

URBAN-OHB-HO-0002
12nd December 2018
ESA/ESTEC



SPACE SYSTEMS

URBAN: conceiving a lunar base using 3D printing technologies

FINAL PRESENTATION

We. Create. Space.

- I. Background**
- II. URBAN Study :Objectives and Challenges**
- III. URBAN : Hardware classification overview**
- IV. URBAN : ALM technologies classification overview**
- V. Systematic analysis : ALM technologies Roadmap**
- VI. Bring or Print considerations**
- VII. Conclusions and Next Steps**

I. Background



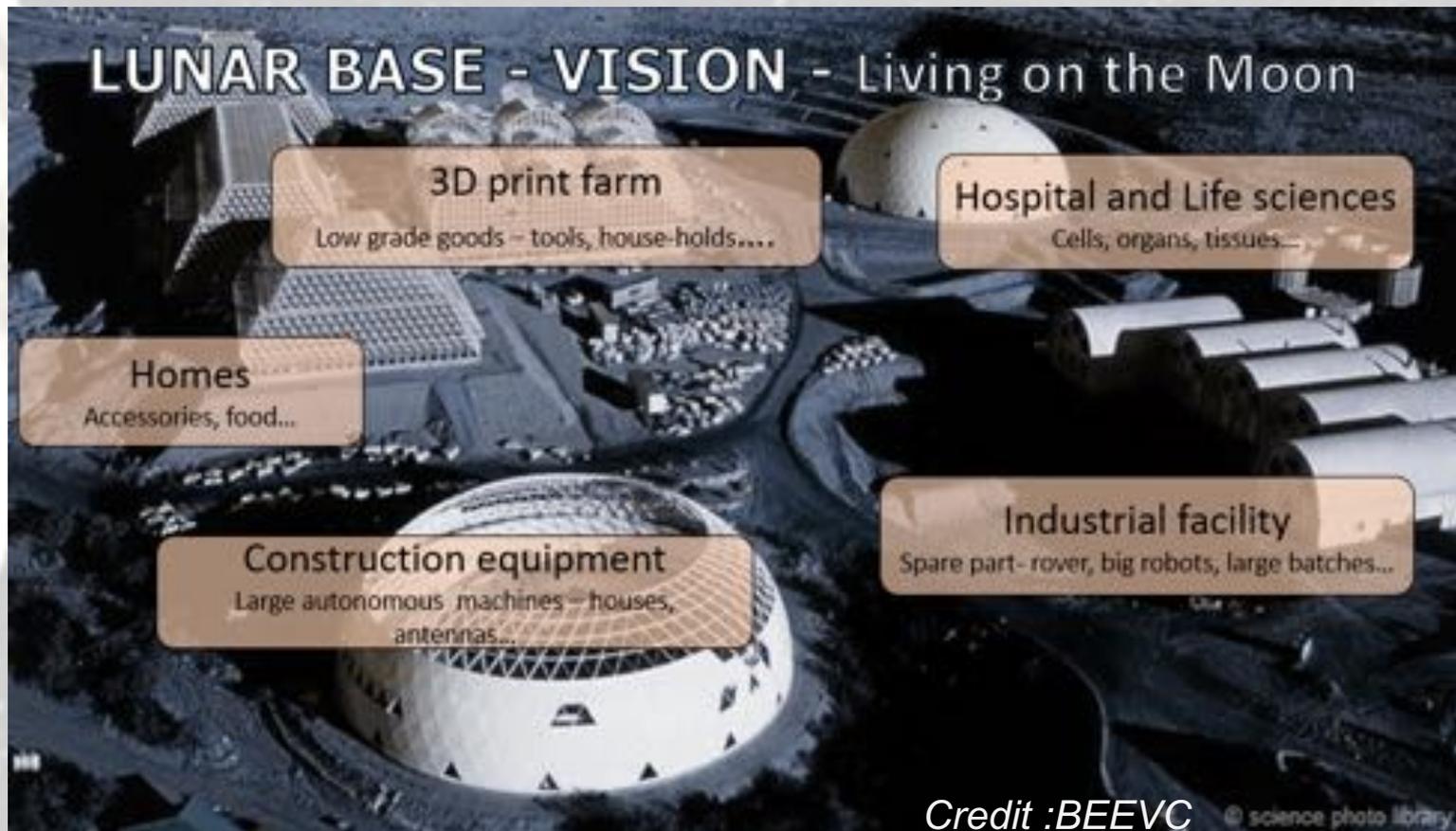
One of the most critical points in space exploration beyond Low Earth Orbit is the provision of systems that ensure the **long-term survival** of both crew and technological assets in the harsh space environment.

One of the key to any **sustainable presence** in space will be the capability to be, as far as possible, **Earth-independent**.

Additive Manufacturing (AM) has the potential to provide a number of sustainability advantages; such as the ability to manufacture necessary structures, spares, in situ and on demand reducing the cost, volume, and up-mass constraints.

II. URBAN Study : Objectives and Challenges

The ESA General Study project **URBAN** aims to evaluate the feasibility and implementation effort required in establishing the possible uses of Additive Manufacturing in easing the construction, expansion and maintenance of a lunar base.



Public outreach initiatives



Two Public surveys on Hardware and AM technologies

WHAT'S YOUR IDEA TO 3D PRINT ON THE MOON – TO MAKE IT FEEL LIKE HOME?



69TH INTERNATIONAL
ASTRONAUTICAL CONGRESS
BREMEN 1-5 OCT 2018

Paper , presentation

Global Networking Forum



Press release, Journal publications, news, exhibition , postcards, illustration and video clip



II. URBAN Study : The Team



in charge of the coordination, systematic analysis, roadmap and cost analysis considering the Moon mission. OH B developed the affinity algorithm between hardware and AM technologies.



contributed to the assessment of the environmental impact in building infrastructure in harsh environment

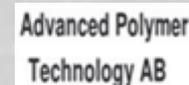


Coordinated the Hardware Survey thanks the high heritage in several human settlement concepts and technique in buildings.

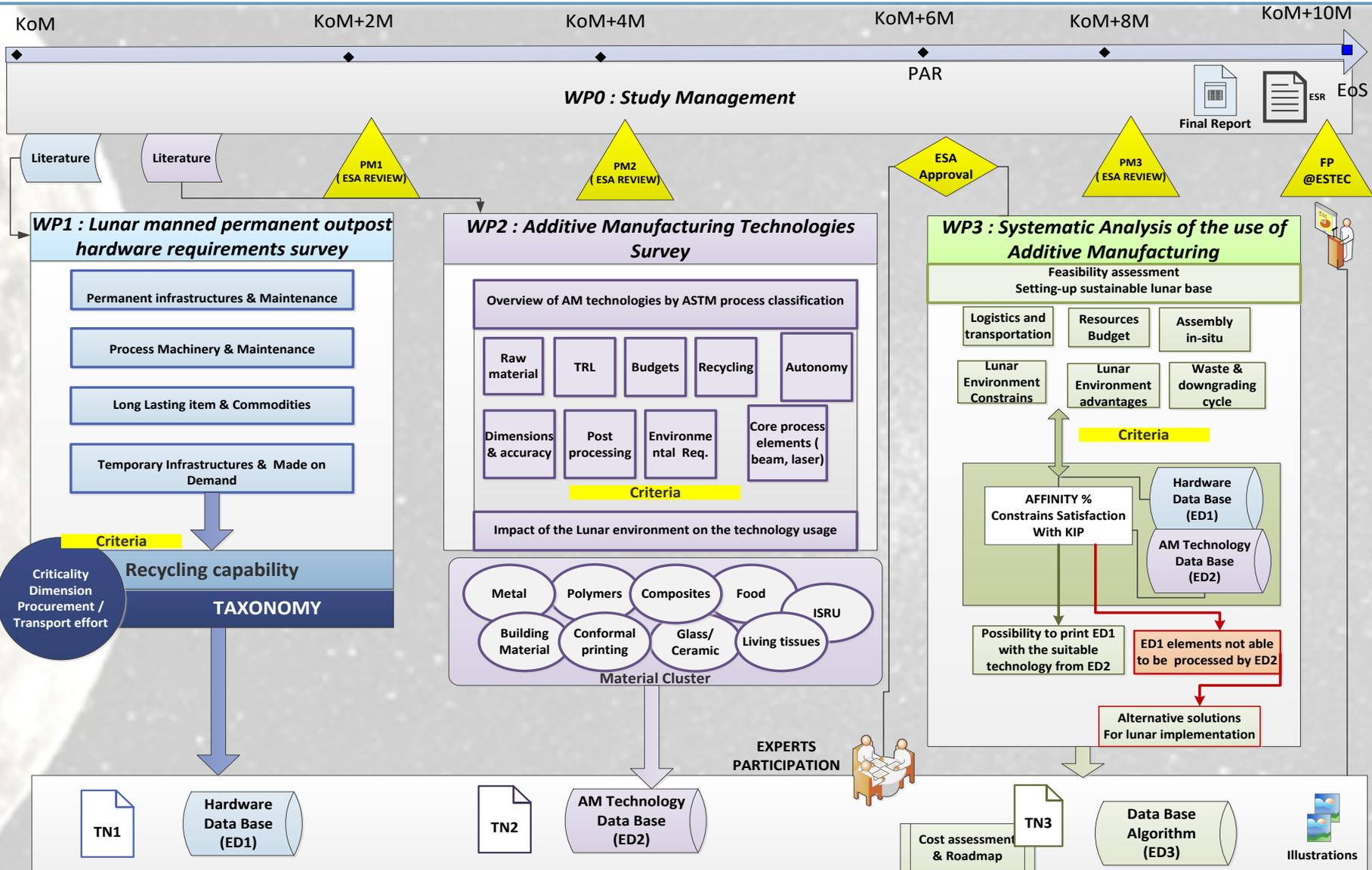


Thanks to the relevant in house capability in AM technology for polymers and metals; they were in charge of the AM technology survey

Experts

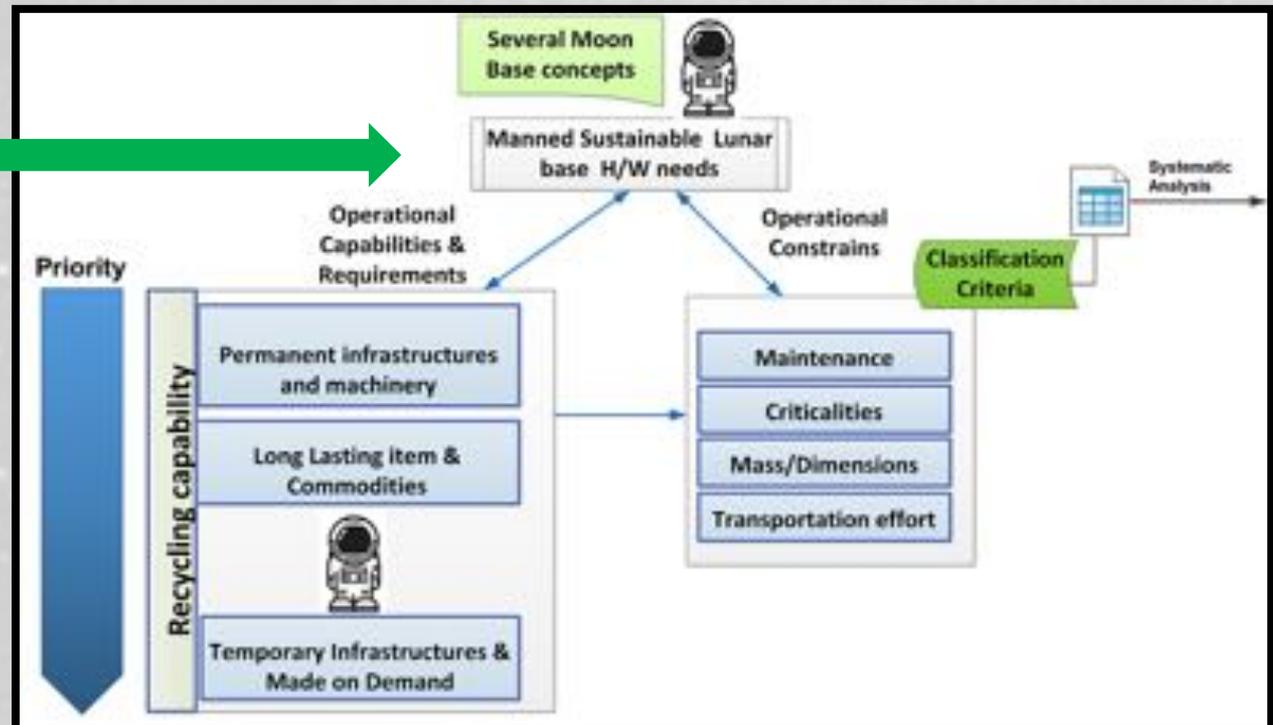


II. URBAN Study : Work logic



II. URBAN Study : Hardware Survey

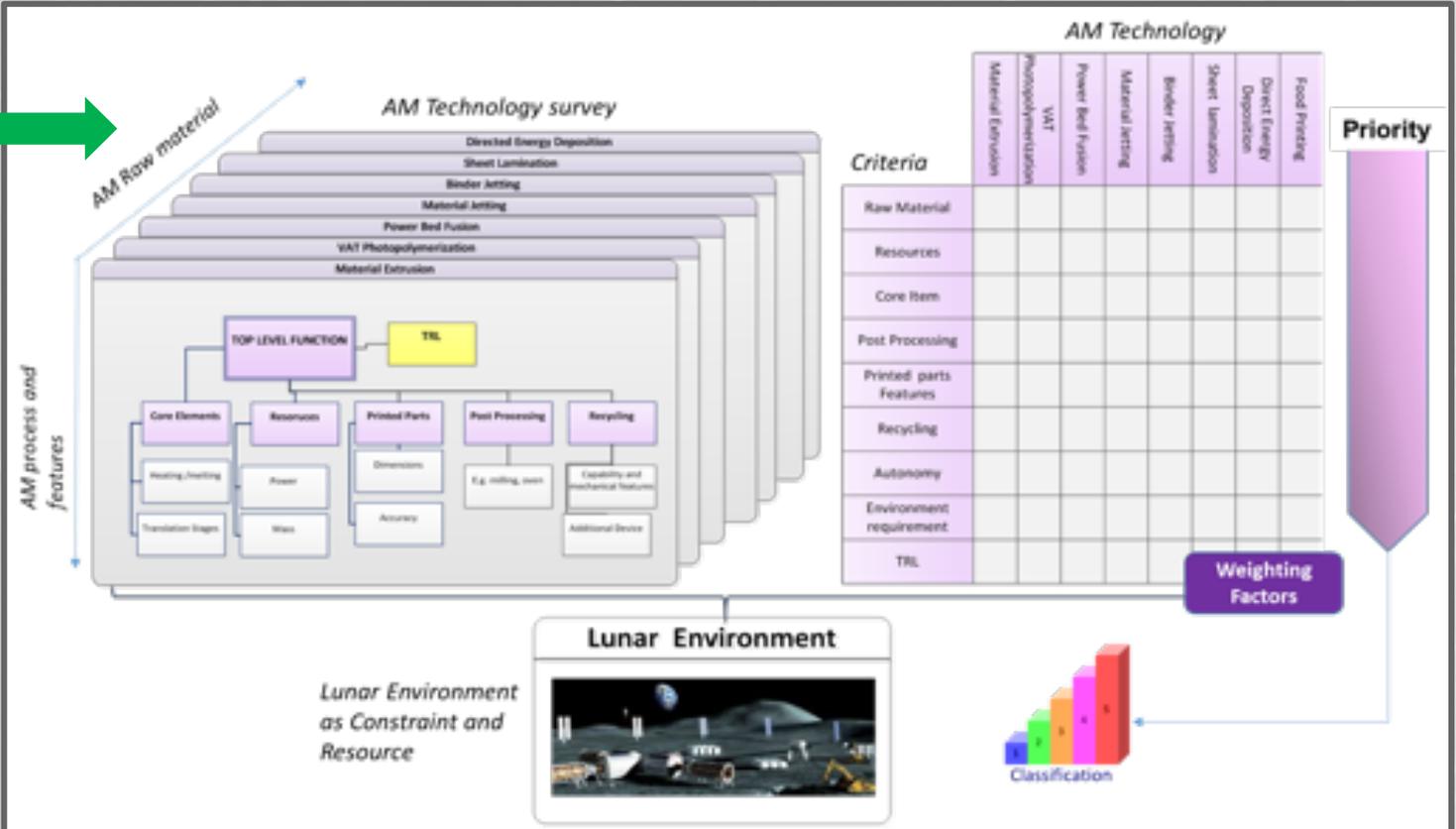
Comprehensive survey of the elements/hardware required in a permanent and sustainable manned lunar base, based on a hierarchical investigation from permanent infrastructures to the “on demand” items.



