements that will be established at the onset of constructing a lunar base and are thus the most critical items. It includes all structural and primary elements that are needed to shield humans, machines and commodities alike against the lunar environment.

- Group 2: Permanent machinery and maintenance

Permanent machinery will be used to explore the potential sites for the lunar base construction and create the permanent infrastructure, prior to arrival of the astronauts. It includes robots that enable the construction of the lunar base and its operation, addressing issues like energy and oxygen generation. For sustainable exploration, ISRU should be used which includes mapping resources, mining them and transforming them into water/oxygen and other elements used in construction. As machinery will be brought in the beginning of the construction phase, it needs to be reliable. I.e. it should have a high probability to operate without failures over extended periods of time, as well as a short maintenance cycle.

- Group 3: Long lasting items and commodities.

This group includes the long lasting items such as secondary structures, furniture and tools used in the interior (understood as items of low maintenance) or items which need to be replaced regularly due to the known degradation in the lunar environment (e.g. rotating parts, mirrors, etc.). Group #3 items are to be found mainly in an interior environment of a habitat and/or only come into play once a base has been established, a crew has moved in or a production process is running. The function of these elements is to support the everyday activities of a crew in a lunar habitat.

- Group 4: Temporary and made on demand items.

This group describes hardware items that in the timeline for establishing a lunar base would come after the previous groups. Nevertheless, they will play an essential role in establishing a long-term human presence and ensuring the sustainability of product and process life cycles. Made on demand items such as food and biological tissues, orthopaedic prostheses to address medical emergencies and temporary items, such as lab equipment or single use tools, belong to this family.

3.2 Hardware literature and public survey

The team conducted a scientific survey in order to identify the elements belonging to the four described hardware survey groups not only related to the construction phase but including all the items needed in the daily activities for the maintenance, operation as well as well-being of the crewmembers. In addition, an online survey using surveymonkey® was set up to directly address professionals involved in both human spaceflight and analogue site campaigns.

Table 1 summarises the total number of elements identified from the scientific and online survey. As it can be seen, the highest number of elements is those manufactured on demand.

Table 1. Hardware on-line survey main elements

	Group 1	Group 2	Group 3	Group 4
Number of elements	19	11	20	51

3.3 Criticality of hardware requirements.

Besides identifying all the hardware requirements in each of the above steps, an assessment also needs to be made of the criticality of each hardware item. Clearly, the criticality of a hardware requirement depends on a number of factors in this study. For example, a requirement to build a greenhouse facility maybe very critical in Step 3 when the base is to a large extent operating autonomously. But in Step 2, a greenhouse is less critical as most fresh food will still be transported from Earth.

Also within a particular step, the criticality of hardware items will depend on various factors, such as their relevance to life support, scientific research, exploration, base operations and psychological health of the crew.

In the URBAN study, the assessment has been made along both dimensions: i.e. the criticality of a hardware element regarding its applicability in the successive lunar base development steps and the hardware element's criticality regarding its relevance within a particular step (Figure 5).

After identifying and categorising the hardware elements as described above, a database has been set-up listing:

- Current materials used in the manufacturing of the hardware, dimensions, procurement time
- Maintenance parts identification
- Current heritage or experience to replace the current manufacturing methods with AM.

The searchable database will help to sort-out or group the hardware elements according to the screening selective criteria.

