



Executive Summary Report

ESA Contract 4000122380

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1 INTRODUCTION

The URBAN project “lUnaR Base Additive maNufacturing” was conducted under ESA contract No. 4000122380/17/NL/LvH/ab “Conceiving a lunar base using 3D printing technologies”.

1.1 Scope

This document is the executive summary of the URBAN project and provides a concise description of the project objectives and achievements. Only a general overview of the project’s activities is given. For more details, the Final Report of the project presents all the necessary information [AD1].

2 REFERENCES

2.1 Applicable Documents

This document shall be read in conjunction with documents listed hereafter, which form part of this document to the extent specified herein. In case of a conflict between any provisions of this document and the provisions of the documents listed hereafter, the content of the contractually higher document shall be considered as superseding.

Table 2-1: Applicable Documents

AD	Doc. No.	Issue	Title
[AD01]	URBAN-OHB-RP-0001	1	URBAN Final Report

It should be noted that all requirements listed in the documents of Table 2-1 are applicable unless noted otherwise or exceptions are identified and agreed.

2.2 Reference Documents

The following documents contain additional information that is relevant to the scope of this document.

Table 2-2: Reference Documents

RD	Doc. No.	Issue	Title
[RD01]	URBAN-OHB-TN-0001	01	Lunar manned permanent outpost hardware requirements survey
[RD02]	URBAN-OHB-TN-0002	01	Additive Manufacturing technologies survey
[RD03]	URBAN-OHB-TN-0003	01	Methodology Analysis for implementing AM technologies on a permanent manned lunar base
[RD04]	IAC-18.D3.3.7x42605	N/A	URBAN: conceiving a lunar base using 3D printing technologies A.Sgambati, M. Berg, F.Rossi, A. Dauriskikh, B. Imhof, R. Davenport, P.Weiss, M.Peer, T.Gobert, A. Makaya 69th International Astronautical Congress (IAC), Bremen, Germany, 1-5 October 2018.

2.3 Abbreviations & Nomenclature

For all terms, definitions and conventions used, if available.

Table 2-3: Abbreviations & Nomenclature

Abbreviation	Meaning
CI	Configuration Item
AD	Applicable Document
RD	Reference Document

3 URBAN PROJECT EXECUTIVE SUMMARY

3.1 Context

Several studies have been addressing the building of a lunar base either under ESA or other space agencies and entities initiatives. These studies are looking at conceptual designs, often of one specific element of the base, while most of the requirements are not adequately or not at all taken into consideration.

Logistics remains as one of the major constraints in long-term human space missions. Space agencies have shown great interest in the utilization of lunar resources as the next logical step in implementing a global strategy for human exploration of the solar system. The key to any sustainable presence in space is the ability to manufacture in situ, and on-demand the structures, items and replacement parts that are required. The production of goods locally reduces the cost and volume of long-duration missions.

Additive layer manufacturing is a promising solution because it reduces the lead time from design to implementation, and manufacturing waste due to the recyclability of in situ materials.

ESA has awarded a General Studies Programme activity, under Contract 4000122380, to the URBAN Consortium (Comex, Liquifer Systems Group, Sonaca Space GmbH under the coordination of OHB System AG) to evaluate the feasibility and implementation effort required in establishing the possible uses of Additive Manufacturing in easing the construction, expansion, operation and maintenance of a lunar base.

3.2 Objectives

The objective of this activity is to study the possible uses of Additive Manufacturing (3D printing) in a lunar base perspective.

The URBAN study performs two parallel surveys looking into the capabilities of the additive layer manufacturing technique to meet set goals.

One is concerned with the identification of hardware parts required for a permanent human-tended lunar base, ranging from large-scale permanent infrastructures to smaller on-demand items. The feasibility of 3D-printing these different elements are investigated.

The other survey includes an analysis of state-of-the-art additive layer manufacturing technologies and an assessment of their capacity to 3D-print several materials such as metals, polymers, ceramics, concrete, food ingredients, and living tissues. An objective of the project is to explore the possibility of recycling elements that have become obsolete in a lunar station of the future, by using them as printing material for the construction of new objects. While such technology is primordial for the construction of a lunar base in the future, ESA and the URBAN consortium foresee terrestrial spin-offs for the project.