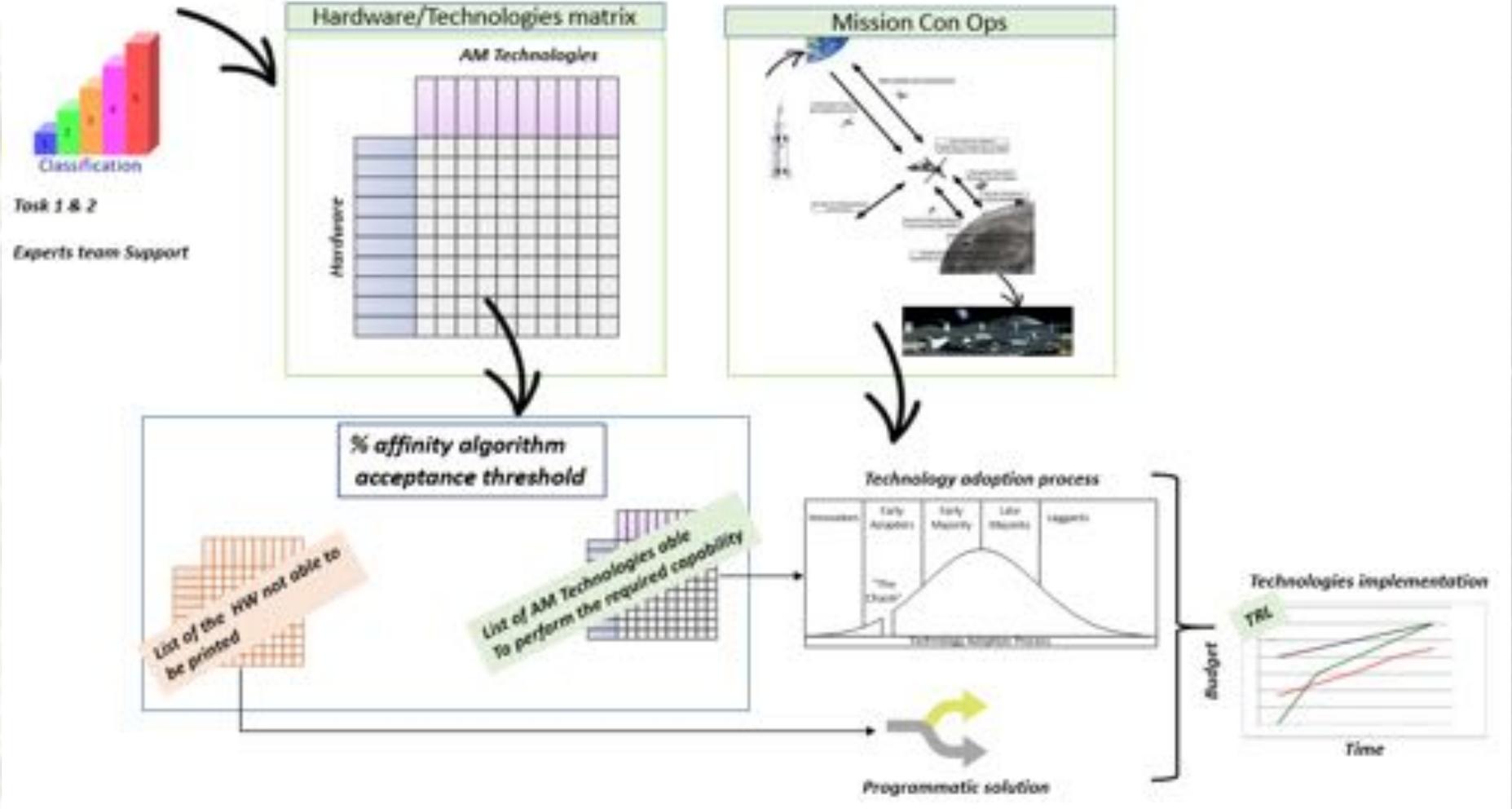
II. URBAN Study : AM technologies Survey



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.

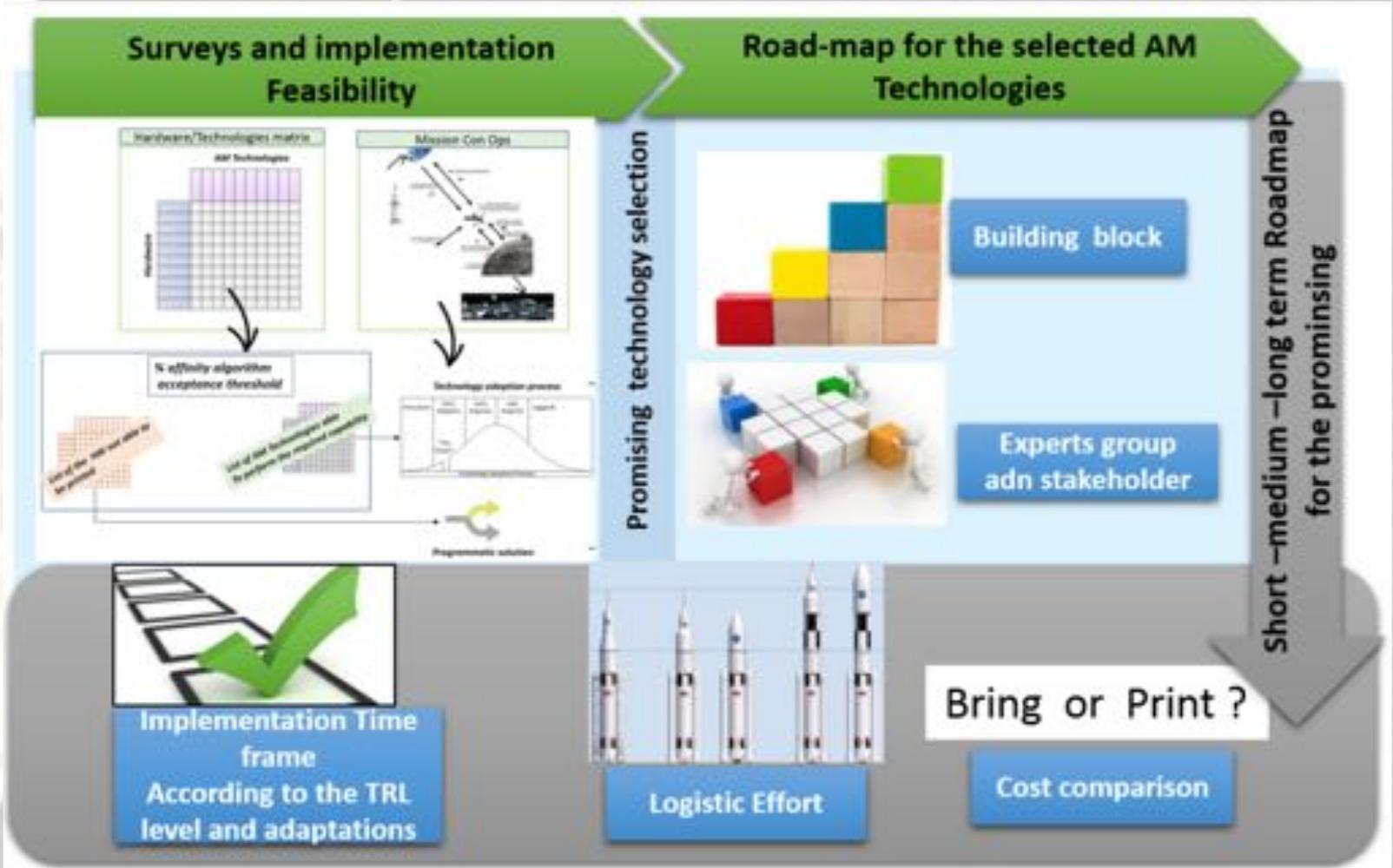


II. URBAN Study : Systematic Analysis



II. URBAN Study : Roadmap

Implementation Approach related to the roadmap and cost analysis





Task 1 : Hardware classification overview

III. URBAN : Hardware classification overview



Task 1 objectives:

- Provide a comprehensive survey of the elements/hardware of a permanent and sustainable manned lunar base, investigate them hierarchically from permanent infrastructures to the “on demand” items and classify according to identified criteria: e.g. criticality, mass, dimensions, logistics and recycling.

Task 1 study approach:

- Comprehensive review of literature to identify hardware needs related to manned lunar permanent infrastructure, Earth based analogue simulations and remote exploration (Polar research, oceanography, oil/gas exploration).
- Perform a survey of infrastructure needs by using a questionnaire distributed to professionals in the areas of space engineering/research, manned space and robotic analogue simulations, remote exploration.
- Perform assessment if identified infrastructure can be 3D printed

III. URBAN : Hardware classification overview

Evolution of a Lunar base

- ❑ **Survivability** – minimum crew, permanent presence, critical hardware only
- ❑ **Sustainability** – larger crew, additional less critical hardware
- ❑ **Operational** – full crew, complete hardware of all criticalities “MOON VILLAGE”



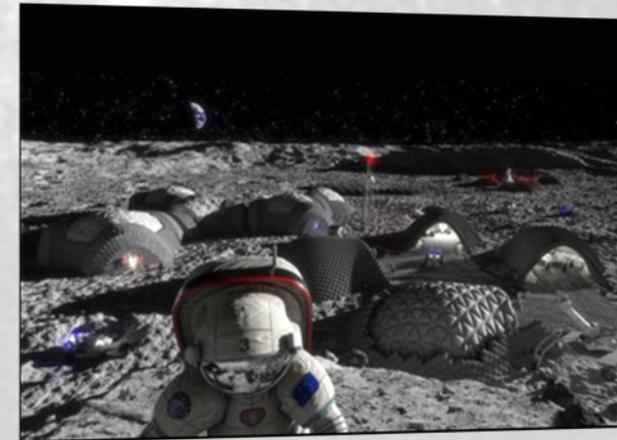
Credit: SHEE Consortium

Near Term



Credit: British Antarctic Survey

Mid Term



Credit: RegoLight Consortium

Long Term

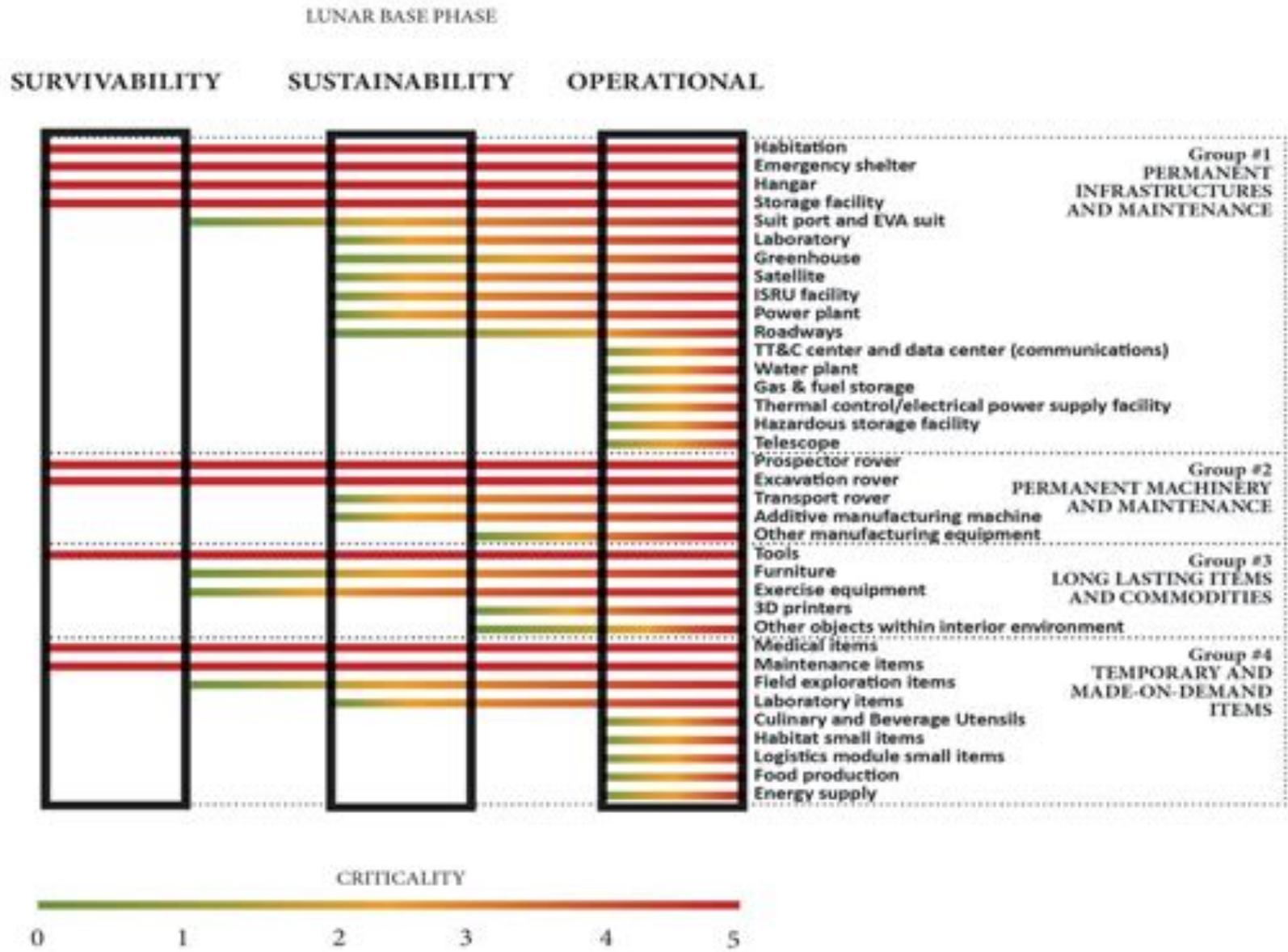
III. URBAN : Hardware classification overview



Hardware infrastructure categories & requirements

Group #1	Group #2	Group #3	Group #4
Permanent infrastructure & maintenance	Permanent machinery & maintenance	Long lasting items & commodities	Temporary & made on demand items
Habitat and storage modules, communications infrastructure, rigidizable inflatable structures and building blocks using lunar regolith, ISRU plant using hydrogen reduction of FeO etc.	Transportation, rovers, oxygen reactor, AM & ANC machines, mixer, plastic re-cycling machinery, Direct Energy Deposition machine, homogenizer, 3D printers for building large and microscopic parts etc.	Mechanical and sampling tools equipment, 3D printers, furniture, exercise equipment, fuel etc.	Spare parts for items in Group #1 & #2. Made on demand items such as medical/dental, laboratory, culinary, habitat small items, textiles, logistics, food and biological etc.

III. URBAN :The Hardware criticalities



Group 1- Permanent Infrastructures and maintenance

- Research data obtain from various space mission architecture, analogue station such as Antarctic stations and online survey

Purpose

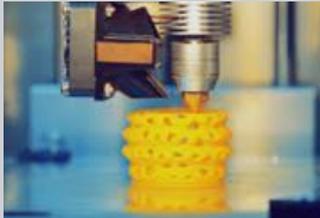
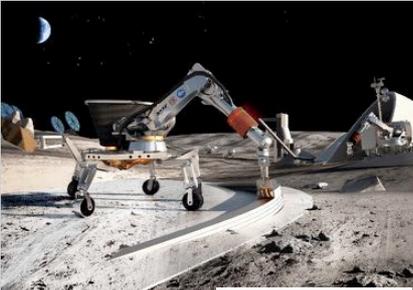
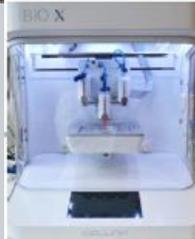
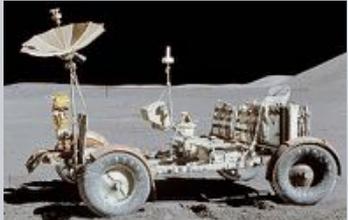
- To provide shelter for human, robots and other equipment's from the harmful lunar environment

Build (Survive)	Run (Sustain)	Maintain (Operational)	Research
<ul style="list-style-type: none">• Habitat• Hanger and storage facility	<ul style="list-style-type: none">• Laboratory• Green house• Satellite• ISRU facility• Power plant	<ul style="list-style-type: none">• Operational pads• Roadways• TTC and Data center• Water Plant• Gas and fuel storage• Thermal Control and• Electrical Power Supply facility	<ul style="list-style-type: none">• Telescope• EVA suit

III. URBAN : Hardware Groups



Group 2 – Permanent Machinery and Maintenance

Explore (Phase 1)	Build (Phase 2)	Run (Phase 3)	Research (All phases)
  	  	    	 

Credit: NASA, ESA, SpaceX, RegoLight consortium, Foster+Partners, pinintrest

Group 3: Long lasting items and commodities

- Items that are to be found mainly in an interior environment of a habitat
- Commodities will represent the backbone elements of the processes (raw materials, seeds, energy, packaging)



Common material

- Fiberglass, plastic, stainless steel, aluminum, rubber and composite materials.
- Nano cellulose

Current status of AM printing compatibility

- Mostly yes . Strongly correlation with recycling capability for the raw material availability

Group 4 – Temporary and made-on-demand items

- Included here are on demand items such as spare parts for Group 1 & 2 items, food, biological tissues or orthopaedic prosthesis due to an emergency need. Temporary items, for example, include single use tools (items that address specific needs).