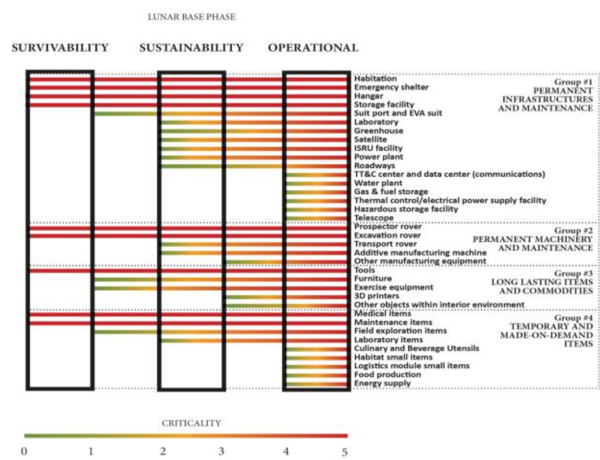

Figure 5: Hardware categories' classification and criticalities

4. Additive Layer Manufacturing Survey

Currently, the 3D printing technologies are evolving rapidly, and the amount of information on existing processes is large. The survey was not limited to the processes used today in aeronautic or space industry but addressed all uses of additive manufacturing technologies i.e. metals, polymers, ceramics and glasses, concrete, plaster and other building materials, food ingredients, nutrients and living tissues. Therefore, it was important to adopt a structured and efficient approach to perform this study. An extensive literature research has been conducted, using online databases of peer-reviewed publications. Proprietary modifications have been searched through industry publications and reviews and technology developers were contacted when information was not available in open sources. Additionally, URBAN involved a team of experts comprising specialists from TNO, ATG Europe, BEEVeryCreative, Lithoz, Advanced Polymer Technology AB, Fraunhofer ENAS, CELLINK to assess AM applications from a lunar implementation perspective, as well as provide a set of consolidated information about their specific technology and foresight.

4.1 AM technologies state-of the art and public survey

The literature survey was organized according to the ASTM (American Standard Test Method) process group classification:

- Material Extrusion,
- VAT Photopolymerization
- Powder Bed Fusion
- Material Jetting
- Binder Jetting,
- Sheet Lamination
- Directed Energy Deposition.

Within the process groups, the effort was focused on covering a variety of technologies, including proprietary modifications, as well as experimental technologies. The largest group is extrusion, and it covers a wide range of materials: from commodity plastics to metals and even biological materials.

Additionally, a public survey at the technology developers was conducted where participants could provide their inputs. However, in many cases, the participants disclosed only a few details on the capabilities of their technologies.

The following information has been collected for each of the AM processes:

- Processed materials
- Core elements
- Feedstock form
- Build environment
- Means to consolidate the part
- Post processing
- Mandatory post-processing infrastructure
- Recycling
- Unbound material recycling
- Printed parts recycling
- Recycling infrastructure
- Power
- Part dimensional accuracy
- Max build volume
- Parts features
- Pre-production infrastructure
- ISRU infrastructure
- Lunar environmental impact
- TRL (Technology Readiness Level)

4.2 Recycling and Sustainability of the process

Additive Manufacturing is expected to become a key manufacturing technology in a sustainable future society. In this view, the AM processes to be implemented on the Moon need to be long-lasting and embedded within the complete life cycle of a product. The *life cycle* of a product or an item is defined as the life expectancy of the item from the time it is made until it is no longer available or functional. It is also closely connected to recycling, and therefore many items have been investigated with respect to their recyclability (e.g. plastics – shred/melt, extrude new filament/pelletize, and print again). The more recycling capability is implemented (whether it is up- or down-cycling), the more sustainable a lunar base will be. The recycled material can have lower structural performance, compared to its original utilization; therefore, a downgrading of the performance needs to be considered. The downgraded material can be used for printing a part that will require lower structural properties or different functionalities (e.g. a recycled plastic from a rack structure can be reused for a one-shoot tool or non-structural parts). Recycling together with ISRU would allow making a Moon base almost self-sustainable, as can be seen from Figure 6, [3].

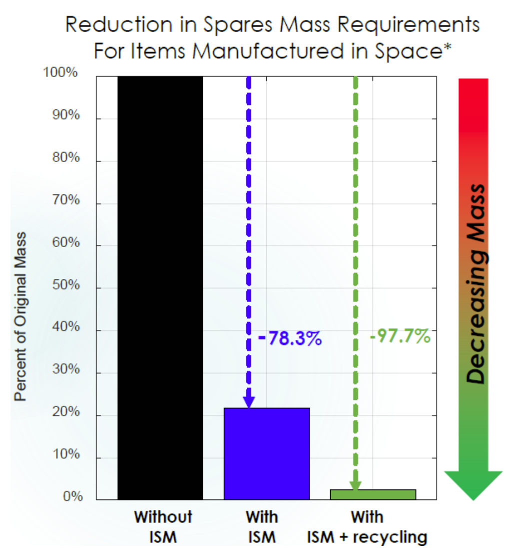

Figure 6: Reduction in spares mass requirements for items manufactured in space [4]. *ISM: In-Space Manufacturing

