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HARMONISE

HArdware **R**ecycling for **MO**o**N** and Mart**I**an **SE**ttlement

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1 INTRODUCTION

The HARMONISE ((Hardware Recycling for Moon and Martian Settlement) project was developed by OHB in collaboration with Azimut Space and Liquifer Systems Group in the frame of an ESA-funded study. The project aimed at conceiving, developing, manufacturing and testing three demonstrator concepts as a starting point towards creating a sustainable closed-loop system for future lunar or martian settlements, using no-longer needed spacecraft parts applying different recycling and re-use strategies. The HARMONISE study will significantly contribute to ushering a new, more sustainable Space exploration era, supporting an emerging circular economy through in-orbit servicing and off-Earth manufacturing by 2050.

1.1 Purpose of this Document

This executive summary report provides an overall description of the HARMONISE study objectives, activities and achievements referred to the re-use of no-longer useful hardware. Hereby, only a general outline of the project's activities is given. For a more detailed overview, the Final Report of the project can be referred to, which contains all the necessary and relevant information [RD16].

1.2 Scope

Human Moon and Mars exploration, and the consequent desire to establish a permanent settlement on their surface, represents a fascinating prospect that raises the problem of the huge amount of payload required for the establishment of a continuously manned base. The need for a constant input of consumables such as food, water or oxygen for the crew, but also the provision of module elements, power generation, module interior fittings, laboratory resources and medical facilities require a major logistic implementation in terms of transportation from Earth which imposes a complete rethink of previous missions concepts and design.

As a solution, the recycling of waste material (plastic and metallic) generated in crewed mission could be processed as feedstock material or reintegrated in combination with other available items to accomplish a different task and overcome the constant Earth-dependency. Several aspects of Moon and Mars settlements can benefit from this if, for instance, maintenance tools, utensils, medical patient-specific back-up implants, habitat elements and research instrumentation can be envisaged as outcomes of such a recycling process.

The HARMONISE project can, therefore, offer a solution to a rapid and in-time supply of material and spare parts useful for activities carried *in-situ* for future Moon and Mars settlements. In the frame of HARMONISE, the recycling concept was implemented in three different ways. The first one is the recycling of basic materials, where individual materials can be extracted from the original hardware or where components can be transformed into small particles. The materials can then be used as feedstock for diverse processes, such as additive layering manufacturing, or by making advantage of melt and casting techniques. The second option is the partial re-utilisation of the original hardware, where EOL items are re-combined with other dismissed parts to create new design solution which could benefit from a different shape for reuse. Lastly, the third option brings in the complete re-utilisation of hardware parts in their specific form and function for a new application.

To prove the feasibility of these three options, three demonstrators were developed from TRL 1 to TRL 3 and tested. The first recycling process demonstrator proposed the recycling of commercial low-density polyethylene Ziplock® bags of various sizes into filament useful as feedstock for 3D-printing applications. Another demonstrator addressing the first recycling concept was the one based on the recycling of scrap aluminium alloy 7075 to cast a multi-tool, that included two wrenches suitable for M5 and M6 hex head bolts, Allen keys compatible with M5 and M6 socket head bolts, and an opening in the centre that can be used as an attachment point. Finally, the demonstrator of the second and third recycling concepts was developed out of close-out-panels fitted with the help of 3D-printed connectors and Cargo Transfer Bags dividers in the form of a chair suitable to be used by astronaut for future off-Earth manned settlement scenarios.

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 No. / Title	Doc. No.	Issue
[AD01] ESA AO-10595 Statement of Work	ESA-TDE-TECMSP-SOW-2021-025936	01
[AD02] Recycling of hardware for Moon and Martian settlement DETAILED PROPOSAL	OHB-404192	01

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 No. / Title	Doc. No.	Issue
[RD01] Technical Note #1 – Part 1: Survey of Missions to the Moon and Mars	HRM-OHB-TN-0001_TN_Part 1	06
[RD02] Technical Note #1 – Part 2: ESA Hardware on Moon & Mars – Mapping Of Materials To Parts And Demonstrators Proposals	HRM-OHB-TN-0001	02
[RD03] Technical Note #1 – Part 3: Definition of KPIs and Demonstrators‘ Trade-off	HRM-OHB-TN-0001_TN1_Part 3	02
[RD04] Technical Note #2 – Part A: Functional requirements and preliminary design of the “payload rack blind panels reused as furniture” demonstrator	HRM-OHB-TN-002_TN2_Part A	01
[RD05] Technical Note #2 – Part B: Functional requirements and preliminary design of the “Food package recycling into filament” demonstrator	HRM-OHB-TN-0002_TN2_Part B	01
[RD06] Technical Note #2 – Part C: Functional requirements and preliminary design of the “metal tool casting” demonstrator	HRM-OHB-TN-0002_TN2_Part C	01