3.3 Study content and progress

During this activity following main activities have been performed:

- Task 1: Lunar base hardware identification and classification survey (see [RD1])
- Task 2: ALM technologies classification overview (see [RD2])
- Task 3: Systematic Hardware vs ALM technology (see [RD3])
- ALM technologies roadmap definition (see [RD3])
- A significant number outreach activities were performed in parallel to the technical study tasks above, such as a survey to Industry, organisation of an interdisciplinary workshop, public competition, Global Networking Forum, paper and presentation at the IAC, ESA Technology Image of the Week

3.4 Task 1: Lunar base hardware identification and classification survey

A 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. A huge data set of lunar base infrastructure elements and items have been identified based on intensive literature reviews. The items were classified in the hardware groups as shown in Figure 3-1 in which the concept of the Lunar Base hardware survey is illustrated.

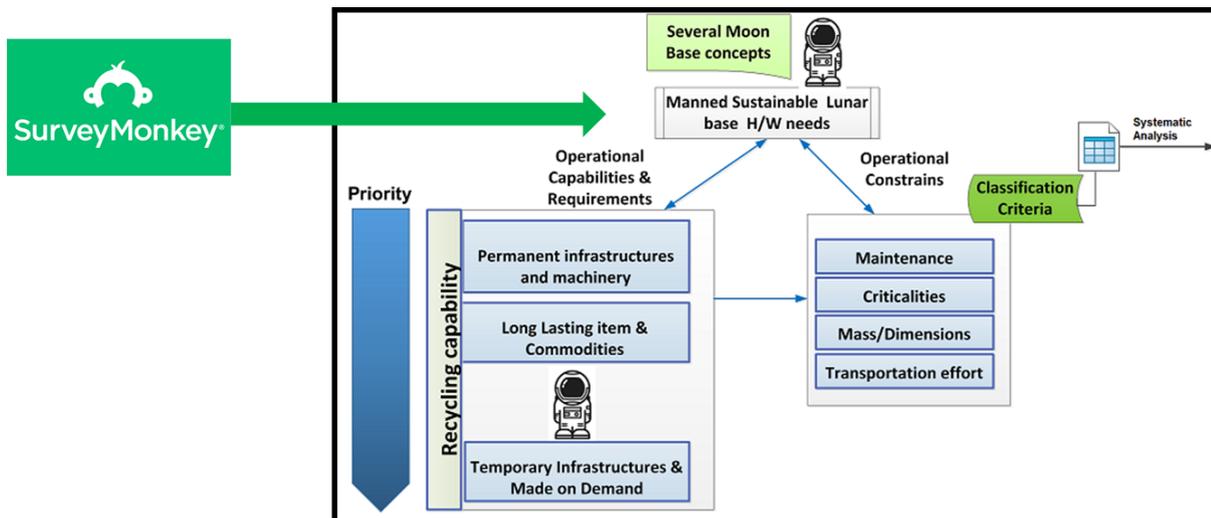


Figure 3-1: Lunar Base Hardware Survey

Besides identifying requirements via literature and web review, an objective of this study was to directly address persons involved in both human spaceflight and analogue site campaigns regarding additional hardware requirements. For this purpose an on-line public survey questionnaire was established using the online service SurveyMonkey. Relevant names were identified and invited to participate in this survey. Requests for participation in the on-line survey were sent out to 78 individuals covering space industry, analogue site campaign, remote exploration and AM technology related disciplines. Replies have been received from 25 persons, which were carefully evaluated. Consolidated lists of all hardware requirements identified by the surveys have been created in tabular format including their detailed properties, criticality, 3D print manufacturing compatibility (i.e. current status and potential) and recycling potential.

3.5 Task 2: ALM technologies classification overview

A dedicated survey of the available additive manufacturing technologies that can be useful in the lunar base perspective, addressing a broad range of possible applications. Lunar 3D printing is often viewed in the context of in-situ resource utilisation (ISRU) and habitat construction, a number of studies using various technologies having been dedicated to those aspects. But the scope of the current GSP activity is much broader, as it looks at the lunar base from a system point of view and includes the state of the art of 3D printing related to several materials such as metals, polymers, ceramics, concrete, food ingredients and living tissues.