Common material

- Plastic, stainless steel, aluminum, rubber and composite materials.

Current status of AM printing compatibility

- Extensive applications already available.

III. URBAN : Hardware Data base

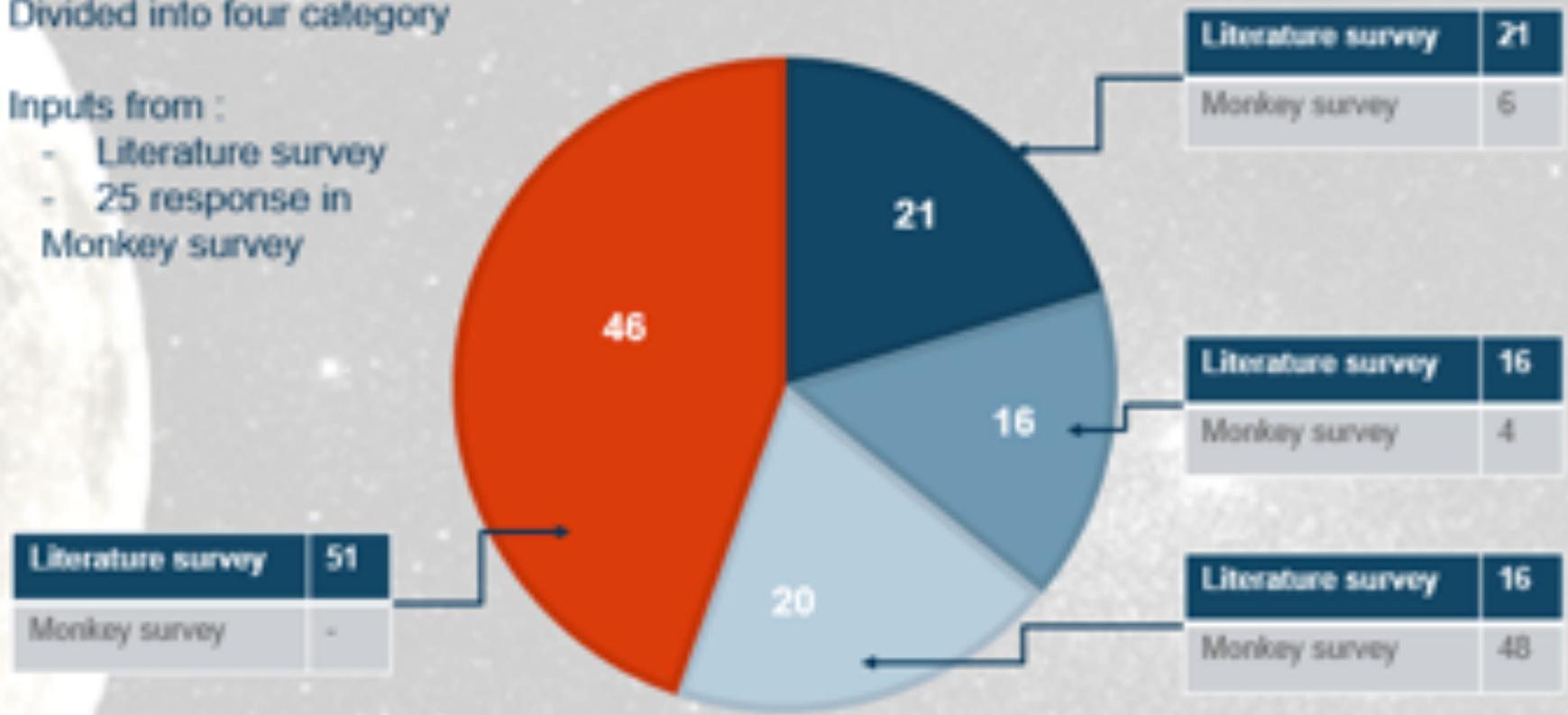
Temporary and Made on Demand Items - Medical & Dental											
	Material	Main features / application	Dimensions	Mass	Maintenance of permanent infrastructure including spare parts	Criticality (1 = low 5 = high)	Current status of AM printing compatibility	Procurement		R&D costs	Recycling/ down cycling
								Sent from Earth	Transport time		
	polyurethane) or latex Wound-care glass adhesives						Boron trioxide glass-based fibres and particles patent [RD72]				Other application
Bandage 	Cotton, nylon	Treatment of cuts etc.	Various lengths and widths	< 100 g	One-time use tailored to patient	4	[RD67], [RD68] [RD69]				Yes, for application not requiring special purity
Suture Thread 	Nylon, Polyester, PVDF, Polypropylene	Holding together wound tissue	0.01 – 0.8 mm thickness	< 1 – 2 g	One-time use tailored to patient	4	3D printed automated surgical suturing device in development [RD09]				Yes, for other application
Oxygen mask 	ABS	Used to administer Oxygen	10-50cm		One-time use tailored to patient	4	Produced by Stratasys Medical Solutions Group, 3DMD and GrabCAD in 2016 [RD57]				Yes for other applications

Example of the data-base structure

III. URBAN :Hardware Requirement Survey



- Divided into four category
- Inputs from :
 - Literature survey
 - 25 response in Monkey survey

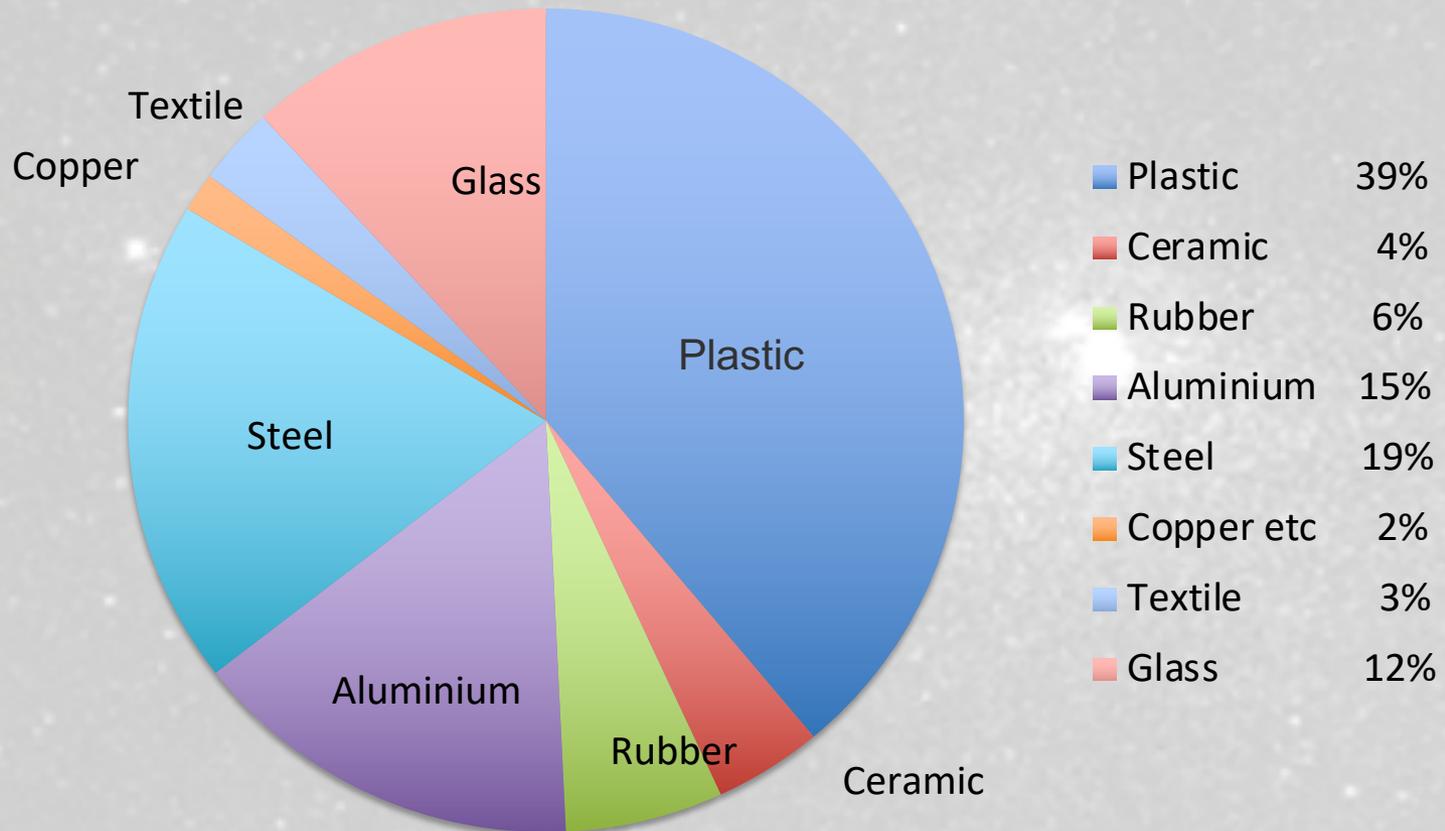


- Permanent Infrastructures and maintenance
- Permanent machinery and maintenance
- Long lasting items and commodities
- Temporary and made on demand items

III. URBAN :Hardware Requirement Survey



Relative distribution of materials used in hardware
Identified by survey





Task 2 : AM technologies Survey

IV.URBAN : ALM technologies classification



INPUT 1 : Literature survey according to the **ASTM** (American Standard Test Method) process group classification

INPUT 2: Public survey at the technology developers was conducted where participants could provide their inputs.

INPUT 3: Support from experts leading different AM technologies in terms of process and scope

Experts



INPUT 1: ASTM process grouping and literature



- AM process groups (ISO/ASTM 52900:2015)
 - Material Extrusion
 - Vat Photopolymerization
 - Powder Bed Fusion
 - Material Jetting
 - Binder Jetting
 - Sheet Lamination
 - Direct Energy Deposition
- Emerging technologies
- Lunar environment effects
- Current research in in-space and on-planet printing

INPUT 1: ASTM process grouping and literature

Material Extrusion

- Material is dispensed through a nozzle or an opening
- Materials: Consumer-grade plastics, and thermoplastics, ceramic slurry, food
- Already tested in microgravity environment

Core element	Power	Max part dimension current/theoretical	Mandatory Post processing	TRL for Moon
Extruder	Low to Medium (<5kW)	14m x 7m x 3 m unlimited	Depending on the surface requirements: from none to support removal, CNC machining. Ceramic parts: washing, sintering	9



Desktop 3D printer
(Credit: BEEVERYCREATIVE)



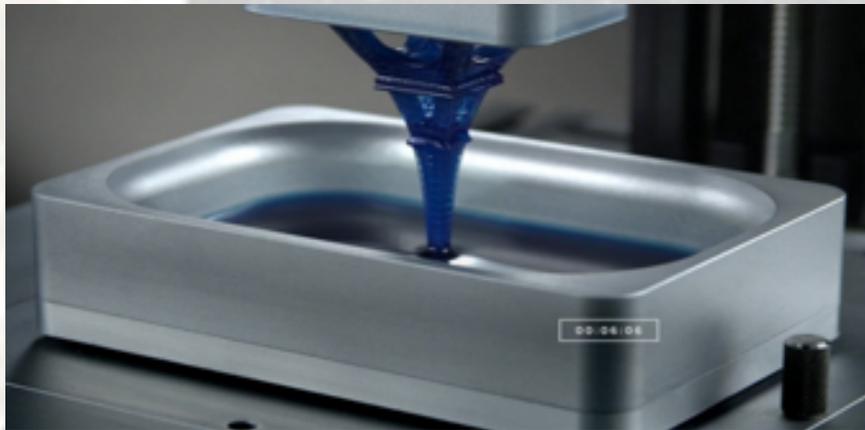
BAAM printing process and printed part
(Credit: 3dprint.com)

INPUT 1: ASTM process grouping and literature

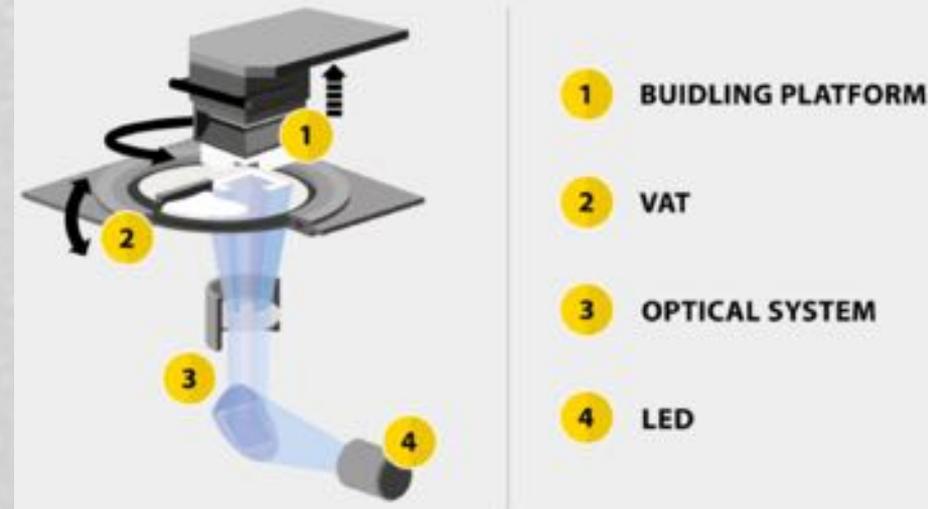
Vat Photopolymerization

- Liquid photopolymers are selectively cured by ultraviolet (UV) light
- Material: Photopolymer, ceramic

Core element	Power	Max part dimension current/theoretical	Mandatory Post processing	TRL for Moon
Light source, VAT with liquid	Low to Medium (<5kW)	1500 × 750 × 550 mm Limited by the VAT size	Depending on the surface requirements: from none to surface finish Ceramic: debinding, sintering.	4



CLIP process by Carbon (Credit: Carbon)



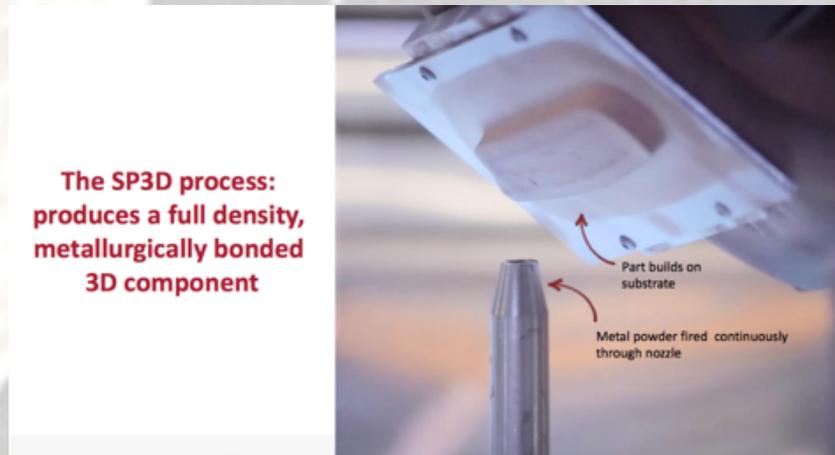
Process core elements (Credit: Lithoz)

INPUT 1: ASTM process grouping and literature

Direct Energy Deposition

- Focused thermal energy to melt materials as they are being deposited onto another, and with it fusing them together
- Materials: metals

Core element	Power	Max part dimension current/theoretical	Mandatory Post processing	TRL for Moon
Energy source: a laser, an electron beam, or a plasma arc	High to Very High	7112 × 1219 × 1219 mm ³ unlimited	Depending on the application, CNC machining to achieve surface finish	7



Sciaky's EBAM printer (Credit: Sciaky)

INPUT 1: ASTM process grouping and literature



Multi-Material Printing

- Selective Laser Reflow
- Printed circuit boards (PCBs)
- Li-ion batteries
- Parts with integrated electronics



Solar cell printing (Credit: Utilight)



2-layer assembled board (Credit: Nanodimensions)

IV.URBAN : ALM technologies classification



INPUT 2: Online survey

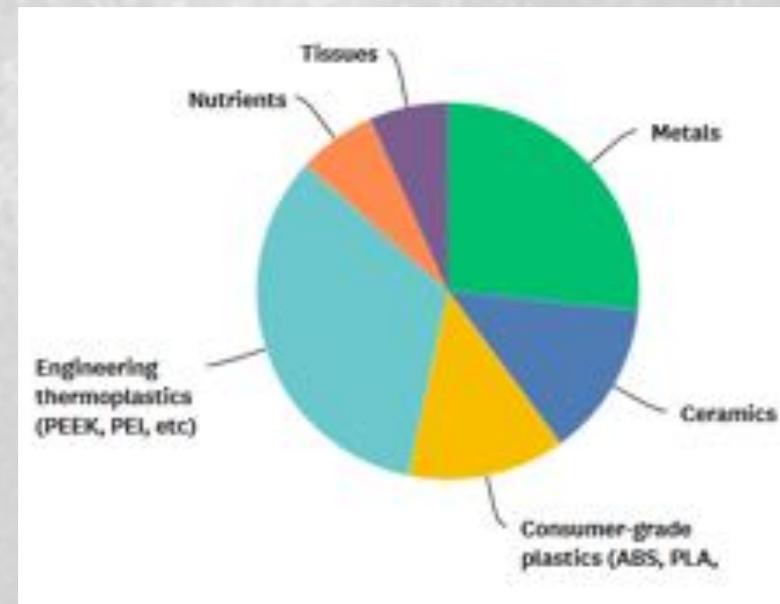
Objectives were to collect information and opinions of the technology providers

Questions

10 questions, addressing technology type and features, print size, post processing needs, recyclability and potential for adaptation to Moon environment.