Recycling of consumer-grade plastics has been tested extensively, and several studies have addressed how properties change for different materials. Commercial off-the-shelf recycling machines are also available. [4]

The recycling of metals is slightly more complex – with powder-bed machines, the unused powder from one build can be used for the next build. However, parameters like flowability and grain size need to be monitored. Several studies have shown that there is little difference in the properties of the end part, even after the powder is reused more than 10 times [5-7]. Recycling of 3D printed metal parts is also possible but it is a more labor-intensive process. As metals are the most used materials for the construction of the

permanent infrastructure and machinery, these issues have to be considered. Also, the environmental impact of such processes needs to be addressed.
To make recycling easier and improve the possibilities of reusing material, reducing the variety of materials used to build hardware on the Moon is a good option, in combination the implementation of very versatile AM technologies.

4.3 Current research on in-space and on-planet printing

Several studies have addressed 3D printing under microgravity and vacuum conditions. Currently, two fused filament fabrication (FFF) machines have been tested on the ISS (AMF and POP3D), both are printing with consumer grade plastics. Recycling is addressed in NASA studies with *Refabricator* that can extrude material directly in the chamber. Recycling of packaging into filament is considered within the NASA CRISSP project. [8]

On-planet printing with the presence of partial gravity is covered by technologies that use regolith; Contour Crafting could be used for creating transport infrastructure and landing pads. Tethers Unlimited is looking at technologies that allow creating long trusses in space, thus eliminating the rather challenging launch phase requirements. [8]

Even though liquid and powder-based processes are considered more difficult to implement in space, it is not impossible and they should not be discarded from consideration. A successful example of powder-based 3D printing in microgravity was carried out at BAM (Bundesanstalt für Materialforschung und –prüfung) during a parabolic flight campaign. [9]

4.4 Lunar impacts

The harsh lunar environment poses serious challenges for the usage of identified AM technologies on the Moon. The main lunar environment characteristics have been assessed to identify the challenges imposed by them and the possible risk mitigation strategy to be applied to avoid such challenges and showstoppers (Figure 7).

For example, the lunar dust will affect the technology only if it is exposed to the external lunar environment, especially, for lunar base construction. In general, all AM processes will be required to have a protective enclosure against the electrically charged floating lunar dust.

5. Results of the Preliminary Activity Review

5.1 Results of the online survey and outcomes

The online survey was conducted to collect information on parameters and features of various 3D printing technologies, as well as technical assessments by the technology developers on the potential application of these technologies for Lunar base construction.

The results of the online survey confirm the outcomes of the literature survey. Plastics and metals are the most popular materials. Industrial materials with high strength/functionality are most often thermoplastics or metals that can be used to produce optimized designs.

Technology	Vacuum	Gravity	Temperature
Material extrusion	Nozzle clogging Lower porosity - better interlayer adhesion	Microgravity effect on material sedimentation and crystallization will strengthen the printed material	Many materials are temperature sensitive
VAT photopolymerization	No effect: the process takes place in an enclosed volume	Requires additional control measures to maintain a flat liquid photopolymer bed	Requires protection if used in outdoor lunar conditions
Powder bed fusion	No effect: the process takes place in an enclosed volume	Requires additional control measures to maintain a flat powder bed to prevent cloud formation	Requires protection if used in outdoor lunar conditions
Material jetting	Requires temperature controlled printing environment	Material jetting AM process depends on gravity to deposit the liquid droplets on the print layer. Precise droplet deposition under lunar gravity will require additional calibration and control difficulties.	Temperature sensitive
Binder jetting	Doesn't require atmospheric air/condition for heat convection or transfer medium	Binder jet AM process will require very high degree of control to prevent powder clouding and liquid blobbing against the lunar environment	May require protection if used in outdoor lunar conditions
Sheet lamination	No oxide formation under vacuum	UAM is not affected by microgravity	Requires protection if used in outdoor lunar conditions
Directed energy deposition	Processes exists that are designed to work under vacuum – EBF	Microgravity effect on material sedimentation and crystallization can strengthen the printed material	High temperature can be used as thermal energy source. However additional cooling system will be required to control excessive heating.