An extensive literature review survey of existing additive manufacturing technologies have been performed- The AM processes have been categorised and shortly described addressing the main aspects, such as process, materials, general advantages and disadvantages, examples of machines and possible post-processing steps. The survey included Material extrusion, Vat Photopolymerization, Powder bed fusion, Material jetting, Binder jetting, Sheet lamination, Directed energy deposition, bio printing of living cells and tissues and Bio-based material 3D printing for commodities, food printing, multi-material printing.

Furthermore state-of-the-art metal powders recycling, Plastic recycling as well as conversion of waste and bio-products into products processes have been analysed in view of potential moon base applications.

Existing technologies and demonstrations for in-space and on-planet manufacturing have been identified and assessed including Lunar base construction based on In-situ Resource Utilization (ISRU), ISS 3D printer and Refabricator demonstrations and in-space Powder-bed AM and situ manufacturing have been analysed.

Preliminary consideration of the lunar environment on AM processes and machinery have been assessed as well.

The complete AM technology survey concept followed in the study is shown in Figure 3-2.

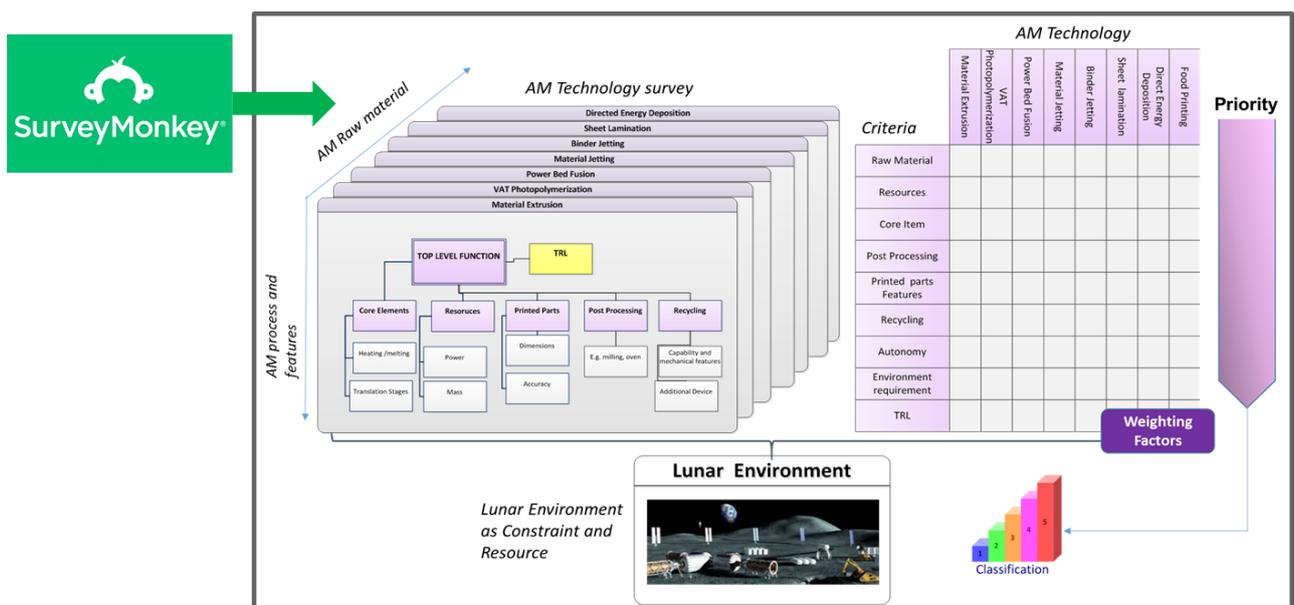


Figure 3-2: AM technology survey concept

In addition to the literature survey and assessment a SurveyMonkey online survey was conducted to collect information on parameters and features of various 3D printing technologies and opinions of the technology developers on the potential application for Lunar base construction. A total of 21 replies were collected out of more than two hundred companies that were contacted.