Results

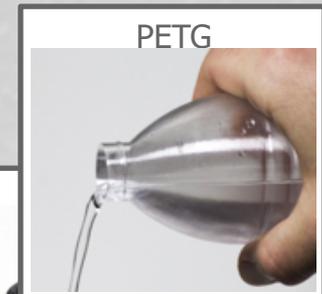
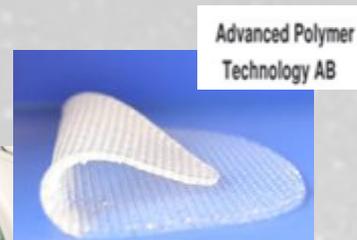
- Over 200 invites to participate sent out, 22 replies received
- High-end plastics and metals are the most popular materials - industry demands materials with high strength/functionality
- The majority of technologies have requirements on environmental conditions: specific temperature range and/or humidity



IV.URBAN : ALM technologies classification



INPUT 3: Experts' support



Lunar Environment Impact

- Vacuum
- High radiation
- Extreme temperatures
- Lack of natural convection
- Lunar dust
- Low gravity (unchangeable)
- Moonquakes
- Micrometeorites

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 a 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 a 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 ³	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.

Recycling and Sustainability of the process

The establishment of an AM process in support of the Moon base will be strongly correlated to the **self-sustainability** of the process itself and the possibility in **reusing the recycled materials**.

Components and products can be redesigned to take advantage of AM's beneficial properties and flexibility to create new geometry able to compensate by structural design the potential loss of the original performance (**Downcycling**)

Waste material can be used as source of the AM process to produce a functional item (**Upcycling**)

CRISSP (Customizable Recyclable ISS Packaging) from Tethers Unlimited is a suite of materials designed as launch load protection and then be recycled into feedstock for 3D printers

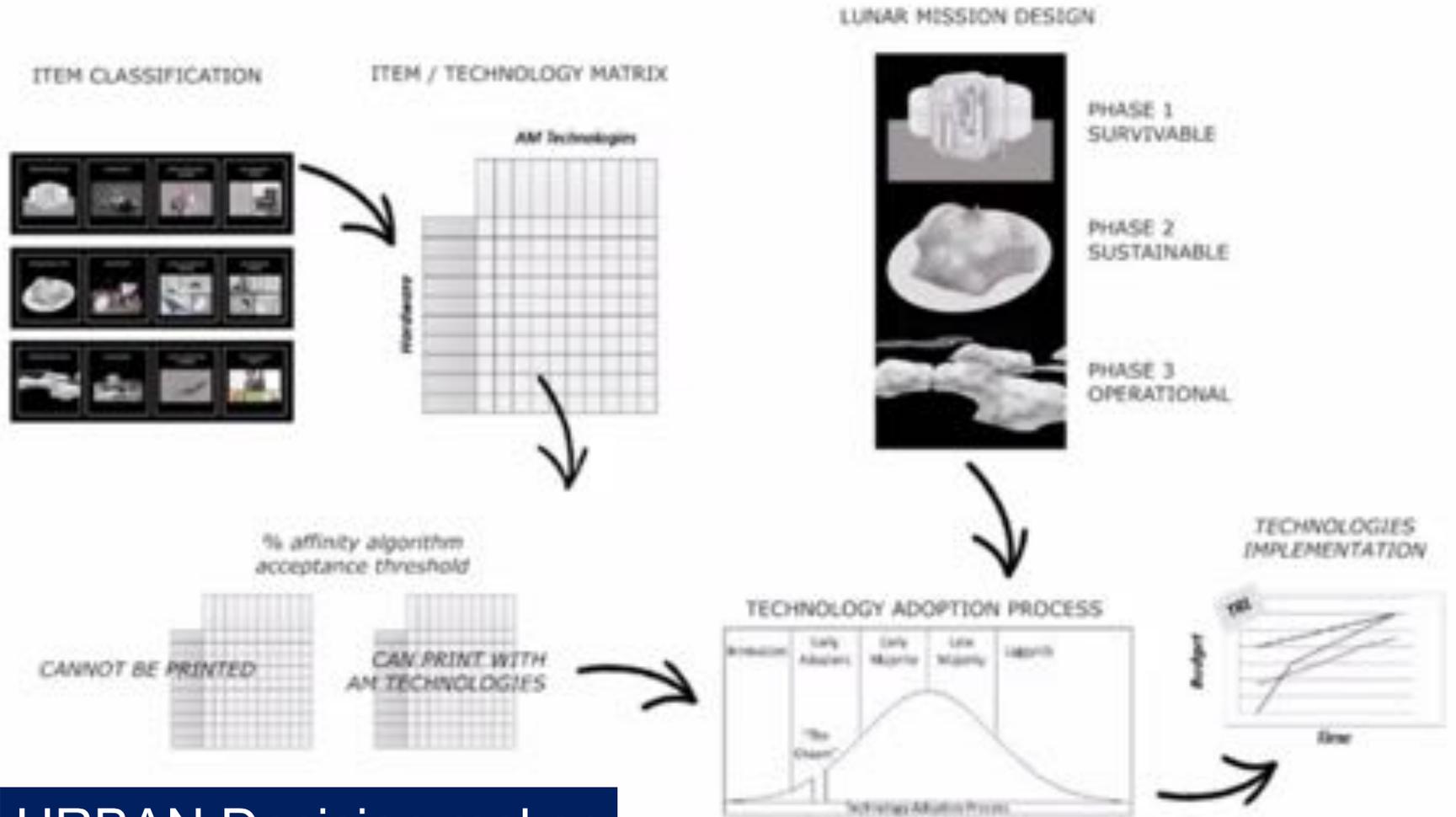


V.URBAN : Systematic analysis approach



Survey and Implementation Feasibility

Roadmap for the AM process



URBAN Decision maker

V.URBAN : ALM technologies selection



NUMBER OF IDENTIFIED HARDWARE

144

TREND



Aluminum, its alloys, steel, and its alloys as well as copper, titanium and both consumer-grade and high-performance plastics



AM TECHNOLOGIES

52

MATERIALS	ADAM	BAAM	CC	CH	EDW	FF		REP	WHAM	C-LRI	CLP	SLP		LCM
Adis	FALSE	TRUE	FALSE	FALSE	FALSE	TRUE	FALSE							
Alumina	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	TRUE							
Aluminum	FALSE													
Aluminum Alloys	FALSE													
Boerite Inks	FALSE													
Bonglers	FALSE	TRUE												
Bonded Tungsten	FALSE													
Brass alloys	FALSE													
Carbon Fiber	FALSE	FALSE	FALSE	TRUE	FALSE									
Carbon Fiber filled Nylon	FALSE													
Ceramic Inks	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE								
Ceramic slurry	FALSE													
Cermet	FALSE	TRUE												
Chromite	FALSE													
Cobalt Alloys	FALSE													
CoCr alloys	FALSE													
Concrete	FALSE													
Conductors	FALSE													
Copper	FALSE													
Copper alloys	TRUE	FALSE												
Corderite	FALSE	TRUE												

The match of the two databases (task 1 & task 2) has been evaluated by a software which is able to show whether an item could be printed or not with respect to on demand constraints entered to the system.

“URBAN decision maker” tool

open dynamic tool that will be act as decision support algorithm for the identification of the suitable AM manufacturing versus the identified /listed items. 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 decision of the adequate technology utilization has to be taken in-situ and with constrains (e.g. time in printing) that can be defined on-demand by the existing needs.

LIVE DEMONSTRATION DECISION MAKER SW



V.URBAN : ALM technologies selection



Grade	Key performance indicators for AM technologies ranking							
	Necessity of main elements	Estimated low gravity influence	Estimated outside compatibility	Estimated Power-Required Resources	Estimated feedstock sourcing	Estimated material waste	Estimated post processing	Estimated lead time
	5	4	2	3	3	4	3	3
1	needed for 1-5 elements	Extreme interference with process	Extreme interference with process	High	Earth	High	High	> 6 Months
2	needed for 5-10 elements	Considerable interference	Considerable interference	Medium to High	Extensive recycling	Low	Substantial	< 6 Months
3	needed for 11-15 elements			Medium	Extensive ISRU	Partly recyclable	Medium	Weeks
4	needed for 16-20 elements	Low interference	Low interference	Medium to Low	Recycling	Recyclable	Low	Days
5	needed for >21 elements	No interference with process	Designed for outside use	Low	ISRU & recycling	None	None	Hours

Then the utility function is calculated as the sum of all key indicators multiplied by the weighting factors

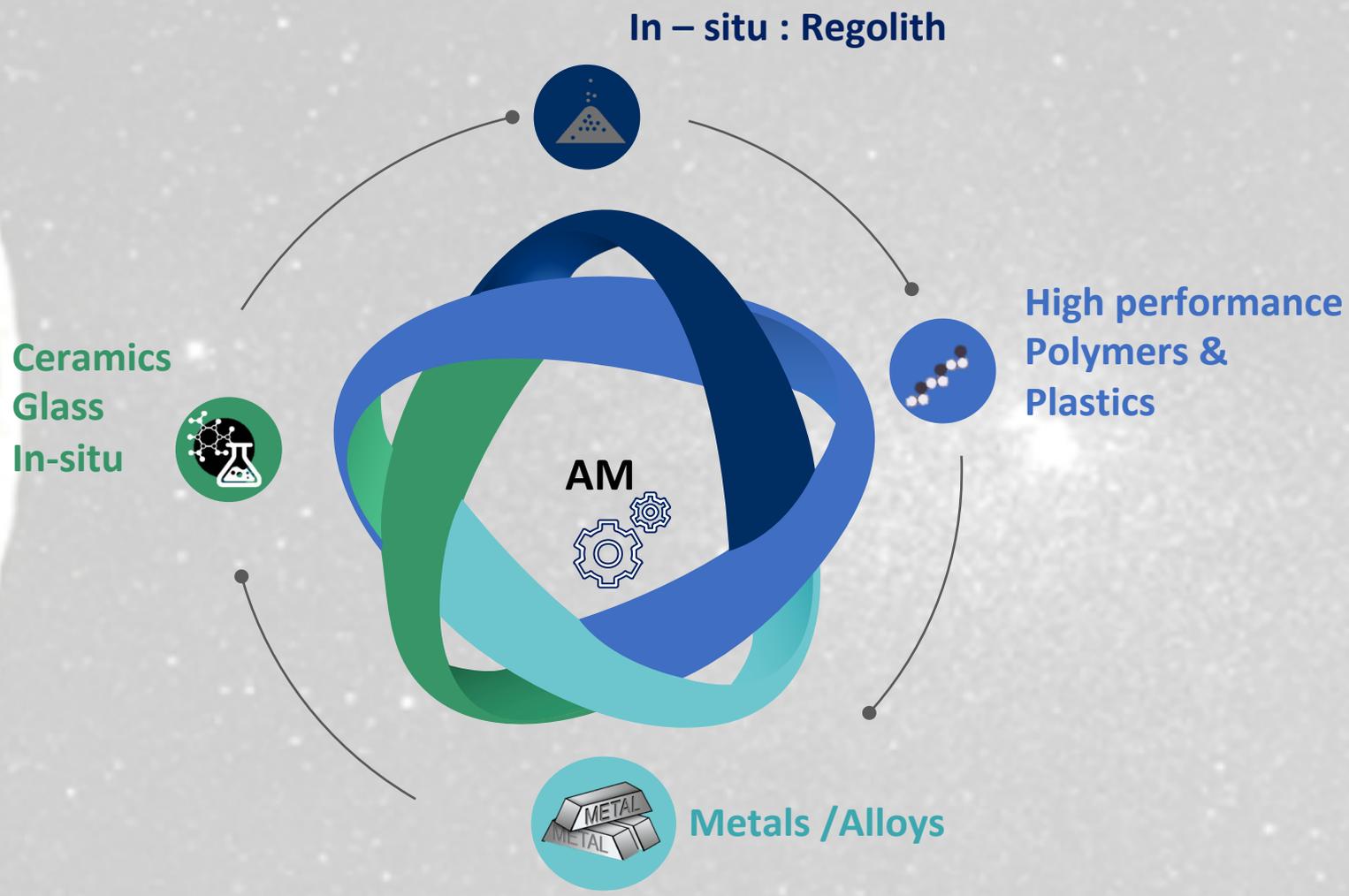
V.URBAN : ALM technologies selection



Ranking	Abbreviation	Process name
1	FFF	Fused Filament Fabrication
2	CFF	Continuous Filament Fabrication
3	CC	Contour Crafting
4	BAAM	Big Area Additive Manufacturing
5	ADAM	Atomic Diffusion Additive Manufacturing
6	LMD	Laser Metal Deposition
7	-	Solar Concentrator
8	WHAM	Wide and High Additive Manufacturing
9	SSS	Selective Separation Sintering
10	Binder Jetting	Binder Jetting
11	Material Jetting	Material Jetting
12	DIW	Direct Ink Writing
13	LENS	Laser Engineering Net Shaping
14	SP3D	Supersonic 3D Deposition
15	UC	Ultrasonic Consolidation
16	EBF	Electron Beam Freeform Fabrication
17	SLS	Selective Laser Sintering
18	-	Magnetojet
19	EBAM®	Electron Beam Additive Manufacturing
20	EBM	Electron Beam Melting
21	LCM	Lithography-based ceramic manufacturing

Top 21 AM process short list from 52 classified

Selected technologies and Roadmap



Solar Sintering Printer:



AM technology: Solar Sintering

Reference Project: RegoLight

TRL level: 5



Reason for Technology Selection:

The main advantage of the RegoLight technology is that it utilizes naturally available resources on the moon

1. Sunlight to power and print, and
2. Regolith to print the building blocks.

Thus requiring only the machinery (printers, sand collection, assembly robots) to be launched from Earth.