Figure 7: Assessment of the AM technologies versus the main characteristics of a lunar environment

Extrusion-based and directed energy deposition technologies are the least affected by the lunar environment. On the contrary, implementing technologies that use liquids or powders as a raw material is much more complicated. A low return on the survey should be noted; commercial technology providers often do not see a direct benefit in participating. Also, in many cases, the participants disclosed only a few details about the capabilities of their technologies.

5.2 AM technologies ranking

For each of the AM technologies present in the database, a value was assigned to each of the performance indicators, based on the current state of technology development. Then, the utility function was calculated and technologies were ranked. To calculate the utility function, each of the key performance indicators was assigned a weight:

- Processing material – 4. This is to reflect the importance of material as discussed earlier and select the ones that can process the largest variety of printed parts
- Low gravity influence – 4. Low gravity, on the contrary to radiation or temperature, can't be mitigated
- External environment compatibility – 2. It's considered that the AM machines can be also placed in a laboratory or enclosed environment, according to the purpose.
- Feedstock sourcing – 3. This indicates the level of complexity of raw material sourcing.
- Power requirements – 3. As power will be produced on the Moon and will be a limited resource, this needs to be accounted for.
- Recycling capabilities – 4. It's important to be able to reuse failed prints or parts to ensure sustainability.
- Estimated post-processing – 3. While it is desirable to have low post-processing efforts, high-quality surface finish can be needed for important functional parts.
- Estimated lead-time – 3. This indicator shows how quickly the material can be acquired: whether it has to be shipped from Earth or if it is available on the moon.

The utility function is calculated as the sum of all key indicators multiplied by the weight factors. The technologies are then ranked according to their utility function values. Table 2 summarizes the ranking results.

Table 2 AM process ranking

Ranking	Process name
1	Fused Filament Fabrication (FFF)
2	Continuous Filament Fabrication (CFF)
3	Contour Crafting (CC)
4	Big Area Additive Manufacturing (BAAM)
5	Atomic Diffusion Additive Manufacturing
6	Laser Metal Deposition
7	Fiberoptic Solar Concentrator/Solar Sintering
8	Wide and High Additive Manufacturing
9	Selective Separation Sintering
10	Binder Jetting
11	Material Jetting
12	Direct Ink Writing
13	Laser Engineering Net Shaping
14	Supersonic 3D Deposition
15	Ultrasonic Consolidation
16	Electron Beam Freeform Fabrication
17	Selective Laser Sintering
18	Magnetojet
19	Electron Beam Additive Manufacturing
20	Electron Beam Melting

Highest on the list are FFF and CFF, material extrusion processes that can cover a wide range of plastics. CFF, using filaments with embedded reinforcements, can produce plastic parts with improved strength. The FFF technology has already been tested under low gravity providing a good TRL as starting point. The recycling process has been tested and as well as impact of volatiles or toxic fumes release which may contaminate the environment. Post-processing varies depending on the needs, but often parts can be used directly from the printer. A number of direct energy deposition technologies have been shortlisted as they are not affected by gravity, they can process metals and some can operate under vacuum. Therefore, they can be used to produce parts for the outside infrastructure, as well as machinery.

Technologies used to process regolith are also present: BAAM, CC and Solar Sintering as they are critical for the creation of the infrastructure: roads, landing pads, habitat outer shells. One of these technologies can be selected for implementation in the roadmap. These high ranked AM technologies need to be further investigated, in order to select the most suitable process (or maximum two) within this group, as they cover a similar range of materials and parts. One of the key parameters to assess the suitable technology will be the resources needed to be brought from Earth in establish the process (e.g. binders, raw materials, special post processing machinery).

6. Discussion and next steps

The results obtained in the completed phases of the URBAN study are in agreement with a previous ESA study where it was found that Aluminium alloys, Titanium alloys and CFRP are suitable for recycling and 3D printing [10]. Many printers already use these as base material. This is a significant overlap with needs – the materials that the hardware is made of, which means that there is a magnitude of technologies to choose from and a feedstock produced in different forms.