The results of the online survey confirm the outcomes of the literature survey. Plastics and metals are the most popular materials Industrial demands materials with high strength/functionality, these are most often thermoplastics or metals that can be used to produce optimized designs. Extrusion-based and directed energy deposition technologies are the least affected by lunar environment, implementing technologies that use liquids or powders as a raw material is much more complicated.

In order to minimize shortcuts and consolidate the study output, an expert support team has been established to provide direct input on the particular AM technology challenge or adaptation effort. The selection of the experts has been based on the need of collecting other expertise despite the ones inside the consortium (ISRU, metal and plastics) and complement with consolidate technologies (polymers and ceramic) and emerging ones (Composites ,electronics, Food and bio printings)

The expert's team is composed by **TNO, ATG Europe, BEEVeryCreative, LitHoz, Advanced Polymer Technology AB, Fraunhofer ENAS, Cellink.**

The experts' support team has been defined due to the wide spectrum of the technologies needed to be assessed and analyzed in the frame of the study.

Each entity has been involved and engaged as consultants in support of the activity; including their participation to the PAR at ESA/ESTEC on 18th June 2018.

The results of the AM technology surveys have been included in data base providing for each identified AM process a big set of information, e.g. processed materials, Core elements, post processing, Recycling, power consumption, part dimensional accuracy and TRL.

3.6 Task 3: Systematic analysis of Lunar Base Hardware vs ALM technology

A systematic analysis as matching point between the outcomes of the two surveys has been defined. In order to support and quantify the feasibility of manufacturing the identified elements with the available technologies, Key Performance Indicators (KPIs) have been defined, allowing a ranking of the elements.

As result of these surveys a large amount of information and data has been gathered, assessed and sorted. A searchable database has been created. The database allows filtering of categories like consolidating technology process types, material or maximum dimensions. It allows to determine the most appropriate AM technology for a given need.

From the several AM technologies identified in AM Technology survey suitable for printing the hardware identified in the hardware survey, the feasibility of their implementation in a lunar environment has been assessed. The complete end- to-end mission has been analysed, including a possible launch scenario that will represent the first element of the mission chain. The list of the identified AM technologies with respect to identified hardware coming from the two databases, has been screened according to the following cluster criteria and following the approach as illustrated in the: **Figure 3-3**

- Flexibility to use the technology with different materials
- Resources Budget for logistic and transportation
- Capability to assembly in- situ item with different procurement
- Lunar environment constraints on the process chain
- Lunar environment a simplification. Resources available to us at the lunar surface can act as a AM feedstock as well, simplifying some process steps or raw material procurement (e.g. glass/ceramic printing).

The 52 AM technologies identified have been shorted to 21 ones; based on agreed weighting factors.