Possible Applications:

Permanent Infrastructure category

1. Terrain modelling (eg: operation pads, roadways, towers, telescope etc..)
2. Non-pressurized building structures (shelters, launch apron) to protect machinery from dust, micrometeoroids and radiation
3. Building structures Habitat envelopes to protect and shield humans against dust, micrometeoroids and radiation

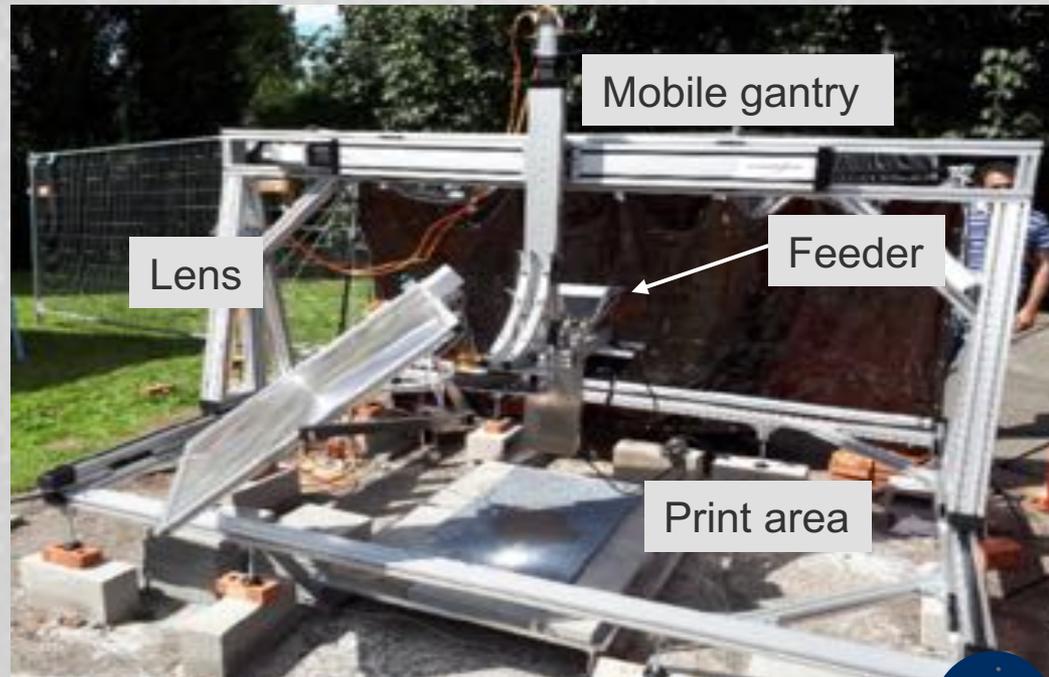


Solar Sintering:

Regolith is deposited to the print tray from the feeder.

A mobile gantry or a robotic arm holding lens, or a solar concentrator accumulates the solar rays into regolith sintering temperature.

After reaching the sintering temperature, the concentrated solar ray/ radiation is guided in 3-axis to sinter the required shape

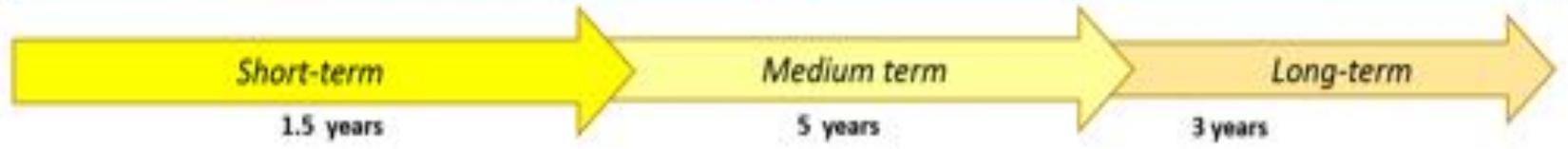
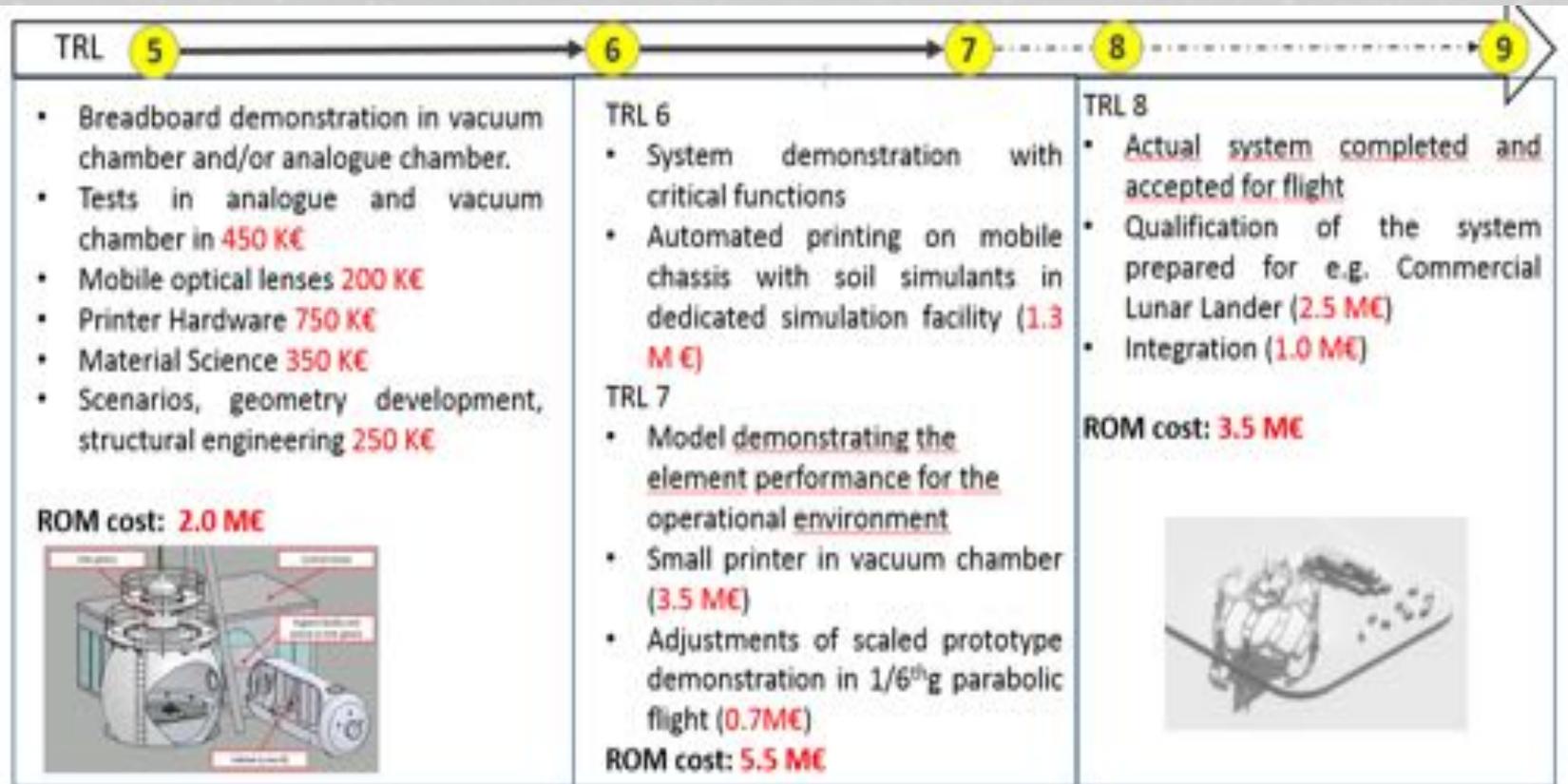


Related works:

- Physical Sciences Inc - NASA
- Markus Kayser, Solar Oven
- RegoLight consortium, EU
- University of Surrey, UK



Solar Sintering Printer:

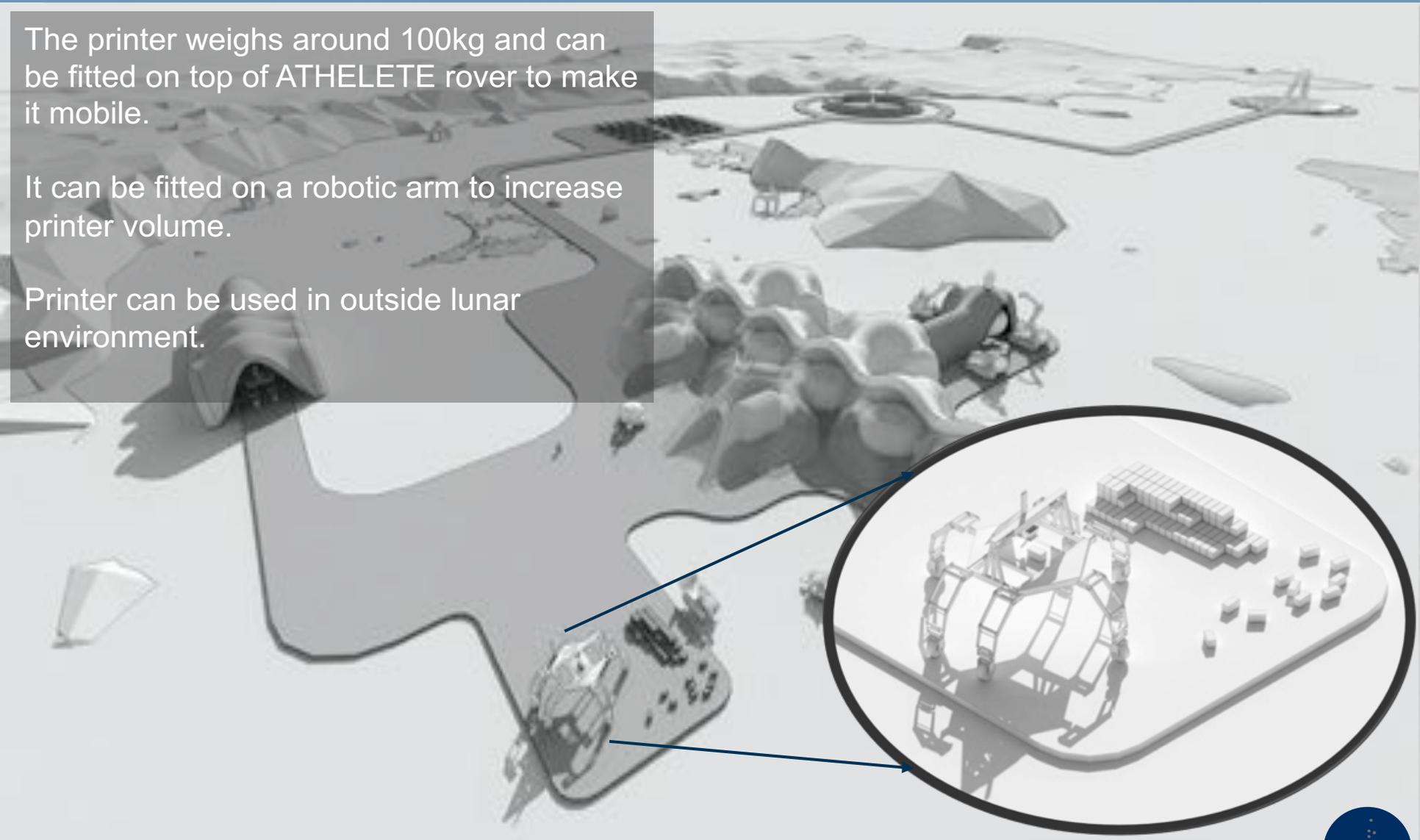


Solar Sintering Printer:

The printer weighs around 100kg and can be fitted on top of ATHELETE rover to make it mobile.

It can be fitted on a robotic arm to increase printer volume.

Printer can be used in outside lunar environment.



Solar Sintering Printer mobile system:

Hardware elements

NASA ATHLETE serves as a mobile device to move the solar sintering printer

ATHLETE specs
Mass: 850kg
Hexagonal platform
Dm= 2.75 m

Payload capacity= 300kg in earth's gravity, which equals approx. 1800kg on the lunar surface

Estimate mass of a sintered interlocking element: 1000 kg (ATHLETE can carry element in a lunar environment)

RegoLight Mobile Printer device to be set on top of the ATHLETE

Size
H=1.5m, L=2.0m, W=1.2m
Mass= 100kg

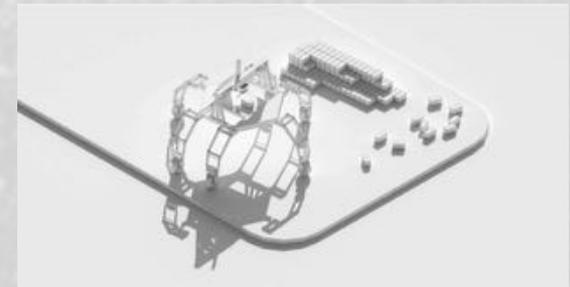
Fresnel lens
dm= 1.0m
mass = 10.0kg

Building volume for a solar sintered element

- H=0.5m, L=1.0m, W=0.5m
- Estimated mass: 1000kg

ATHLETE and mobile printer as mobile solar sintering system

Mass: \approx 1000 KG



EBAM®(Sciaky)/Electron Beam AM



As there are several technologies that produce metal parts, the one with the highest TRL and the least affected by microgravity is selected:

EBAM® is a **metal-processing technology** developed both at NASA and commercially by Sciaky.

- Titanium and Titanium alloys
- Inconel 718, 625
- Tantalum
- Tungsten
- Niobium
- Stainless Steels (300 series)
- 2319, 4043 Aluminum
- 4340 Steel
- Zircalloy
- 70-30 Copper Nickel
- 70-30 Nickel Copper

The technology will be crucial in the lunar base building phase as well as for its maintenance by

- **Producing large parts** (not limited by the print volume) larger than 6 meters in length, with very little material waste
- **High speed manufacturing** (3 to 9 kg/hr)
- **Repairing of existing structures**
- **Operating in pure vacuum environment**, the process doesn't require the use of Argon or any inert gas for part shielding
- **Creating “graded” or “super alloy”** parts using a multi wire nozzle, which will allow having two or more different metal alloys into a single molten pool



EBAM®(Sciaky)/Electron Beam AM



Courtesy of Airbus

Courtesy of Lockheed Martin



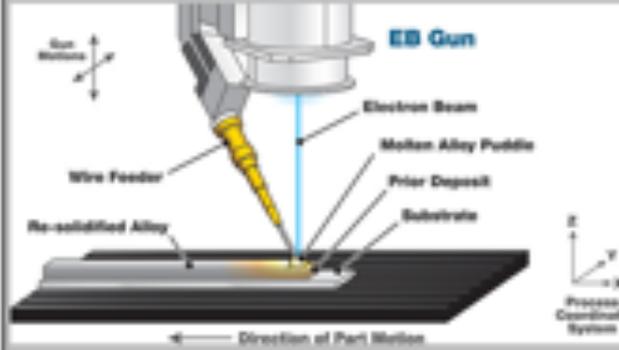
EBAM®(Sciaky)/Electron Beam AM



AM technology: Electron Beam Melting

Reference Project: EBF3, EBAM®

TRL level: 5 (for space)



Reason for Technology Selection:

Metal-processing technology capable of operating under vacuum, developed both at NASA and commercially

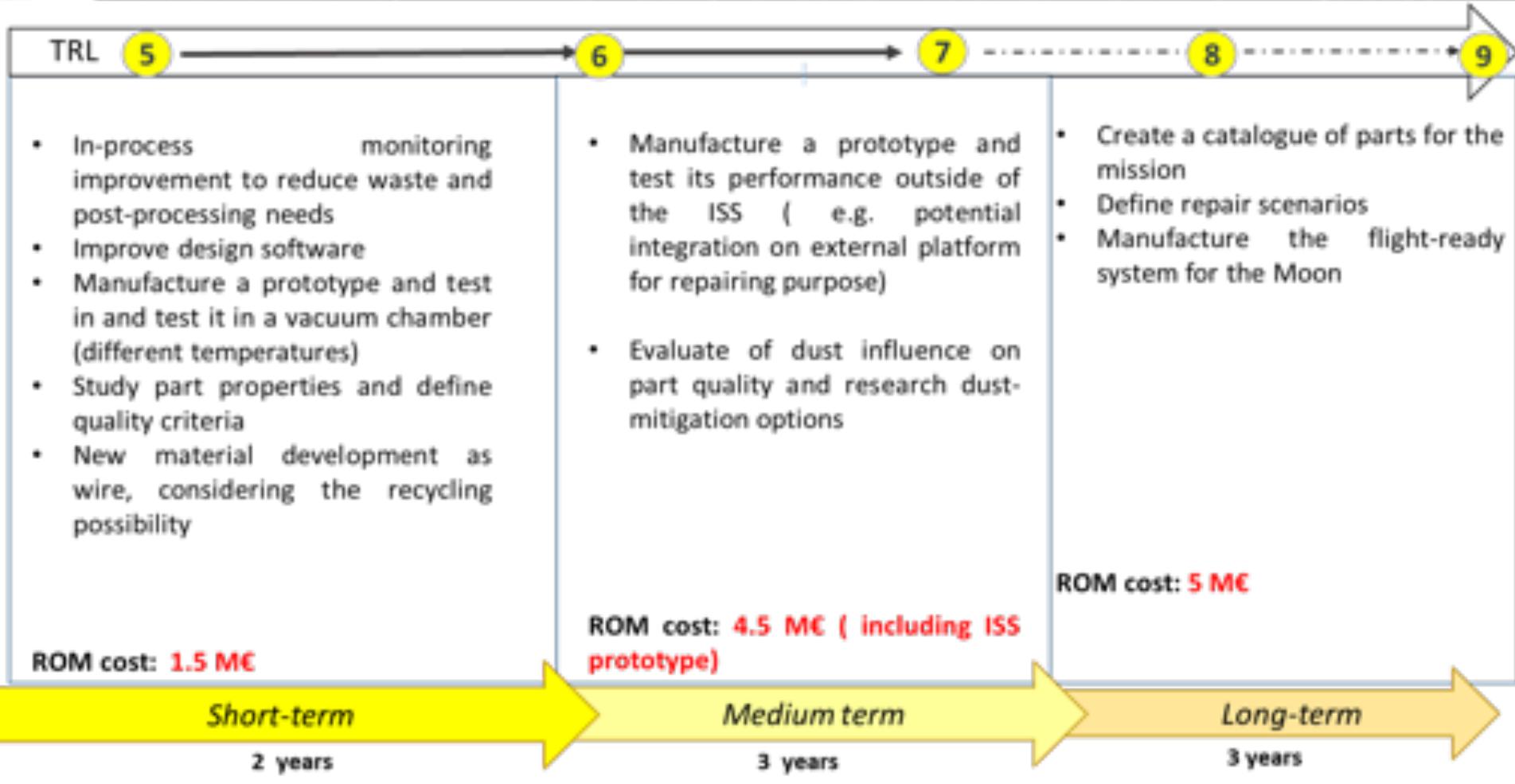
- 1. Fast manufacturing of metal parts
- 2. Large, industrial-scale, part size (potentially unlimited) and design freedom
- 3. Can be used for repair