Results from the survey performed in Task1 correlate with results of Task 2. It's not surprising that there's high degree of correlation between the results: Aluminum alloys, regolith, steel, plastics are materials that are used to produce the elements of infrastructure. And those are materials that can be processed by a high number of AM technologies.

The next step in the project is a preparation of an open dynamic tool to be used as a decision support algorithm for the identification of the suitable AM manufacturing techniques, versus the identified /listed items (see Figure 8). The tool will be a stepping stone for a future decision-making process algorithm, which will be mandatory in the perspective of a permanent lunar base. On the Moon, the selection of the adequate technology utilization will most likely need to be taken in-situ, with constrains (e.g. required printing time) based on the existing needs.

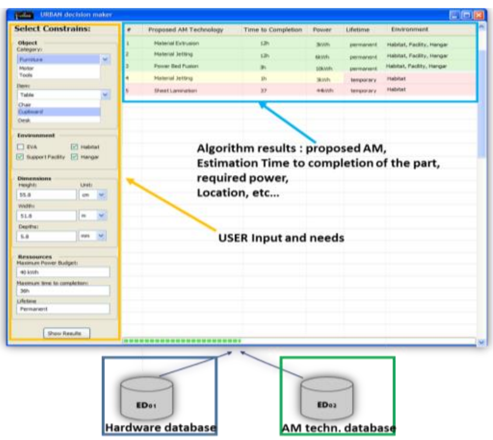

Figure 8: Example of decision making tool

The output of the algorithm will be represented by a list of the printable parts and the non-printable hardware parts for which alternative solutions have to be found. The last step of the study will be focused on the elaboration of a technological implementation roadmap, which constitutes an essential part of an R&D strategy for the identified AM technologies. This roadmap will be complemented by a cost analysis comparing the cost associated with shipping the considered hardware items from Earth against the cost of producing them at the mission destination.

Figure 9 shows a schematic of a potential roadmap of AM technologies, both terrestrial and for space. The x axes indicate the TRL level evolution, timeline, immediate study scope and technology forecast in the short, medium and long term. As a first glance, the utilization of a manufacturing plant in a remote area, such as Antarctica or another desert area, can represent a logical and low risk approach to proving the technology efficiency and simulating several scenarios.

7. Conclusion

The activities performed within this study have confirmed the promising advantages derived from the utilization of in-situ and on-planet (in particular lunar) Additive Manufacturing, to build, maintain and operate any future human-tended base. The key driver capability to make this implementation successful and sustainable is the possibility to recycle end-of-life items and convert them into raw material, thereby closing the material loop. The major benefit of AM is the design freedom it allows [11]. The sustainability will also result from the ability to redesign components, products and the process itself, based on their intended usage in the lunar base. While AM can be used to directly replicate and produce the needed hardware in the forms that we know on Earth, this type of approach fails to take full advantage of the offered design freedom. Exploiting the full potentialities of the implementation of AM processes for lunar exploration will require time. Revisiting the traditional design approach and adjusting the specific AM capabilities for use in environments different from Earth will be the next challenge.

Acknowledgements
The study has been financially supported by ESA under the General Studies Programme, with contract No. 4000122380/17/NL/LvH/ab.
The authors would like to acknowledge support from all the invited experts for making data and information available and for the fruitful cooperation. In particular:
Dr. ir. K.J.C. (Kjeld) van Bommel, Senior Consultant in Technical Sciences / Food Processing at TNO
Professor Paul Gatenholm, CEO of Advanced Polymer Technology AB, specialized in bioprinting
Dr. Johannes Homa, CEO of Lithoz, company specialized in ceramic AM technology
Michiel Vullings BU Manager ATG Europe and responsible of the composite technology
Aurora Baptista, CEO of BEEVeryCreative, responsible of the polymers 3D printer development and *Mario Angelo*, CTO
Dr. Andres Willert, Senior scientist and the Deputy head of the department Printed Functionalities at Fraunhofer Institute for Electronic Nano Systems ENAS
Dr. Itedale Namro Redwan and Dr. Hector Martinez, senior scientists for Bioink and Tissue Engineering R&D at CELLINK
A special thanks to the ESA experts: *Thomas Rohr, Laurent Pambaguian, Ugo Lafont* and *Christel Paille* for the valuable comments and constructive recommendations on this project during the PAR.
The authors would like to thank all the participants of the online surveys for their contributions. Finally, we thank ESA Communication office for issuing the public call “What’s your idea to 3D print on the Moon – to make it feel like home?” and all the participants for their ideas and views, which will make our travel to Moon closer to “Home”.