RD No. / Title	Doc. No.	Issue
[RD07] Technical Note #3 – Part A: Design maturation of demonstrator “payload rack blind panels reused as furniture” and elaboration of development, test and verification plans	HRM-OHB-TN-0003_TN3_Part A	01
[RD08] Technical Note #3 – Part B: Design maturation of the demonstrator “food package recycling into filament” and elaboration of development, test and verification plans	HRM-OHB-TN-0003_TN3_Part B	02
[RD09] Technical Note #3 – Part C: Design maturation of the demonstrator “metal tool casting” and elaboration of development, test and verification plans	HRM-OHB-TN-0003_TN3_Part C	01
[RD10] Technical Note #4 – Part A: Manufacturing, testing and verification of the demonstrator “payload rack blind panels reused as furniture”	HRM-OHB-TN-0004_TN_Part A	02
[RD11] Technical Note #4 – Part B: Manufacturing, testing and verification of the demonstrator “food package recycling into filament”	HRM-OHB-TN-0004_TN_Part B	02
[RD12] Technical Note #4 – Part C: Manufacturing, testing and verification of the demonstrator “metal tool casting”	HRM-OHB-TN-0004_TN_Part C	01
[RD13] Technical Note #5 – Part A: System-level analysis and critical assessment of the demonstrator “payload rack blind panels reused as furniture”	HRM-OHB-TN-0005_TN_Part A	01
[RD14] Technical Note #5 – Part B: System-level analysis for maximizing material usage efficiency and hardware recyclability and critical assessment of the demonstrator “food package recycling into filament”	HRM-OHB-TN-0005_TN_Part B	01
[RD15] Technical Note #5 – Part C: System-level analysis and critical assessment of the demonstrator “metal tool casting”	HRM-OHB-TN-0005_TN_Part C	01
[RD16] HARMONISE Final Report	HRM-OHB-RP-001	01
[RD17] PODIUM Final Report	PODIUM-ASG-RP-051-1-0	01
[RD18] MELT Executive Summary Report	MELT-SSG-RP-084-1-0	01
[RD19] IMPERIAL (ISS ALM Printer Suitable for Large Part Production Using High Performance Polymers). ESA GSTP 30TH ANNIVERSARY EVENT	N/A	N/A
[RD20] On the Glass Transition Temperature of Polyethylene as Revealed by Microhardness Measurements - S. Fakirov & B. Krasteva	N/A	N/A

RD No. / Title	Doc. No.	Issue
[RD21] PE-LD: Polyethylene low density - NETZSCH Measurements	N/A	N/A
[RD22] Polymers’ Glass Transition Temperature (Tg) in the Context of Plastic Injection Molding - Boyicnc	N/A	N/A
[RD23] Thermo-mechanical degradation of polypropylene (PP) and low-density polyethylene (LDPE) blends exposed to simulated recycling – S. Saikrishnan et. all	N/A	N/A
[RD24] Oxidation Induction Time Measurement by DSC – Hitachi High-Tech Science Corporation	N/A	N/A

2.3 Abbreviations & Nomenclature

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

Table 2-3: Abbreviations & Nomenclature

Abbreviation	Meaning
3D	Three Dimensional
AD	Applicable Document
ASTM	American Society for Testing Materials
CI	Configuration Item
CTB	Cargo Transfer Bag
DMA	Dynamic Mechanical Analysis
DSC	Differential Scanning Calorimetry
EoL	End of Life
ESA	European Space Agency
FFF	Fused Filament Fabrication
GD	Generative Design
ISS	International Space Station
LDPE	Low-Density Polyethylene
MFI	Melt Flow Index
NASA	National Aeronautics and Space Administration
OHB	Orbitale Hochtechnologie Bremen
PCB	Printed Circuit Board
RD	Reference Document
Re-PE	Recycled Polyethylene
TGA	Thermogravimetric Analysis
TN	Technical Note

3 HARDWARE RECYCLING AND RE-USE PROCESS

During the golden age of Space and the years that followed, numerous spacecraft have been left behind on the Moon and Mars. The Apollo, Luna and the recent Chinese, Indian and Israeli missions have sent and left their rovers and landers on the surface of the Moon, where they still lie. On Mars, there are rovers and landers left behind by NASA, as well as the Beagle 2 and ExoMars spacecraft owned by ESA, and the Soviet Mars 3 lander. All these objects represent a fascinating prospect for repurposing and giving new life to abandoned Space objects.

In recent times, the prospect of colonising the Moon and Mars has been increasingly more attractive, and the next logical step after landing manned mission on Mars is the creation of permanent settlements. For this, the main issue that arises is the Earth-dependency that early lunar or Martian colonizers would have to face.

A possible solution to this is EoL hardware recycling and re-use. The materials in these spacecraft, including aluminium, titanium, stainless stell and various electronics could be repurposed for the construction, maintenance and sustaining of the lunar/Martian base. However, challenges include the difficulty of accessing these materials, their scattered locations and the need for advanced robotics or human presence to carry out possibly complex retrieving and recycling operations.

On the other hand, waste material such as food packaging, personal hygiene by-products, used towels and clothes could also be envisaged for recycling and re-use as, for example, radiation protection or feedstock for an extrusion process.

3.1 Recycling possibilities

The key to any sustainable presence in Space is the ability to manufacture necessary structures, spares, *in-situ* and on demand by recycling and re-using the available resources, consequently reducing the cost, volume, and up-mass constraints, that could prohibit launching everything needed for long-duration and/or long distance missions from Earth. In this frame, there are three ways in which the recycling concept can be implemented:

1. **Recycling of basic materials:** where individual materials can be extracted from the original hardware or where components can be transformed into small particles. The materials can then be processed into new hardware by techniques such as additive manufacturing.
2. **Partial re-utilization of parts:** parts of the original hardware can be re-combined with other parts e.g. to convert them into a different shape for reuse (e.g. reuse of modular elements).
3. **Complete re-utilization of hardware parts** (e.g. module structure) in their specific form and function, for a new application.

It is understood that lunar and Martian environment (constraints and advantages) will also be taken into account to assess the main challenging adaptation and implementation of the identified process and the technologies required to make the entire recycling/re-using procedure feasible in such a harsh condition. Figure 3-1 shows a complete life cycle of items at a destination, with three different exit points when they reach the end-of-life:

1. **Repair:** the hardware part presents minor defects that can be repaired and that can thus facilitate its re-use for the same purpose.
2. **Complete re-utilization for a new application:** the part can no longer be used for the same purpose, but it is still considered a good, qualitative tool for a new scope.
3. **Waste sorting and separation:** the hardware component is not suitable for a new application in its current form, and is taken to waste sorting where it can be either partially reused and recombined with a different part, recycled as a basic material or deemed not recyclable.

It is worthy underling that these concepts should be analysed and then design guidelines should be drawn for future missions, so that the recycling and re-use approach could be implemented already in the design phase.