Possible Applications:

- Permanent Infrastructure (primary structures)
- Permanent machinery (rover parts, main elements of industrial machinery)
- Repair and maintenance system



EBAM®(Sciaky)/Electron Beam AM



EBAM®(Sciaky)/Electron Beam AM



H a r d w a r e e l e m e n t s

NASA ATHLETE serves as a mobile device to move the EBAM printer for repair in -situ



or Fixed platform shielded from Lunar dust



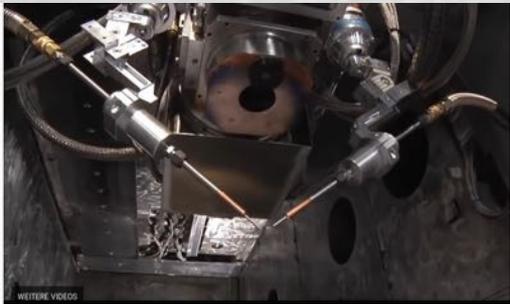
Internal Boom Mounted Gun with High Resolution Optics & Servo Gun Tilt Axis

X, Y & Z Servo Axes with Multiple Part Positioner Options

Wire feed with Motorized Wire Nozzle

CNC Control–Joint Scanning and Digitizing System

Estimated mass range : 2t (for the mobile version) to 4t for the fixed platform



(Credit: Sciaky)



Fused Filament Fabrication

The Fused Filament Fabrication is the most widespread additive manufacturing technology and it's been **validated in low gravity conditions** .

Moreover, it covers a **wide range of materials** and allows printing parts identified for the laboratory usage, tools, structural elements as well as it is also the technology based for food and tissue printing.

Recycling of prints is being actively researched.



Multi-material printing

Recycling and post processing integrated in the process :end-to-end manufacturing during space missions

Reproducibility /Standardization



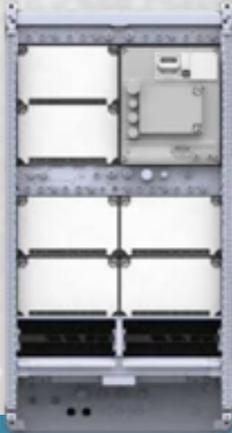
Fused Filament Fabrication for ISM



(Credit: NASA : ISM technology Roadmap)

NASA is focusing on an integrated “Fab Lab” facility with the capability to manufacture **multi-material components** (including metals and electronics), as well as automation of part inspection and removal will be necessary for sustainable Exploration opportunities.

The dimensions are based on an Express Rack Location < 250Kg.



ERASMUS: Food Contact Safe Plastics

Recycler and 3D Printer System

The ERASMUS technology integrates a plastics recycler, dry heat sterilizer, and 3D printer to create a system that accepts previously-used plastic waste and parts, sterilizes these pre-used materials, **recycles them into food-grade and medical-grade 3D printer filament, and 3D prints new utensils and implements.**



Examples of medical devices and utensils that have been 3-D printed on the dedicated ERASMUS printer.



(Credit: NASA)

Fused Filament Fabrication

AM technology: Fused Filament Fabrication

Reference Project: AMF

TRL level: 9* for polymers

SRL :4-5 (ref. FabLab)



Reason for Technology Selection:

Versatile technology covering a wide range of materials that is currently already at TRL 9

1. System has been operational on the ISS under microgravity
2. Can be used to manufacture parts in all 4 categories; post processing needs are low
3. Excellent recycling/down cycling capability

Possible Applications:

Permanent infrastructure category (secondary structures, parts)

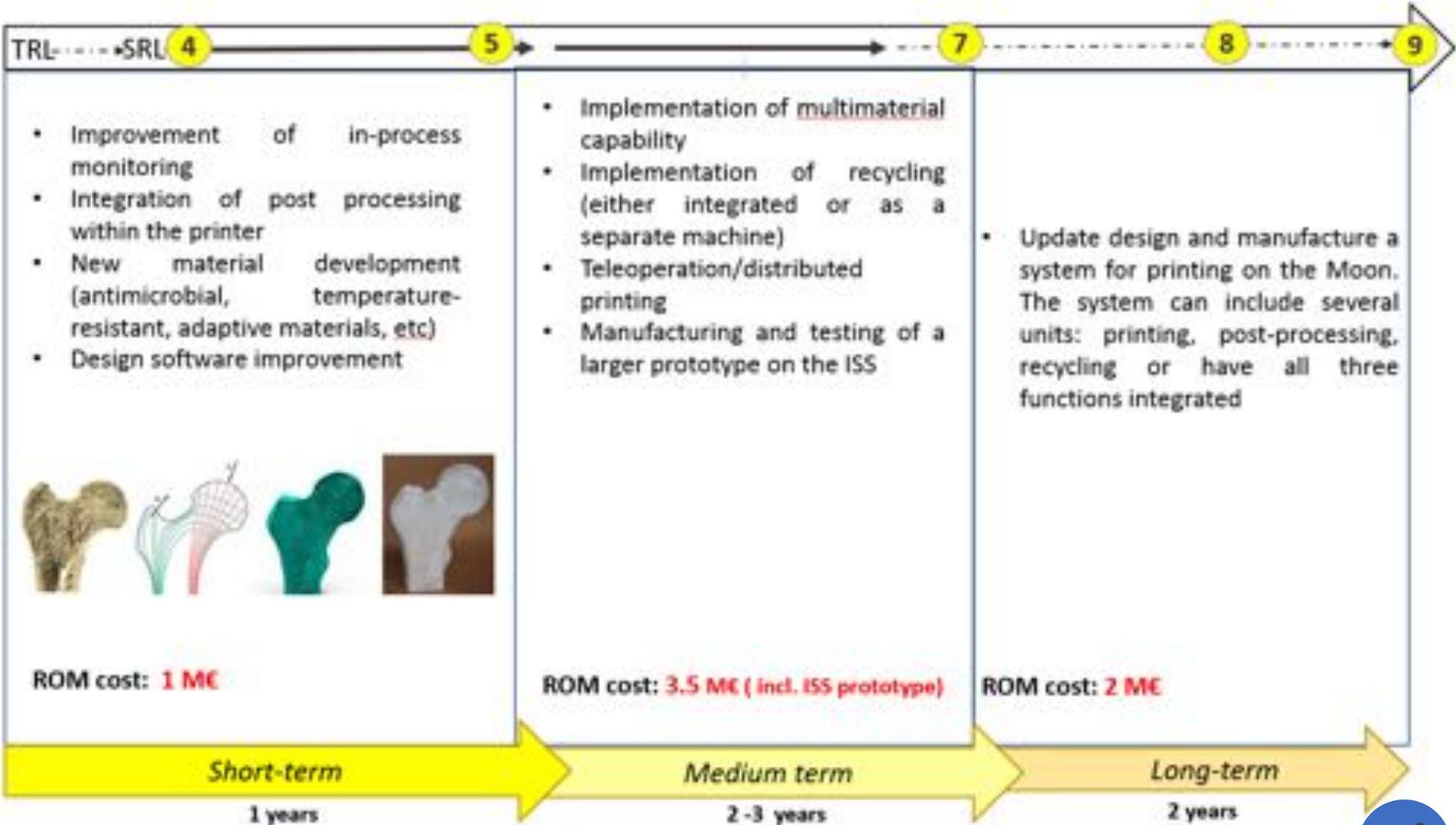
Permanent machinery (spare parts)

Long lasting items and commodities

Temporary and made on demand items



Fused Filament Fabrication

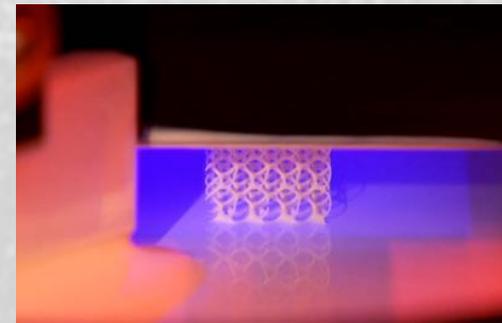
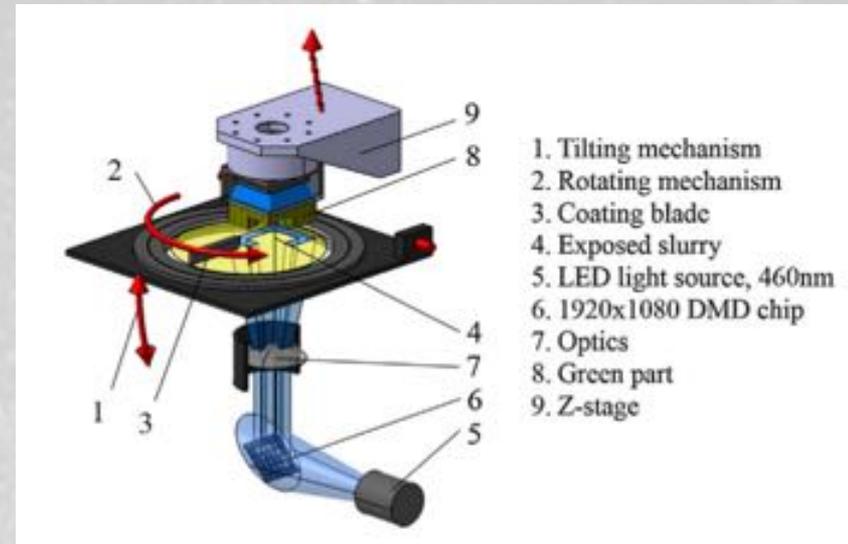


Lithography-based ceramic manufacturing

LCM works by polymerizing a ceramic powder suspended in a photosensitive resin. An LED light source projects onto the resin, and through mask exposure, selectively cures the resin and builds up the part layer-by-layer.

This is the green part :“composite of ceramic particles within a photopolymer matrix” acting to bind together the ceramic particles.

The green part must then go through thermal post-processing: debinding to remove the photopolymer matrix and sintering to achieve final part density.



(Credit: Lithoz)



Lithography-based ceramic manufacturing

Electrically insulating, substrates in the electronics industry, thread guides in textile engineering, protection in thermal processes, etc.

- Alumina
- Zirconia
- Silicon nitride
- Tricalciumphosphate

- dielectrical ceramics
- hydroxyapatite
- bioglass
- cermets
- cordierite
- porcelain
- magnesium oxide

High-end metal forming, valves, bearings and cutting tools, dental applications.

Excellent biocompatibility, bioresorbability, osteoconductivity and is therefore a well-established material for bone replacement in regenerative medicine.



Lithography-based ceramic manufacturing

In the frame of the study , Lithoz has performed a feasibility assessment with regolith simulant, demonstrating a process compatibility and capability to achieve high precision in the dimensions and shape of the printed items .



Actual production rate : 1 Kg ceramic powder + 20% binder → 1 Kg printed parts

- Future plan to mix the binder to a reusable resin



Lithography-based ceramic manufacturing



3D-PRINTING FOR HIGH-PERFORMANCE CERAMICS

For the first time high-performance ceramics can be produced cost efficiently in a tool-free process from lot size 1.

SIMPLE DATA PREPARATION AND USER-FRIENDLY MACHINE CONTROL
Data preparation is managed directly and comfortably from the workplace to determine all the relevant process parameters. The intuitive user interface of the machine facilitates an easy operation and handling.

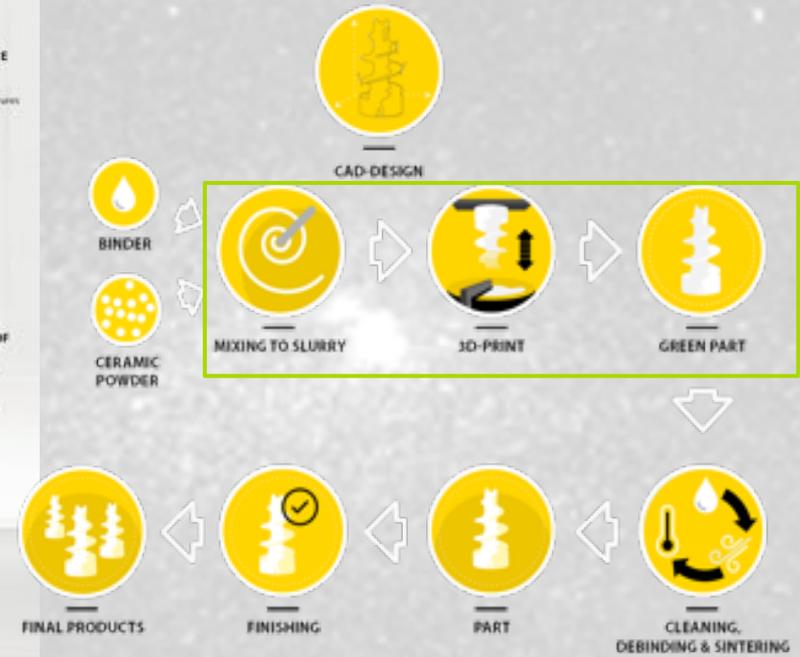
COMPLEX GEOMETRIES WITH HIGH-PERFORMANCE CERAMICS
Highly complex geometries with undercuts, cavities or cellular structures can be implemented without any demoulding issues.

PARALLEL PRODUCTION OF DIFFERENT DESIGNS
High performance ceramic components with variations in design can be produced simultaneously directly from the CAD files without any need for specific tools.

MATERIAL SAVING PRODUCTION METHOD
Bottom-up exposure keeps material consumption very low and the remaining material is left for further use. Due to the quick-locking system a change of material can be completed within 5 minutes.

MACHINE FOOTPRINT
Height: 178 cm
Width: 80 cm
Depth: 128 cm
Weight: ca. 250 kg

LED-BASED LIGHT ENGINE TO GENERATE LAYER INFORMATION
The printer does not require special safety precautions and keeps energy costs at a very low level.