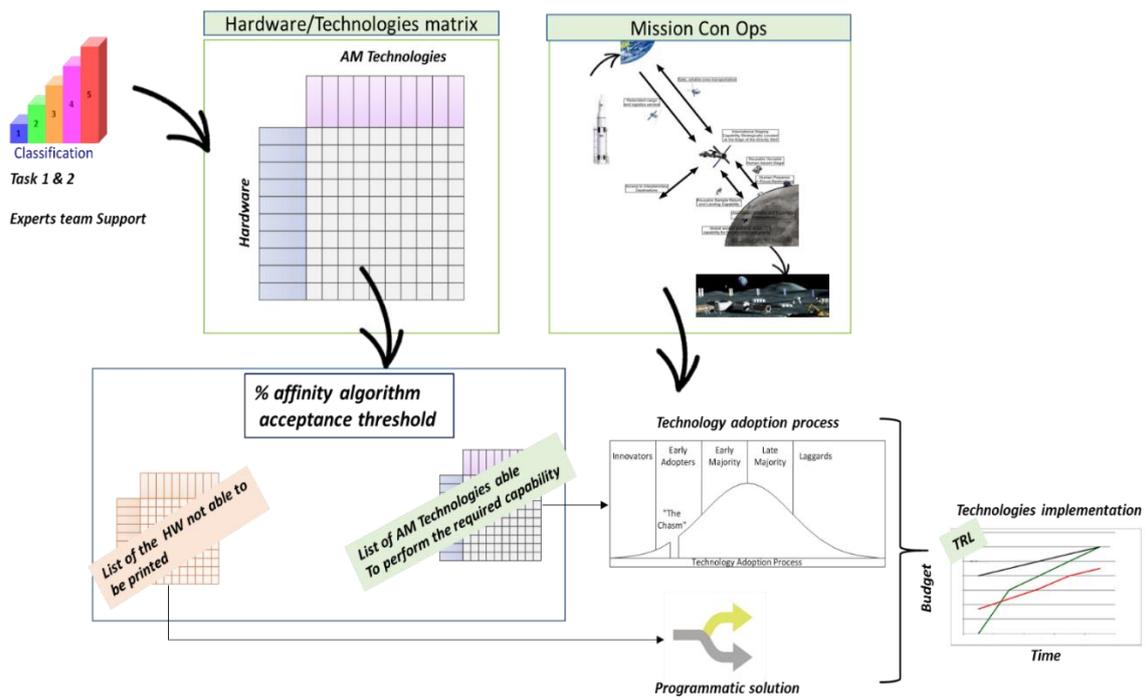


Figure 3-3: Approach for the Systematic Analysis

3.7 ALM technologies roadmap definition

The final study outcome is defined in a roadmap for using Additive Manufacturing to establish a sustainable permanent lunar base. The overall effort required to translate the existing identified AM applications in a lunar perspective has been elaborated in this Roadmap with a step-wise approach:

- The short, medium and long term vision for the AM process implementation from Earth to the Moon.
- A preliminary cost analysis has been elaborated to achieve the AM high technology readiness for the lunar implementation.
- A possible mission scenario has been drafted including the transportation and logistics cost to establish a clear framework to support the decision of “bring” or “print”.

The implementation approach related to the roadmap and cost analysis is illustrated in Figure 3-4

From the twenty one technologies, four have been selected for the roadmap implementation:

- Fused Filament Fabrication (FFF)
- Electron Beam Additive Manufacturing (EBAM®)
- Fiberoptic Solar Concentrator
- Lithography-based ceramic manufacturing (LCM)