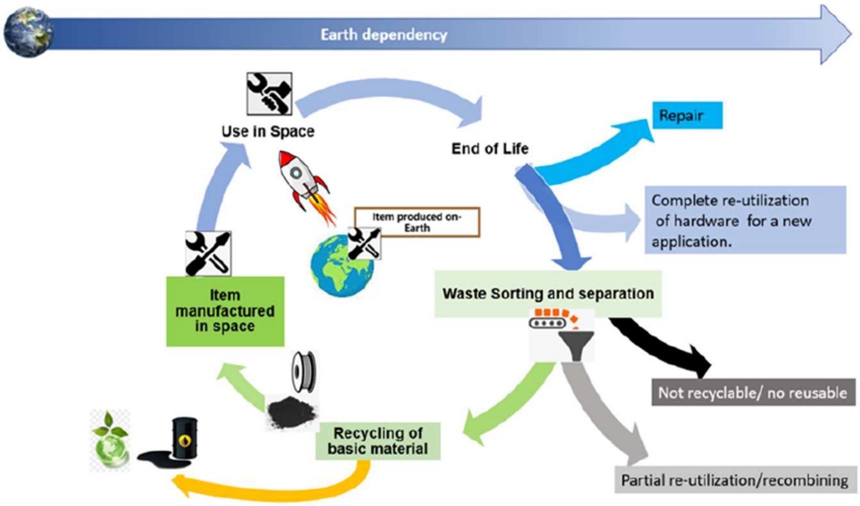


Figure 3-1: Hardware life cycle and potential waste streams scenario.

3.2 Chosen demonstrators

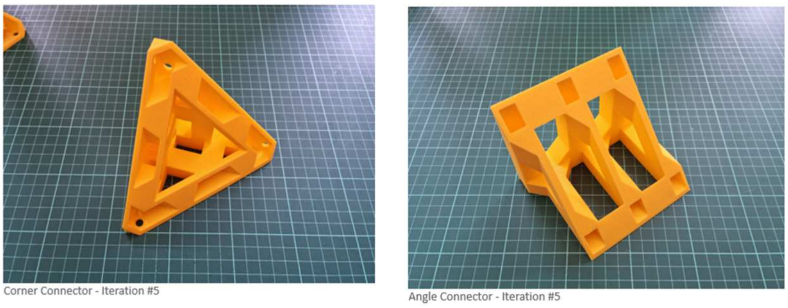
3.2.1 Demonstrator #1

In order to address the concepts of partial and complete reutilization of hardware parts, a demonstrator in the form of a chair was chosen as a candidate to illustrate the concept of payload rack blind panels reused as furniture. The chair was chosen as a design, since it appears to be the most generic object of application that could possibly be used in each of the functional areas of a future planetary human outpost and due to its simple, but challenging structure under static and dynamic stresses. The definitive demonstrator called "*Chair One*" resulted into a total mass of 13.3 kg, including 3D-printed connectors, screws & nuts and CTB dividers used as upholstery elements, and has an available sitting area of 1828 cm^2, making it sufficiently light and compact to be easily carried by an average single person without an assistive device such as a trolley.

Figure 3-2: Example of a typical close-out panel.

Figure 3-3: Example of cargo transfer bag dividers.

Following the design improvement of the demonstrator, ten 3D-printed connectors were added (four interconnected corner connectors on the backrest, four corner connectors below the sitting area and two corner connectors for fixating the backrest to the sitting area in a 90° angle). For the development of the connectors, several sequential changes were implemented through different thickness, overall print volume and filament welding iterations until the desired quality and durability were achieved.



Corner Connector - Iteration #5

Angle Connector - Iteration #5

Figure 3-4: Connector designs.

Figure 3-5: Final manufactured and assembled chair (type one).

For the testing of the chair, several experiments were conducted to establish whether the demonstrator is a feasible option for recycling in Space. The results of the analysis showed that the prototype could sustain up to 100 kg even after three hours of intensive use, while nevertheless being an easily manoeuvrable, quickly assembled, comfortable piece of furniture, with a highly qualitative soft padding. However, some signs of material fatigue were observed in cracked connectors, though this did not affect the performance of the chair.

The demonstrator has thus shown that discarded items such as blind panels in combination with CTB dividers, and 3D-printed connectors are suitable to create a usable chair. As the chair design was primary chosen as a demonstrator example, the spectrum of further designs and up-cycle solutions (e.g. furniture elements, secondary structural elements, tools) is multiple, and various other possibilities of reusing hardware parts exist.

3.2.2 Demonstrator #2

For the first recycling approach, the recycling of basic materials, the proposed demonstrator involved the recycling of commercial low-density polyethylene Ziplock® bags of various sizes into filament useful as feedstock for 3D-printing applications.