Market available system
CeraFab 8500 (Credit: Lithoz)

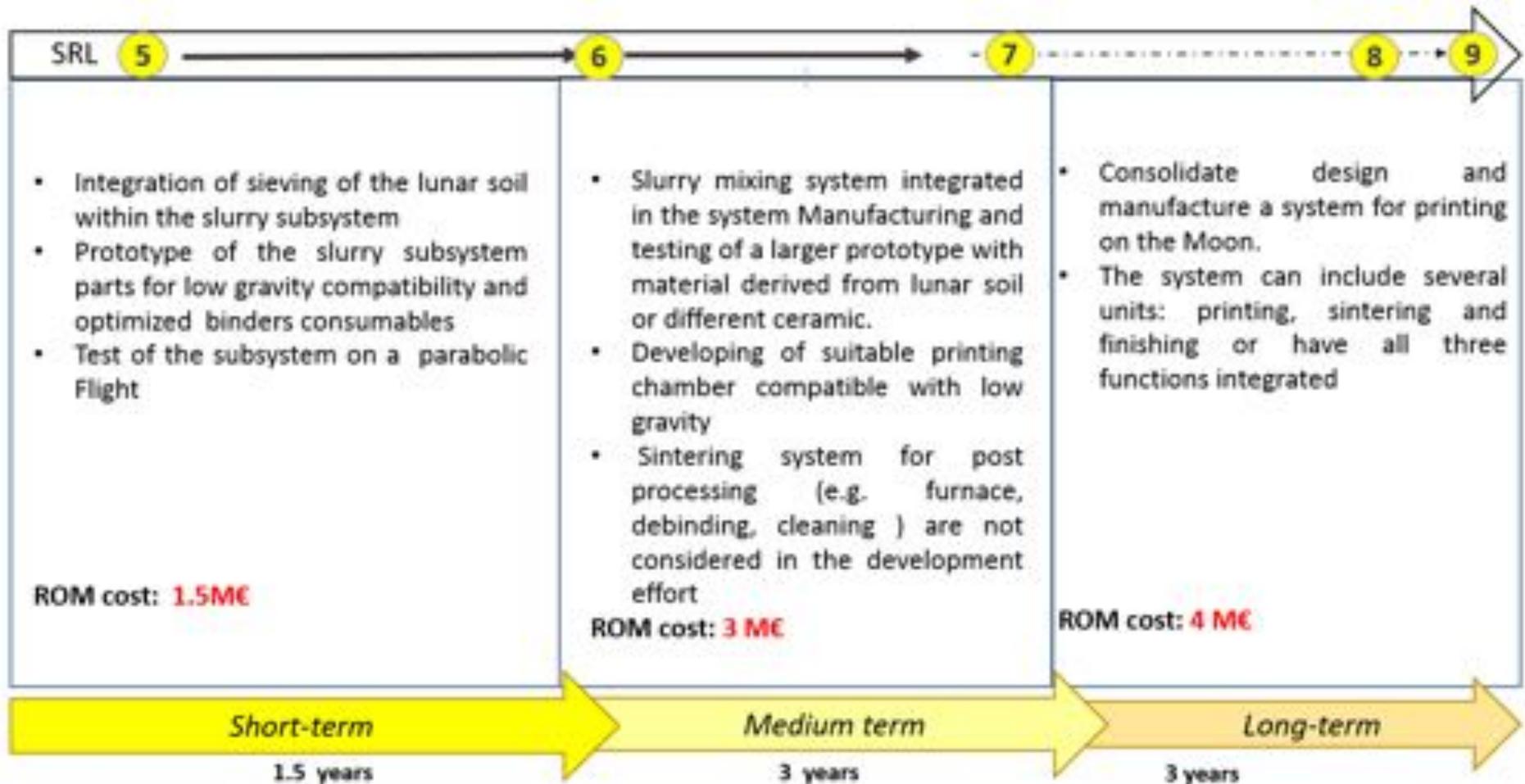


Lithography-based ceramic adaptation

Process			Function	Estimated Mass
Grinding and sieving in one unit	<i>Credit: FRITSCH (Vibratory Micro)</i>		Versatile equipment.	50Kg
Mixing system needed to be integrated to create the slurry			Needed to be integrated in the process for automatic function	50 Kg
Cleaning			Presently solvent bath but in future gas flushing	-
Debinding and sintering			Versatile equipment (Oven /furnace)	80Kg
Core part			Dedicated design to keep the slurry in place (e.g compressed air or confined volume)	100Kg



Lithography-based ceramic Roadmap



Summary of AM technologies TRL

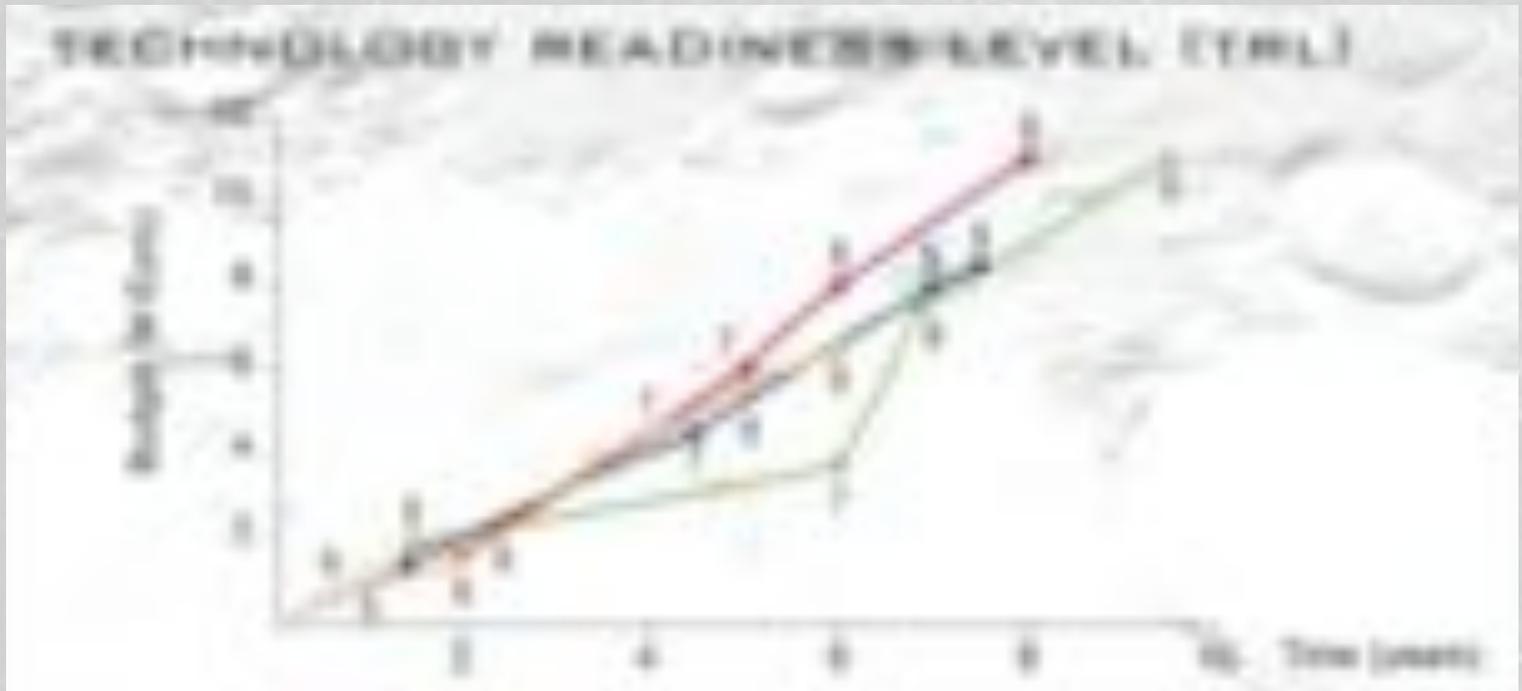


Electron Beam Additive Manufacturing (EBAM)

Solar Concentrator / Solar Sintering

Fused Filament Fabrication (FFF)

Lithography-based Ceramic Manufacturing (LCM)

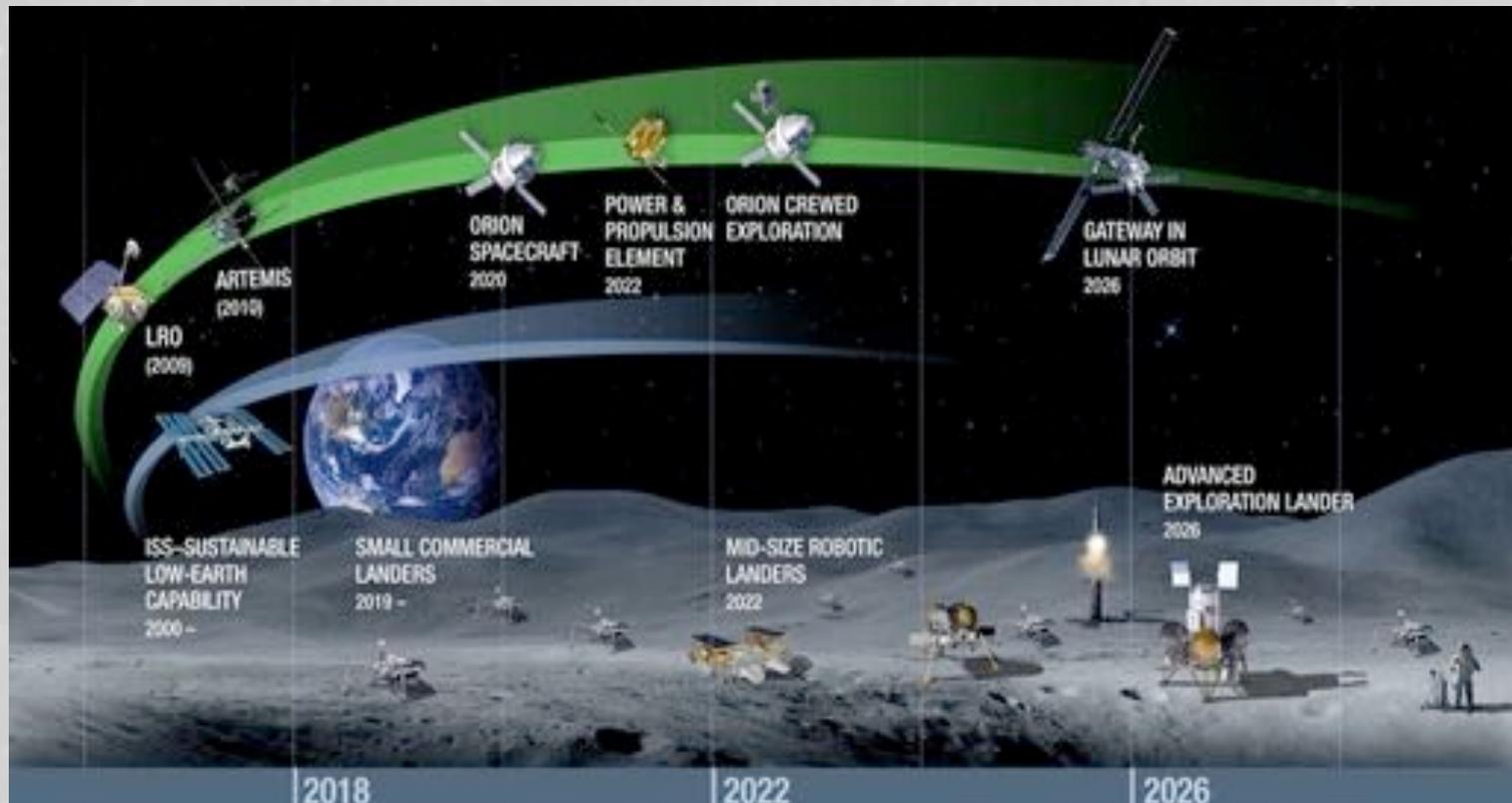




Moon mission scenario and Bring or Print considerations

VI. Moon Mission scenario

Human exploration of both the Moon's surface and its environment requires the capability to transport crews and large masses of cargo beyond LEO. The next wave of lunar exploration will be fundamentally a strong cooperation in bringing human to orbit the Moon, starting in 2023, and land astronauts on the surface no later than the late 2020s*.

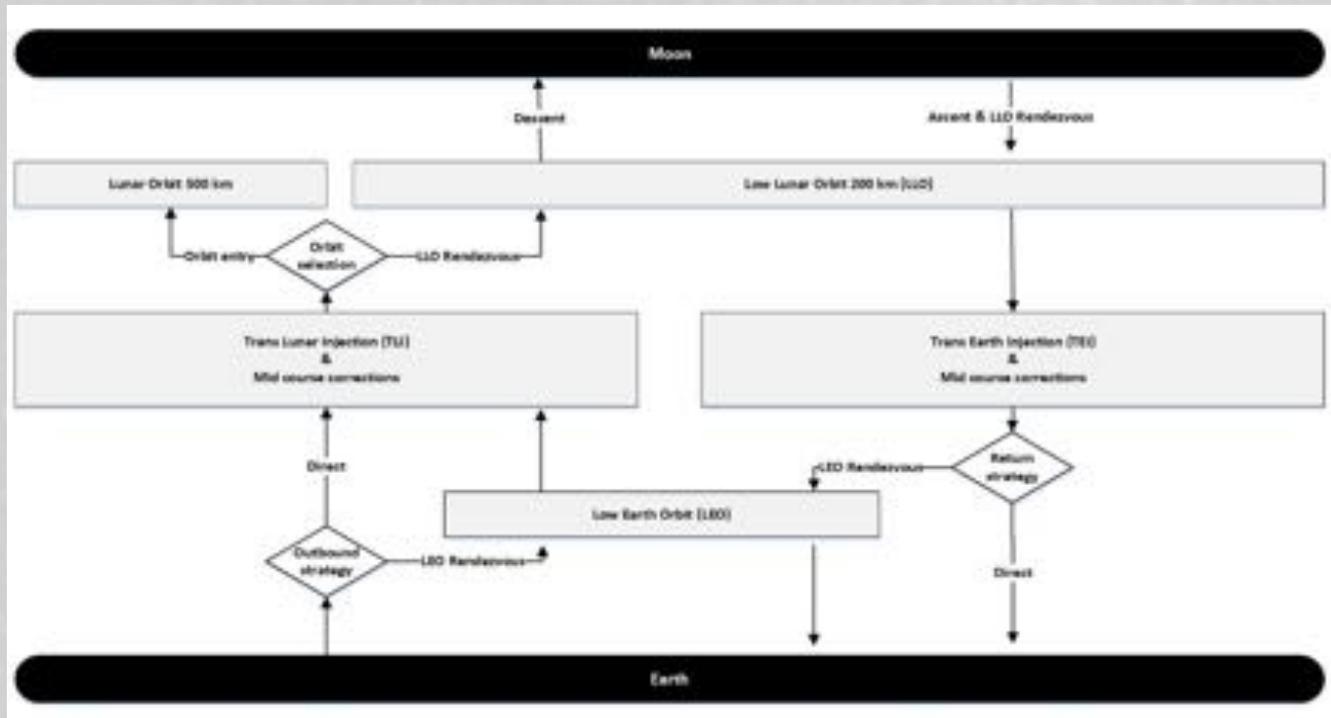


*NASA National Space Exploration Campaign Report –September 2018

VI. Moon Mission scenario



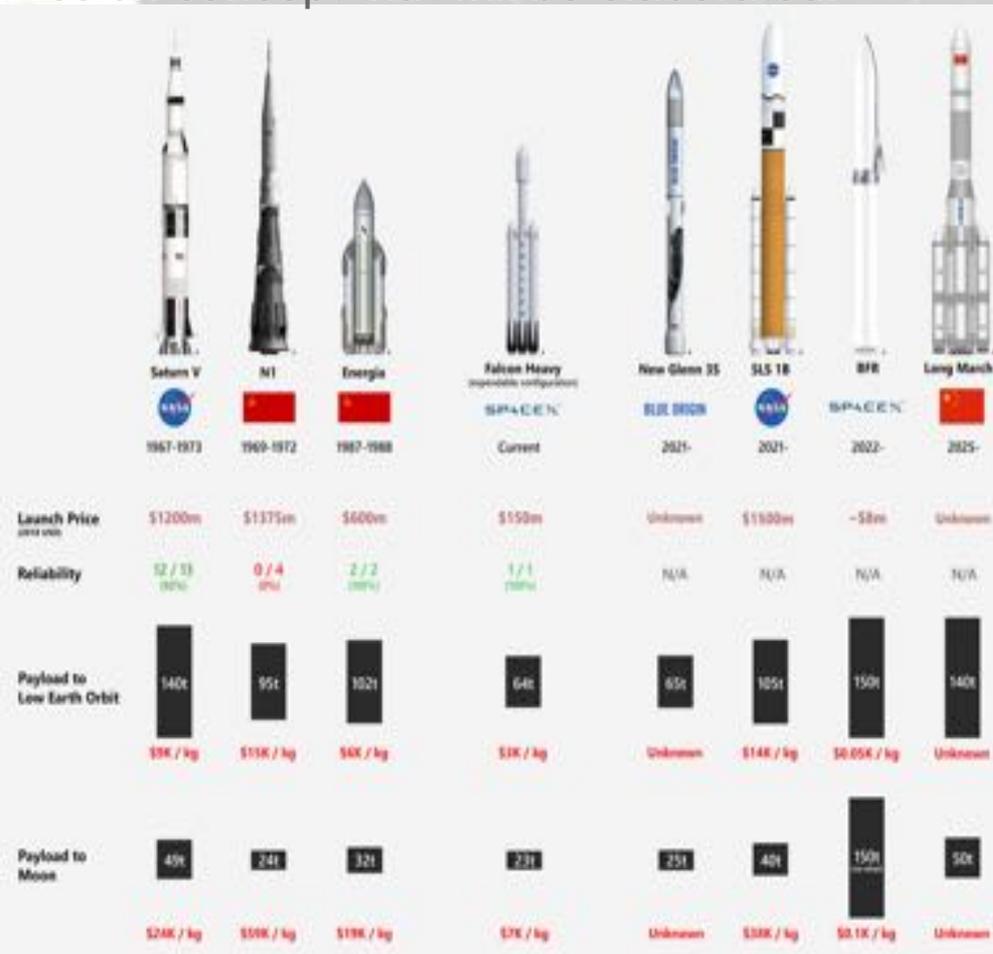
The development of commercial launch vehicles by SpaceX has greatly reduced the cost of launching mass to Low Earth Orbit (LEO). Reusable launch vehicles may further reduce the launch cost per kilogram. Therefore it may be a potential next step by NASA to replace the SLS plan with a commercial low-cost solution also for destination beyond LEO.