References

[1] International Space Station Assembly – Past Flights, https://www.nasa.gov/mission_pages/station/structure/iss_assembly.html

[2] Visiting Vehicles Launches, Arrivals and Departures, https://www.nasa.gov/feature/visiting-vehicle-launches-arrivals-and-departures

[3] Owens, Andrew, and Olivier De Weck. "Systems Analysis of In-Space Manufacturing Applications for the International Space Station and the Evolvable Mars Campaign." AIAA SPACE 2016. 2016. 5394.

[4] Wohlers Report 2017 ISBN 978-0-9913332-3-3

[5] Ardila, L. C., et al. "Effect of IN718 recycled powder reuse on properties of parts manufactured by means of Selective Laser Melting." Physics Procedia 56 (2014): 99-107

[6] Asgari, Hamed, et al. "On microstructure and mechanical properties of additively manufactured AlSi10Mg_200C using recycled powder." Materials Science and Engineering: A 707 (2017): 148-158.

[7] Park, Hyung Ki, et al. "Refining effect of electron beam melting on additive manufacturing of pure titanium products." Materials Letters 187 (2017): 98-100.

[8] Lightweight Materials and Structures, and Advanced manufacturing https://sbir.nasa.gov/printpdf/54829

[9]https://www.bam.de/Content/EN/Standard-Articles/News/Special-pages/parabolic-flight-2018.html

[10] C. Stenzel, L. Weiss, A. Dröse. Sustainable materials concepts Final Report, TRP Contract No. 4000111600. (2016)

[11] S. Ford, M. Despeisse, Additive manufacturing and sustainability: an exploratory study of the advantages and challenges, Journal of Cleaner Production 137 (2016) 1573 – 1587

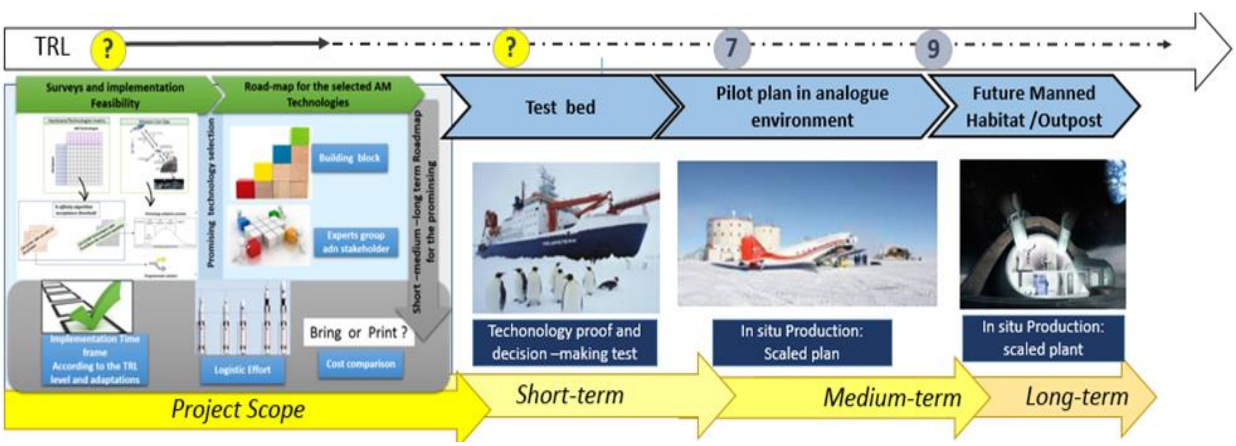

Figure 9: Potential Roadmap for the AM technologies implementation