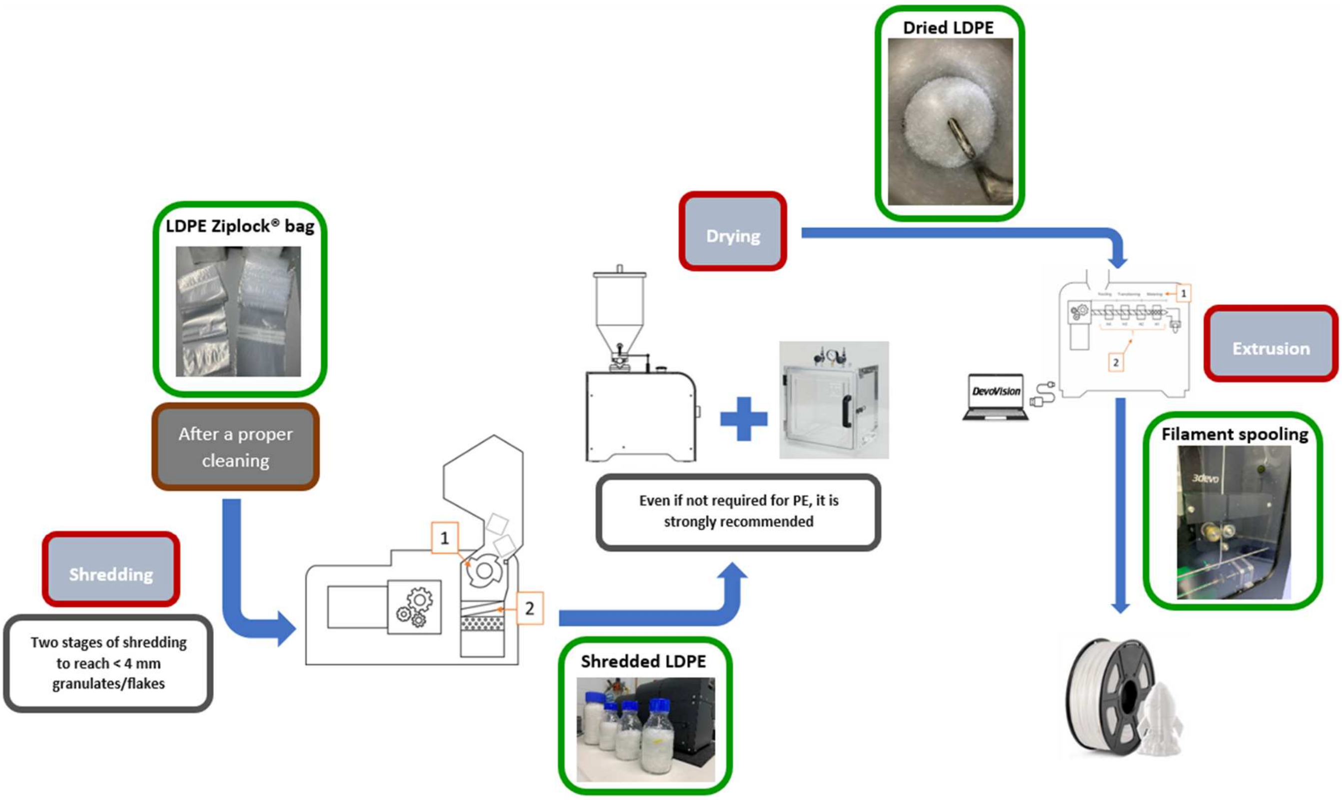


Figure 3-6: Recycling process, from shredding to extruding.

The bags were processed by cutting and shredding to obtain fine granulates that were dried and then inserted into the extruder. In all the extrusion trials performed, at least 80 meter-long spools have been produced. In some cases, the spooled filament exceeded 100 m in length. After a visual inspection to detect discoloration, burnt particles, encapsulated bubbles or any other visible sign of material degradation, the extruded re-PE filaments appeared homogenous in properties. Other dimensional characteristics, such as thickness, diameter roundness and weight distribution, crucial for proper 3D-printing, were analysed and declared to be within the desired acceptable range.

Following the successful extrusion of the LDPE into filament, tests were performed to assess its 3D-printability, which uncovered that, although the filament provides promising results, the challenging bad adhesion, the extremely low MFI (Melt Flow Index) and the overall amorphous nature of the material prevented the 3D-printed parts from achieving a sufficient quality level for ASTM mechanical and thermal testing, at least for now. Additionally, an external thermal test campaign was conducted, which showed that the filament was in line with the evaluated degradation onset temperature and the glass transition temperature criteria. However, the oxidation induction time was far below the reference value, which was the only test considered failed.

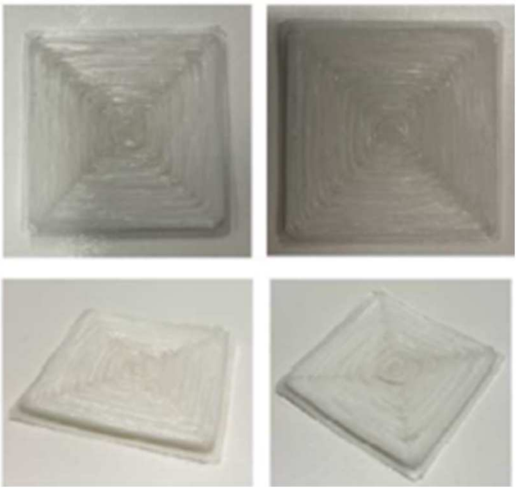


Figure 3-7: Re-PE 3D-printed parts.

Another part of the testing procedure of the filament extrusion was inserting a different LDPE source material, other than the Ziplock® bags, to assess the flexibility of the recycling process. The chosen material was the Plastazote®, very abundant on the ISS and predicted to be widely available in future Moon or Mars settlements as well. The Plastazote® underwent the same recycling steps as the Ziplock® bags, but it proved to be incredibly difficult to extrude. Indeed, due to its softness, it was not possible to obtain a filament since the screw embedded in the extruder was not able to push enough material through the heating system, resulting in a very poor outcome from the extruder nozzle. Multiple solutions for obtaining a filament were tried: combining, for instance, the Plastazote® with the shredded Ziplock® bags, or adding different polymers, till even using a vibrational tool to move the Plastazote® in the upper container of the extruder and allow for a uniform feeding, but the outcome from the extruder could not be spooled.

Therefore, although the Ziplock® bags-derived filament showed promising results with acceptable quality of the 3D-printed samples, the Plastazote® process remains to be improved, perhaps through the use of an additive compound.

Moreover, a number of tests were performed at the ESA Harwell laboratory to thermally characterize the re-LDPE filament. These consisted in:

- **Glass transition temperature** (via DMA);
- **Degradation onset temperature** (via TGA);

- **Oxidation induction time** (via DSC).

A summary of the results is reported below.