VI. Moon Mission scenario



Therefore the budget and mass upload capabilities will strongly depend on the launch and mission concept that will be elaborated.



CAPABILITIES & SERVICES

SpaceX offers competitive pricing for its Falcon 9 and Falcon Heavy launch services. Modest discounts are available for contractually committed, multi-launch purchases. SpaceX can also offer crew transportation services to commercial customers seeking to transport astronauts to alternate LEO destinations.

PRICE	FALCON 9	FALCON HEAVY
STANDARD PAYMENT PLAN (DIR LAUNCH)	\$62M Up to 5.5 mT to GTO	\$90M Up to 3.0 mT to GTO
DESTINATION	PERFORMANCE*	PERFORMANCE*
LOW EARTH ORBIT (LEO)	22,800 kg 50,265 lbs	63,800 kg 140,440 lbs
GEOSYNCHRONOUS TRANSFER ORBIT (GTO)	8,300 kg 18,280 lbs	26,700 kg 58,860 lbs
PAYLOAD TO MARS	4,020 kg 8,860 lbs	16,800 kg 37,060 lbs

*Performance represents max capability on fully expendable vehicle.
Inclination, LEO = 28.5°, GTO = 27°

<https://www.spacex.com/falcon-heavy>

Assuming the usage of the European Ariane 6 :
which can take an 11Ton payload to GTO, the biggest payload which can be landed per Ariane 6 launch is 1.1Tons, using a 2.2Ton supporting lander. Each launch of Ariane 6 costs 90 M€ → 8K€/Kg

Ref. <https://goo.gl/images/fDxdN5>

VI. Moon Mission scenario



Recently 9 U.S. companies now are eligible to bid on NASA delivery services to the lunar surface through Commercial Lunar Payload Services (CLPS) contracts, as one of the first steps toward long-term scientific study and human exploration of the Moon. Lunar payloads could fly on these contracted missions as early as 2019.



MISSION	1	2	3	4	5
NUMBER OF LANDERS					
NOMINAL SURFACE CAPACITY	35 kg	175 kg	265 kg	530 kg	530 kg

LUNAR ORBIT
\$ 300,000 / kg

LUNAR SURFACE
\$ 1,200,000 / kg

DELIVERY ON ROVER
\$ 2,000,000 / kg



VI. Bring or print considerations

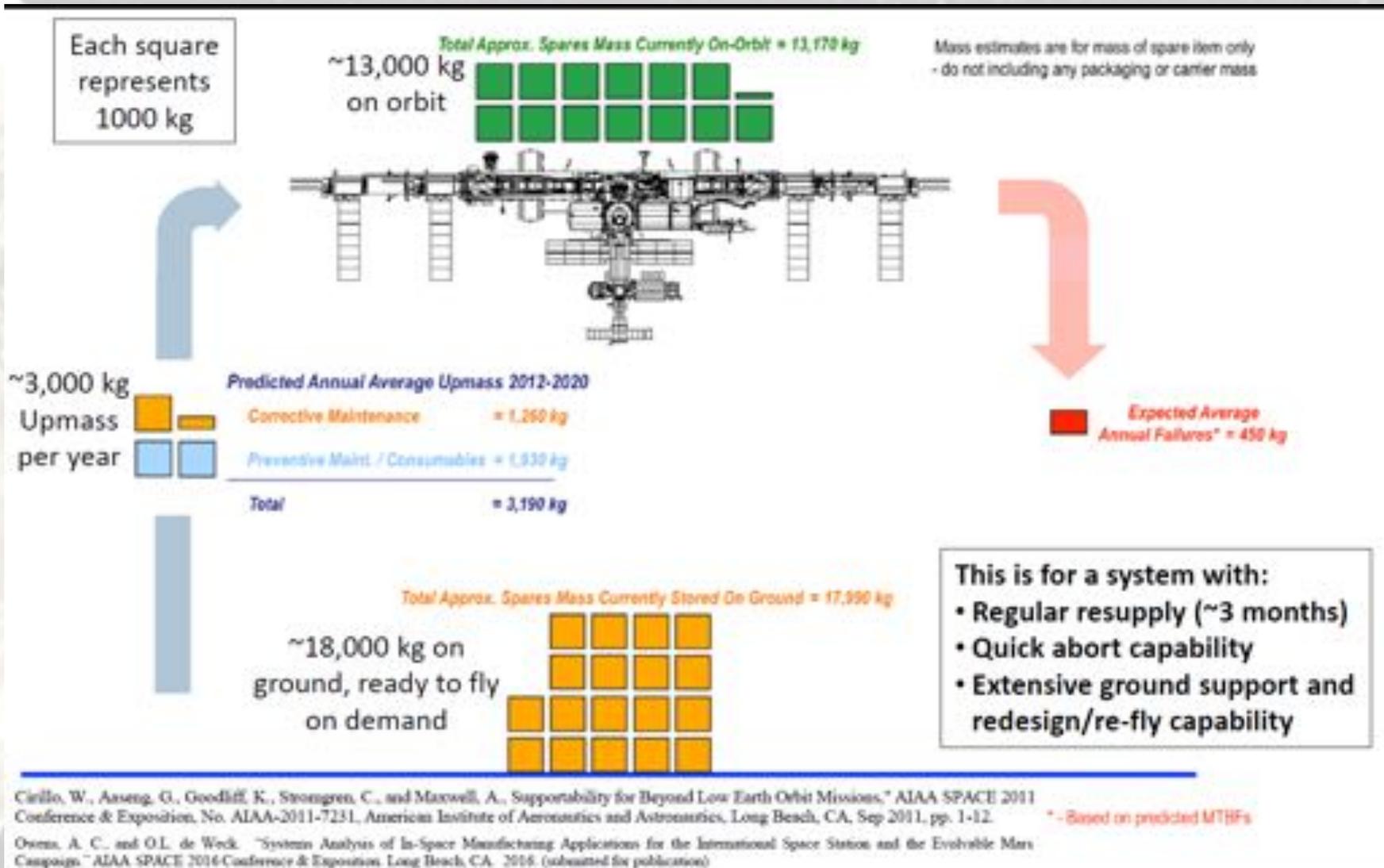


The construction and operation of the ISS provides the only comparable example available to us at present. Although the manned Apollo missions provided a lot of baseline data for future lunar exploration, these were brief missions lasting only a few days.

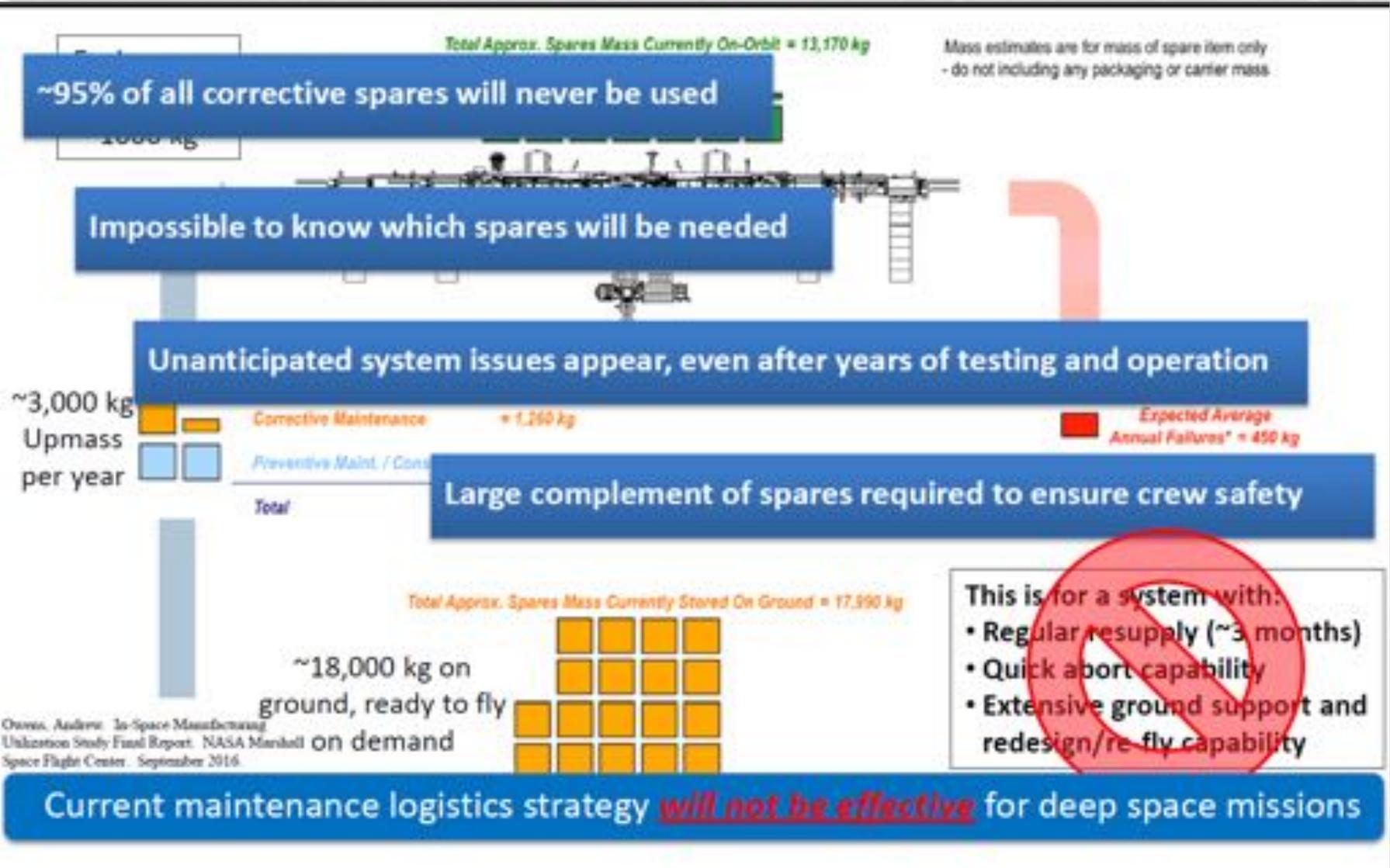
The ISS by comparison is a permanent base in near-Earth orbit supporting the needs of up to 6 crew and a host of scientific experiments.

Clearly a permanent Moon base will have far more resource needs leading to an enormous dependency on the supply of construction materials and resupply from Earth. The lesson to be drawn from ISS is that a permanent Moon base will have to radically find new ways to reduce this dependency from Earth.

VI. Bring or print considerations



VI. Bring or print considerations



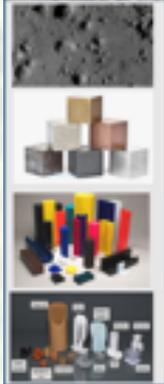
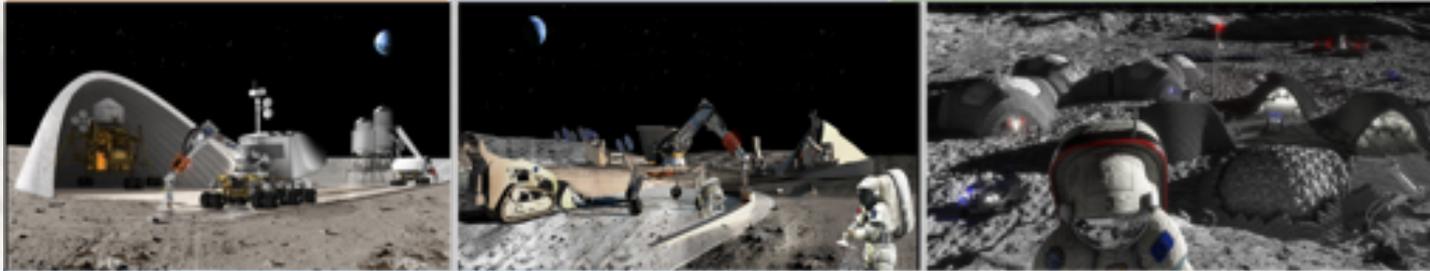
VI. Bring or print considerations



Survivability

Sustainability

Operational

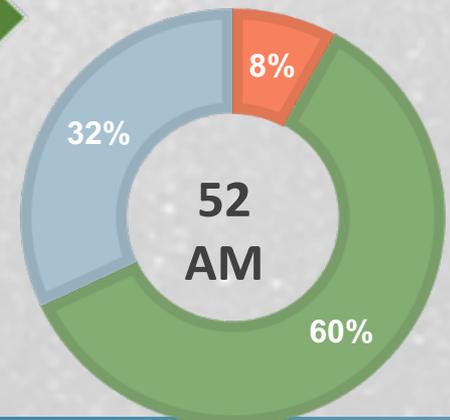


Fiber Optic Solar concentrator

Electron Beam Additive Manufacturing

Fused Filament Fabrication

Lithography-based ceramic manufacturing



VI. Bring or print considerations



To minimize the mission risk and use the transportation to establish a first settlement the big infrastructures will be procured from Earth. The presence of the solar concentration AM technology is crucial in the building up phase, while EBAM® and FFF can represent the provision of spare, broken parts and on demand needs.

Element	Survivability	Sustainability	AM Technology
Inflatable structure to support the initial building phase	BRING	REPAIR	
External shielding (2-3m of regolith or concrete shielding is required over the habitat for protection against radiation)	PRINT	In situ	Fiberoptic concentrator Solar
Suit port and EVA suit	BRING	PRINT Mechanical parts, Hard-shell and fabric layers can be 3D printed for maintenance.	Fused Filament Fabrication and Electron Beam AM
Laboratory and Greenhouse	BRING	PRINT: extension parts, spare, repair	Fused Filament, EBAM®
Windows, sealing and Airlock	BRING	PRINT: extension parts, spare, repair	FFF, EBAM®
Operational Pads and Roadway	PRINT	In situ	Fiberoptic concentrator Solar
Hangar and Storage facility	PRINT	In situ	Fiberoptic concentrator Solar
Power plant	BRING	PRINT: extension parts, spare, repair	Solar cells and panels has TLR low
Thermal Control and Electrical Power Supply Facility	BRING	PRINT: Mechanical components, electronics, Sealing, pipes, gauges shield repairs	LCM, FFF, EBAM® For electronics part Technologies at low TRL
Transportation system	BRING	PRINT: extension parts, spare, repair	LCM, FFF, EBAM®
Rover (prospector)	BRING	PRINT: Mechanical components,	LCM, FFF, EBAM®
Rover (excavator)	BRING	PRINT: extension parts, spare, repair	LCM, FFF, EBAM®
CNC machine	BRING	PRINT: extension parts, spare, repair	LCM, FFF, EBAM®

VII. Conclusions



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 **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**.

Revisiting the traditional design approach and adjusting the specific AM capabilities for use in environments different from Earth will be the next challenge.

VII. Conclusions



Current maintenance logistics strategy will not be effective for deep space exploration missions.

One of the major benefits of an In situ manufacturing capability is the fact that it allows on-demand manufacturing of spares.

Whereas a spare part can only cover a **single type of failure** a manufacturing capability would be able to cover **several different types of failures**.

The In situ manufacturing enables **commonality of material rather than commonality of design** .

The raw materials can be converted into **specific components** in response to **specific failures**, as result, the risk reduction per unit mass of raw materials is higher than for discrete spares, since those raw materials provide a broad risk coverage.

Design for repair culture must be embraced

VII. Next steps

The journey to establish human presence outside the Earth in a permanent way has just started. In order to make it possible, one of the best ways is to proceed on an incremental path with relevant intermediate targets.

Develop and validate the highest priority AM technologies

ISS may be critical test bed for demonstrating some of the AM technologies or crucial part of them

Versatile AM technologies

Evaluating technologies to enable multi-material, digital manufacturing of components

Recycling ability

Recycling is not yet fully developed for most materials

Decision making Tool

Development of an open-dynamic tool to support decision process in-situ



Thank you

(Photo: Sergey Nivens / Shutterstock)