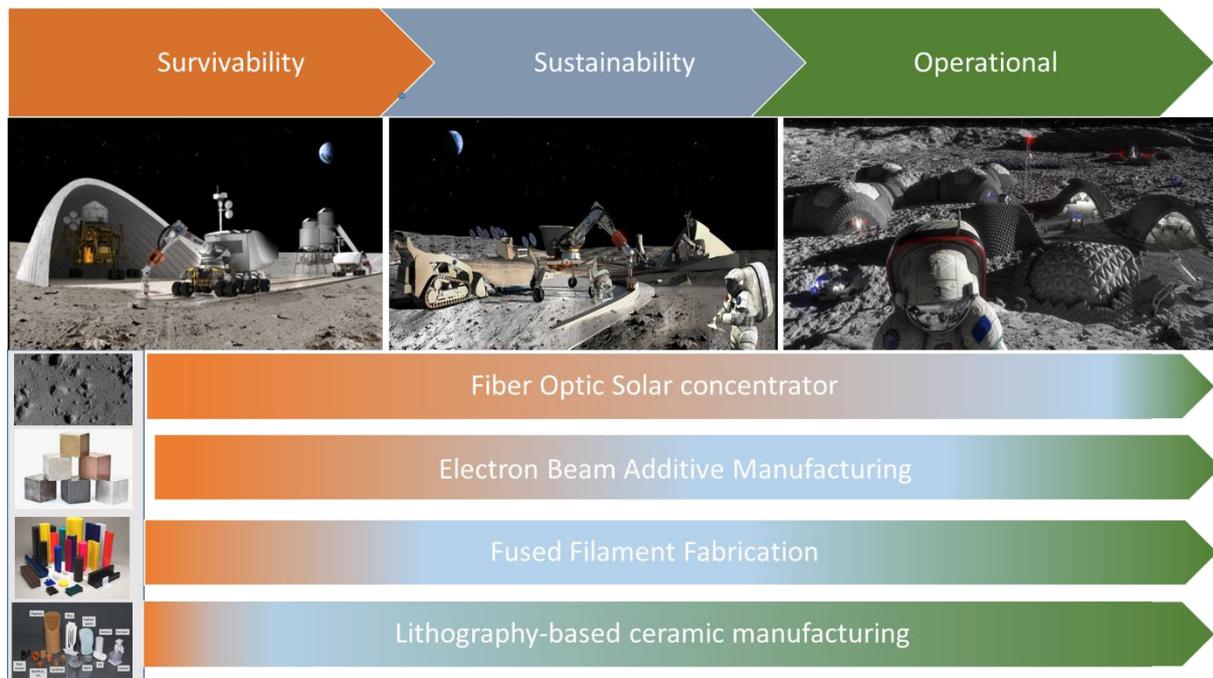


Figure 3-4: AM technologies implementation wrt lunar base evolution

In general the Additive Manufacturing technologies will play a crucial role in reducing drastically the maintenance and resupply needs and be a fundamental key player in the maintain and operational phase of the lunar base; albeit at the beginning the logistic effort from Earth will be higher as shown in the Figure 3-5. The flight schedule is the presentation of the logistics. The survivability phase will start with the transportation of one-time mass from Earth. This mass is necessary for build-up of the Moon base and paving the way for its extension.

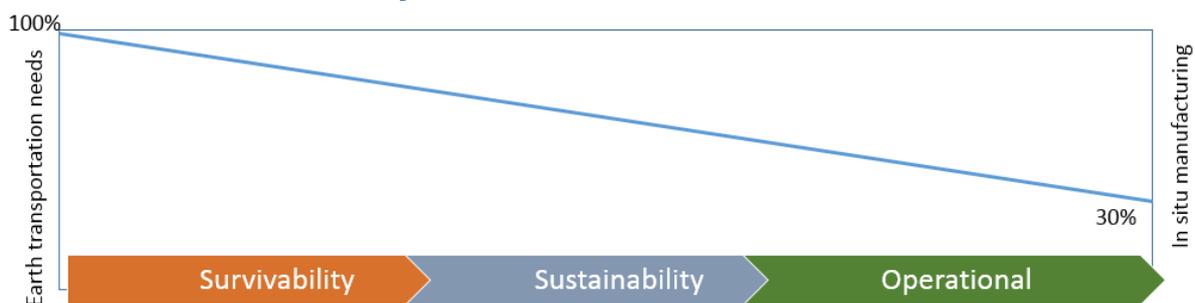


Figure 3-5: Logistics needs trend

3.8 Outreach activities

During the course of study the following outreach activities have been performed:

- Survey of additive manufacturing technologies addressing a broad range of applications and the state of the art of 3D printing related to several materials such as metals, polymers, ceramics, food ingredients and living tissues using the on-line service surveymonkey©. It has been invited to participate in the survey either via email to selected persons/institutions/companies and in addition by the distribution of dedicated postcards with QR-Code links for the two surveys on relevant events.

- IAC Paper: URBAN: conceiving a lunar base using 3D printing technologies (IAC-18.D3.3.7x42605) paper and presentation on 69th IAC Bremen, Germany, 1-5 October 2018 [RD1]
- IAC GLOBAL NETWORKING FORUM, URBAN: Conceiving a Lunar Base Using 3D Printing Technologies, Thursday 4 October 2018, 12:00 – 13:00, 69th IAC Bremen, Germany
- Study Summary Description Flyer, to be distributed at the final presentation
- Video describing the outcome of the study <https://youtu.be/SdycFkvJam0>
- Idea provider for the ESA organised competition “What’s your idea to 3D print on the Moon to make it feels like home”. Refer to http://www.esa.int/Our_Activities/Space_Engineering_Technology/What_s_your_idea_to_3D_print_on_the_Moon_to_make_it_feel_like_home and related message of ESA astronaut Samantha Cristoforetti https://www.youtube.com/watch?v=h-t2XFNB_sk&feature=youtu.be