Table 3-1: Results of the thermal testing at Harwell

Test	Reference Value	Success Criteria	Result	Pass/Fail
Glass transition temperature	From -130°C to -100°C According to [RD20], [RD21] and [RD22]	±5%	-115°C	Pass
Degradation onset temperature	325°C According to [RD23]	±5%	338.8°C	Pass
Oxidation induction time	17.19 min @ 205°C According to [RD24]	±5%	1.5 min	Fail

The conclusions that can be drawn after the thermal test campaign at Harwell are the following:

- Considering that in literature the glass transition temperature foreseen for PE ranges from -130°C to -100°C pending on the material grade, the test was considered **passed** since the obtained result meets the success criteria with respect to the mean value;
- The evaluated degradation onset temperature was in line with the reference value and respecting the prescribed success criteria. Therefore, this test was considered **passed**;
- The obtained oxidation induction time was far below the reference value and not respecting the prescribed success criteria. This test has been therefore considered **failed**. However, in literature is well known that pending the grade of PE (and therefore also if it is pristine PE or re-PE) the oxidation induction time can significantly vary, also reaching at 205 °C values close to the ones obtained during the test at Harwell. Therefore, it is reasonable to assess that the reference value was not appropriate to benchmark and judge the obtained results.

3.2.3 Demonstrator #3

For the final demonstrator, which again addressed the material recycling concept, a multi-tool from aluminium alloy 7075 was casted. The multi-tool includes the following features: two wrenches suitable for M5 and M6 hex head bolts, and Allen keys compatible with M5 and M6 socket head bolts. Additionally, the tool possesses an opening in the centre that can be used as an attachment point.

For the manufacturing of this demonstrator, a sand-casting process was followed. It started with the preparation of a core, which was used to leave a cavity inside the casting sand, later to be filled by molten metal. In this case, the core, which was a 1-to-1 model of the multi-tool, was 3D-printed out of polylactic acid using a Fused Filament Fabrication (FFF) system. Prior to placing the core inside the container and filling it with sand, the section of the core was sprayed with a boron-nitride based release agent which eases extraction of the core. The sand was then placed into the casting container around the core and manually compressed. Finally, the half core was extracted and substituted with an entire multi-tool geometry that was again covered with the casting sand. To extract the cores, they were two holes on both sides where screws were fixed. This way, the core could be pulled on both ends at the same time which allowed achieving more symmetric and uniform extraction of the core.

Following post-processing and intensive testing to determine the measures, weight, density and roughness of the tool, several manufacturing trials of an aluminium multi-tool with sand casting were thus completed.

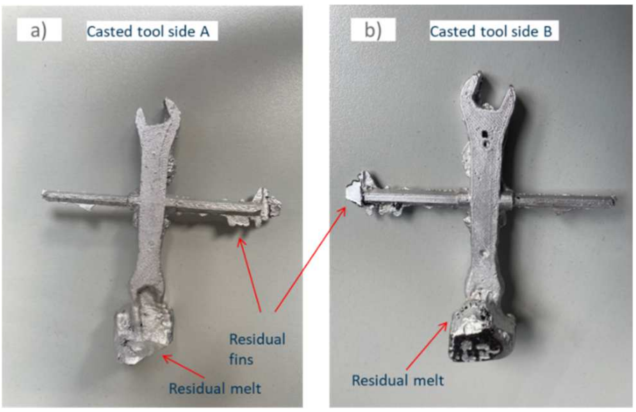


Figure 3-8: a) Top view of the as-casted multi-tool trial 1, b) bottom side of the as-casted multi-tool.

During the first trial, the tool was cast in a vertical configuration with satisfactory results. However, some defects were observed (see Figure 3-8) which indicated that the tool could not be used without post-processing. Additional post-processing steps were undertaken to enhance the surface topography, resulting in a usable tool. As shown in Figure 3-9 a) and b), post-processing enabled the use of both the M5 and M6 hex wrenches present on the multi-tool.

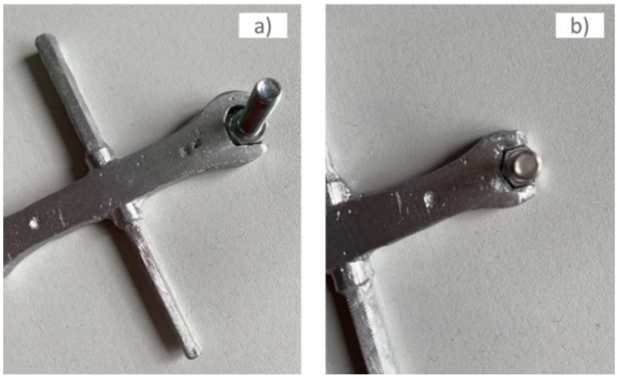


Figure 3-9: a) and b) fit test for M5 and M6 hex head bolts after post-processing of Trial 1.

A second trial was performed in order to explore different methods of achieving better quality results, which involved casting the tool in a horizontal configuration (i.e., flat). In this configuration, the casting procedure was similar to the first trial, except for the location of the pouring and air release openings. In this trial, extra holes were added to the sand mold to allow for the horizontal orientation. Observations showed that the viscosity of the aluminum and high pouring speed sometimes led to air pockets, resulting in incomplete casting of the Allen keys and occasionally the wrenches. However, the addition of air release holes, ensured that the molten material reached all ends of the multi-tool, effectively eliminating air pockets.

The quality of the parts produced in Trial 2 was significantly higher compared to Trial 1, with all tools except the M5 wrench turning out to be usable without extensive post-processing, meaning that the tool could be used in its as-cast configuration, as shown in Figure 3-10.

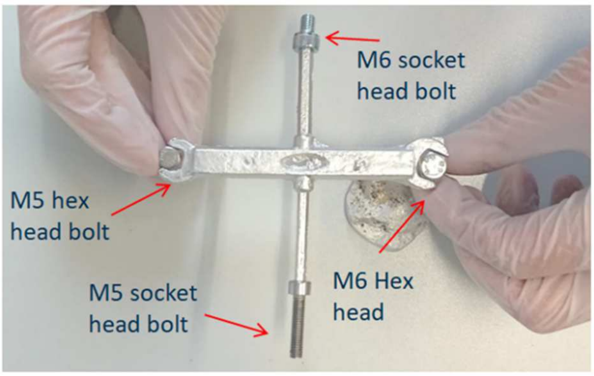


Figure 3-10: Post-processed tool from Trial 2.

An analysis of the casted tools from all trials showed that they were light and comfortable to hold, regardless of the operation and the operator's hand circumference, though continuous use became tedious after 2-3 minutes due to the tools' sharp edges pressing against the operator's hand. The test subjects were also able to sustain only a few cycles of use without failure. Particularly, Allen keys withstood fewer cycles than the wrenches, since the edges were gradually grinded against the inner corners of the bolt's hexagonal insert, an effect that increases with greater tolerances. Such tolerances do mean less post-processing efforts, but may lead to such failure that should be avoided. In addition, it was recognised that both tools cracked at a lower number of cycles than targeted. This is attributed to the fact that the as-cast state represents the least advantageous metallurgical state for the mechanical properties, for the 7075 wrought aluminium alloy, which obtains its optimal mechanical properties through strain hardening or metal working. In conclusion, sand casting technology is feasible for manufacturing multi-tools, and, while post processing of the casted tools is unavoidable, it can be significantly minimized when improved casting routines are employed. On the basis of the test results, it is recommended that a follow-up activity be focused on the casting of less load-bearing parts. Other manufacturing routes for in-situ recycling of wrought alloys, such as 7075, should also be investigated.

4 ENVIRONMENTAL DIFFERENCES ON THE MOON/MARS

4.1 Impact on the recycling machines

The lunar environmental conditions influence the design of any mission aimed for the surface of the Moon/Mars in various ways and to different degrees.

For the assembling and reconfiguring of blind panels for the *Chair One*, no specific technologies need to be developed. Here, common handheld tools are required that are generally used for metal handcraft, such as screwdrivers or hex keys, socket wrenches, drillers, metal saws, files, and a 3D-printer for the connectors. In addition to the mentioned tools, a dedicated work bench is needed as well as sufficient workspace with additional assembly space for building the furniture elements. This workshop infrastructure in combination with an adequate storage place could be the central place for recycling and up-cycling of elements and consumables.

However, the shredder, the dryer, the extruder and the printer used in the filament making process will all have to be modified. The biggest challenge for the design is the thermal environment as all parts of the extruder and the printer will be affected. The very low temperatures will compromise any standard lubrication of the linear units and other moving parts (particularly in combination with microgravity). In Space, all materials also become more brittle, especially plastics, which reduces the structural strength. Furthermore, the large temperature differences during day and night, as well as between the sun-exposed and sun-hidden sides, will introduce stress to the structure due to thermal cycling. This also affects the accuracy of the printer and the diameter of the filament that might come out of the nozzle.

Another problem would be the lack of significant gravitational acceleration, which results in a lack of convection. Hence, all electronics would require dedicated temperature control systems to avoid overheating, but also to prevent too low temperatures when the extruder or the printer are not in operation.

Furthermore, in a non-Earth environment, a conveyor belt or a system of pulling wheels should also be added to the extruder machine design, to cope with the lack of gravity driving force necessary to guide the filament from the nozzle to the spooling system. For an easier redesign of the machines without compromising safety, a Generative Design (GD) approach could be implemented in order to establish which parts can be removed, substituted or reused in other configurations.

On the other hand, electrical devices also are predominantly affected by radiation and need to be designed accordingly. A solution could be the radiation hardening of the electrical devices in order to prevent shorts and damage to the sensitive electronics. Furthermore, lunar or martian dust could create several disruption in the proper functioning of electronics (e.g., PCB), mechanisms and moving parts, which therefore need to be protected from contamination. For the case under discussion, this means that the whole shredder, dryer, extruder and printer should be properly sealed.

Even though an exact possibility of meteoroid impacts is hard to predict, and the probability of large impacts is small, a minimal protection against micrometeoroids should be implemented.

Nonetheless, not only the design of the printer is affected by the extraterrestrial environments, but also the feedstock and the operation would be. If it is too hot, the feedstock becomes liquid and runs down from the material piston. Cold temperatures are not so much of an issue, but the thermal knife might need to be heated more to reach the desired viscosity of the feedstock to apply a new layer.

The vacuum would actually be beneficial to the feedstock quality as it prevents air bubbles, but would also have a non-uniform temperature in the print chamber as consequence. Additionally, the current layer could not be cooled with an airflow, but this might not be necessary anymore. The low gravity could cause the first few layers to warp-up on the outside. It would also be unavoidable to have dust inside the print chamber, which could reduce the print quality.

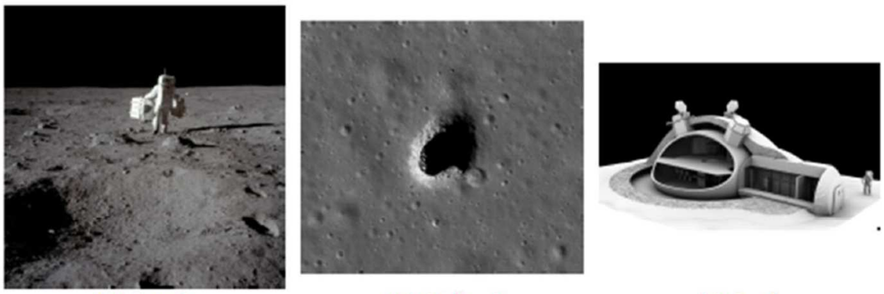
Regarding the casting recycling process, only a limited category of supplies and equipment required for manufacturing can be reused. Utilization of complete sub-assemblies such as melting setup, crucible, mould etc. can reduce the need for preparation of the setup in terms of assembly, but it is impossible to eliminate these steps as parts have to be brought together, configured, connected and positioned in order to execute casting.

As mentioned before, the vacuum could be beneficial for all recycling processes, including the casting operation. However, even though vacuum casting is a well-known and proven technology on Earth, extensive testing should be conducted in order to adapt the technology for lunar or Martian environment.

The equipment relevant for this manufacturing process is standard when used on Earth. It has to be noted that modifications might be necessary to adjust the equipment for the operating environment. It follows that certain components have to be modified to withstand not only vacuum or low pressure, but also dust, extreme temperature variations and increased levels of radiation. Because of these requirements, the range of possible off-the shelf components is limited to low level components such as an all-metal file, graphite crucible etc. The rest of equipment that was used on Earth, for example melting furnace, rotating tools for post-processing and other equipment (including safety equipment) must be properly custom-made to be used in a lunar or Martian environment.

Finally, as far as the casting sand is concerned, the quality of the sand can be ensured by sourcing the sand from the known location and adhering to the procedure while mixing with additives. These steps should be sufficient to ensure a repeatable as well as satisfactory quality of the sand. Given the simple nature of the device in question, one of the tools in the batch (assuming that multiple tools are casted together) can be mechanically tested to verify that it can withstand for instance the required torque.

With these aspects in mind, it is important to consider three different scenarios for possible use locations on the Moon or Mars: on the surface, inside a sheltered environment and in a habitat. An exemplary picture for each case is shown in Figure 4-1.

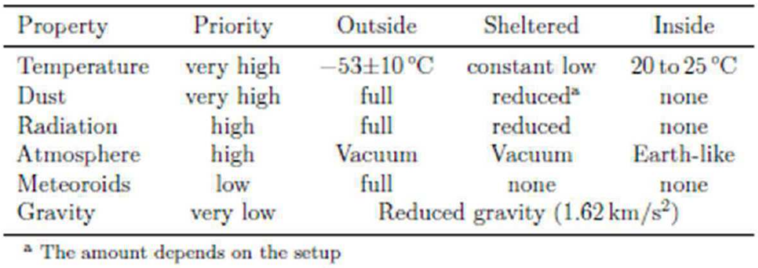


(a) *Outisde* (b) *Sheltered* (c) *Inside*

Figure 4-1: Example pictures for the three scenarios. Credits: Foster & Partners.

Table 4-1 gives an overview of these three different scenarios including a rating of the importance of the environmental conditions.

Table 4-1: Comparison of the three possible use locations for the recycling process, the outside environment being presented as the baseline



Property	Priority	Outside	Sheltered	Inside
Temperature	very high	$-53 \pm 10\,°\mathrm{C}$	constant low	20 to 25 °C
Dust	very high	full	reduced[a]	none
Radiation	high	full	reduced	none
Atmosphere	high	Vacuum	Vacuum	Earth-like
Meteoroids	low	full	none	none
Gravity	very low	Reduced gravity ($1.62\,\mathrm{km/s^2}$)		

[a] The amount depends on the setup

It is evident that the preferred scenario is the third one. It offers Earth-like operational conditions that, as consequence, significantly reduce the modifications to apply to the HARMONISE hardware in a future lunar or martian framework.

4.2 Future challenges

To facilitate the future manufacturing of usable items, an adequate workshop infrastructure needs to be created within habitats on Moon or Mars. This central workshop environment, in combination with an intermediate storage capability and a dedicated assembly area will allow future astronauts to build-up a vast spectrum of different items. On the other hand, the successful implementation of a recycling process involves a multifaceted approach encompassing the selection of appropriate materials, advanced equipment design, robust logistics, and stringent quality control protocols.

Furthermore, since the goal of the HARMONISE project was to reduce Earth-dependency, everything should be planned during the design phase with efficiency in mind. This includes, but it is not limited to, using material connectors that can be easily detached and reattached, applying materials that are useful for many purposes, and generating structures that can serve multiple purposes.

Other bureaucratical aspects that need to be considered on future Moon and Mars settlements in terms of recycling of existing *in-situ* hardware are:

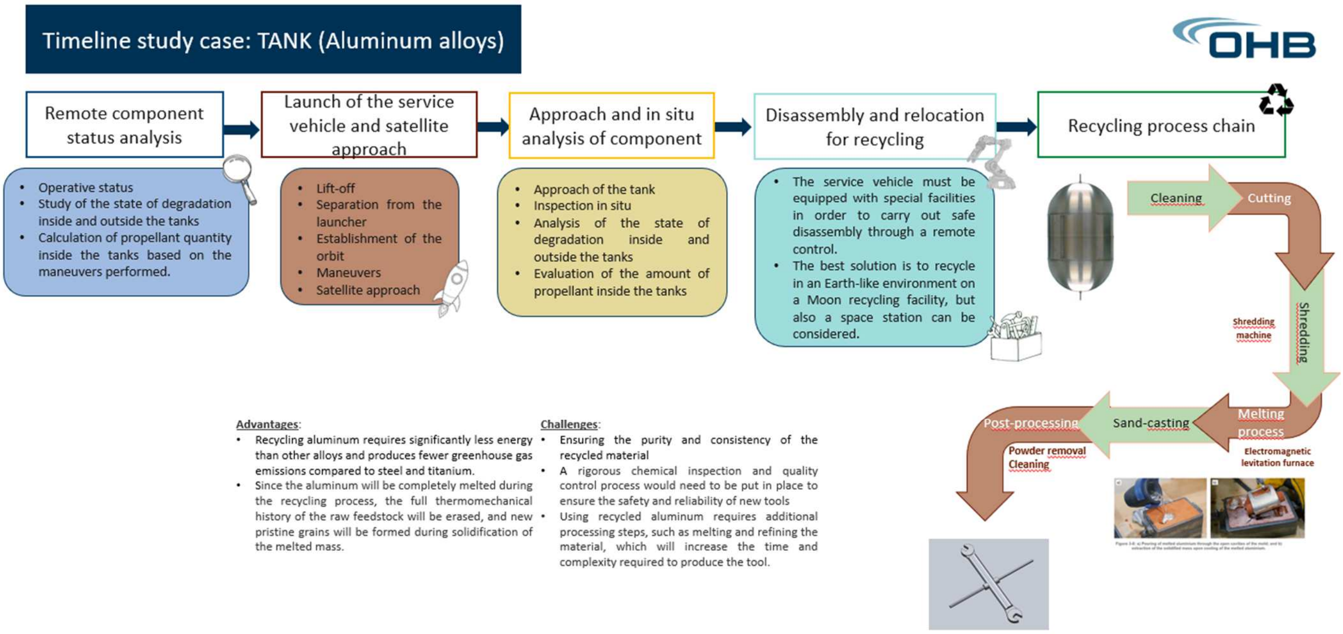
- safety considerations of reused compounds;
- property ownership rights of damaged or abandoned objects;
- insurance upon failure of reused/recycled parts;
- regulatory and legal challenges related to ownership, liability, historical value and intellectual property rights of hardware.

For a more detailed and structures overview on these and other challenges and to learn about recommendations and guidelines to be considered when it comes down to the recycling and re-use of Space items, the Technical Note #5 – Part B [RD14] can be referred to.

4.3 Future possibilities

One case study worth mentioning that could pave the way for future closed-loop recycling processes is the reuse of no longer needed satellite hardware, such as an aluminium tank that could serve as prime material for a casted tool.

A 3D-printed pattern, designed to match the desired tool shape, would be the starting point of the process. After this pattern has been casted and removed from the sand, it leaves behind a cavity that is then filled with molten aluminium. Once the aluminium cools and solidifies, the sand is removed, revealing the completed tool.



Timeline study case: TANK (Aluminum alloys)

Remote component status analysis

- Operative status
- Study of the state of degradation inside and outside the tanks
- Calculation of propellant quantity inside the tanks based on the maneuvers performed.

Launch of the service vehicle and satellite approach

- Lift-off
- Separation from the launcher
- Establishment of the orbit
- Maneuvers
- Satellite approach

Approach and in situ analysis of component

- Approach of the tank
- Inspection in situ
- Analysis of the state of degradation inside and outside the tanks
- Evaluation of the amount of propellant inside the tanks

Disassembly and relocation for recycling

- The service vehicle must be equipped with special facilities in order to carry out safe disassembly through a remote control.
- The best solution is to recycle in an Earth-like environment on a Moon recycling facility, but also a space station can be considered.

Recycling process chain

Advantages:

- Recycling aluminum requires significantly less energy than other alloys and produces fewer greenhouse gas emissions compared to steel and titanium.
- Since the aluminum will be completely melted during the recycling process, the full thermomechanical history of the raw feedstock will be erased, and new pristine grains will be formed during solidification of the melted mass.

Challenges:

- Ensuring the purity and consistency of the recycled material
- A rigorous chemical inspection and quality control process would need to be put in place to ensure the safety and reliability of new tools
- Using recycled aluminum requires additional processing steps, such as melting and refining the material, which will increase the time and complexity required to produce the tool.

Figure 4-2: A timeline study case for the recycling of a satellite tank.

In a lunar/martian scenario, the sand could be replaced with lunar or martian regolith, which can be further reused, making this a sustainable closed-loop solution for a future off-Earth base. The entire process, along with a description of its advantages and possible challenges, is laid-out in Figure 4-2.

CONCLUSIONS

Extensive research on the subject of possible recycling opportunities for the set-up and support of extra-terrestrial habitats (lunar or martian) was conducted throughout the duration of the HARMONISE project. The experiments have shown that discarded items such as blind panels in combination with CTB dividers, and 3D-printed connectors are suitable to create a usable chair. The range of designable products can further be expanded by a general paradigm change in pre-flight design approaches. By implementing certain design adjustments into all habitat elements and consumables, the up-cycling approach can be eased.

On the other hand, although the Plastazote® trial was not successful, the filament extrusion using LDPE derived from Ziplock® bags proved that plastic recycling is a viable solution for the future, since it could potentially decrease the dependency on Earth while promoting a sustainable approach.

The campaign of the re-PE filament extrusion showed that the industry is capable of extruding up to 100 m of recycled LDPE with no material limitation, signs of entanglement, discoloration, contamination, degradation or ovalization. The spools produced during the process determined that this is indeed a suitable option for 3D-printing, although the printed samples were not a very high quality.

As a way forward, it is recommended to find both an additive compound that could improve the 3D-printability of the Ziplock® bag-derived re-PE or a suitable 3D-printer/3D-printer setting able to allow a satisfactory quality for the 3D-printed samples. Improving the stiffness of the re-PE obtained from the Plastazote®, in order to extrude a filament out of it, could be a good direction for the future as well.

Finally, in terms of metal recycling, the testing campaign determined that aluminium sand-casting is feasible for manufacturing tool parts. In terms of performance, however, neither of the tools tested managed to reach the required number of cycles with the specified torque. This is true for both wrenches and Allen keys features. Additionally, it was found that wrenches are much more robust compared to Allen keys which failed after just a few tightening/loosening cycles. Finally, the density analysis indicated that the manufactured tools have a higher level of porosity than expected which further weakened the bulk material and lead to a premature failure. The main outcome of the trials was a set of recommendation such as to reinforce the wrenches and remove Allen keys from the tool to focus on hex-head rather than socket-heads bolts. Further steps include formulation of the de-rated torque values for the aluminium tool, improvement of robustness by adopting square head bolts that could increase the surface in contact and finally changing the design and geometry of the tool so it functions in the same way as a socket wrench. As a lesson learned and on the basis of the main results collected, it is considered preferable sand-casting less structural-critical items in future follow-up studies.

In conclusion, it can be stated that HARMONISE can represent a good starting point in the direction of recycling in Space, which is widely considered as the next natural step towards independency from Earth and potentially laying the foundation stone for achieving long-term off- Earth settlement.