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HARMONISE RECYCLING AND REPURPOSING OF HARDWARE FOR MOON AND MARTIAN HABITATS

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Abstract

The pursuit of establishing permanent colonies on celestial bodies like the Moon and Mars represents a ground-breaking evolution in space exploration. Minimising dependence on Earth is fundamental to the establishment of sustainable space outposts. This endeavour compels researchers, scientists, industries, and agencies globally to reconsider space exploration methodologies, employing inventive thinking, cutting edge technologies and novel strategies to overcome challenges. Essential to this goal is the capacity to fabricate structures and spare parts on-site and as needed, utilising recycling and repurposing of available resources. This approach not only reduces costs, volume and constraints associated with transporting supplies from Earth but also facilitates extended-duration and long-distance missions. By integrating in-situ manufacturing, harnessing advancements in additive layering manufacturing (ALM) and implementing innovative recycling techniques, we can achieve a remarkable 90In this context, this paper aims to present the concepts explored in the HARMONISE (Recycling of hardware for Moon and Martian settlement) study, focusing on in-situ recycling and the partial or complete re-use of hardware from exploration missions. Primarily targeting Moon and Mars scenarios, the study investigates repurposing strategies to serve other purposes at mission destinations. The HARMONISE ESA study is structured into three distinct parts: recycling of basic materials (e.g., recycling polyethylene Ziplock R bags into filament for 3D-printing applications and melting and casting scrap aluminium for tool fabrication), partial re-utilisation of parts and complete re-utilisation of hardware components (e.g., repurposing rack blind panels with integrated Cargo Transfer Bags dividers for furniture elements, recycling of propulsion systems). Each strategy involves designing, manufacturing, testing and benchmarking specific demonstrators against pre-defined success criteria oral to meet functional requirements in both Earth and lunar/Martian environments. The successful implementation of the HARMONISE project will contribute to ushering in a new era of sustainable space exploration, significantly enhancing the circular economy through in-orbit servicing by 2050.

Keywords: human spaceflight, outposts on Moon/Mars, recycling, 3d-printing, furniture, metal casting

1. Introduction

1.1 Up-front Analysis

To establish a baseline for the analysis carried out on recycling technologies and the potential benefits, the study began with a survey of past, present and projected missions to the Moon and to Mars. The survey provided an overview of all known landing missions to the Moon and to Mars. These missions have, to date, delivered 188.6T of material to the Moon and 10.3T to Mars. From this starting point, macro estimates were made of the nature of the material which could in principle be available for processing.

Supplementary, less relevant details such as mission cost, scientific goals and payloads were included where they were easily available. Factors influencing missions expected to take place in the foreseeable future were discussed, and an overview of future missions was presented. Human lunar landing missions are included where planning dates have been announced but the current published schedule is considered to be optimistic. In compliance with the guidance provided by ESA this survey was based primarily on information publicly available.

1.2 Project scope

The next big leap in institutional and commercial space exploration is inextricably linked to the human desire both to reach Moon and Mars and to establish there a permanently inhabited colony. In the last decades, this has been one of the major, more demanding challenges for industry and agencies since this imposes a creative re-thinking of previous missions' approaches.

Earth dependency has always represented the bottleneck for freely conceiving a human outpost on the Moon and Mars. It is widely recognized that a key enabler to any sustainable presence in space is indeed the ability to manufacture necessary structures and spare parts in-situ and on-demand by recycling and re-using the available resources. This will reduce cost, volume, and up-mass constraints, being also in line with the ESA space debris mitigation policy towards environmentally sustainable space activities.

In this frame, the scope of this paper is to present the concepts investigated during the ESA-funded HARMONISE study concerning both in-situ materials recycling and partial or complete re-use of end-of-life hardware to serve different purposes during Moon/Mars exploration missions.

In the course of the activity, the investigation approach was threefold: recycling of polyethylene Ziplock® bags into 3D-printable filament; melting and casting of scrap aluminum for tools fabrication, and partial re-utilization of rack blind panels for habitat furniture design.

For each of these a dedicated design, development, manufacturing and verification phases have been conducted. The verification and testing phase were carried out to fulfil prescribed functional requirements and with respect to predefined success criteria considering both Earth and lunar/martian scenarios. At the end of the study, a comprehensive analysis has been also performed to optimize material usage efficiency and hardware reusability, along with a critical evaluation of the manufactured demonstrators. This also allowed for relevant improvements of them based on observations and lessons learned.

Finally, the HARMONISE team was also able to define innovative guidelines and recommendations for the equipment brought for exploration missions, which pointed out how crucial is that the design for recycling is considered already from the early definition phase of a mission.

2. Payload Rack Blind Panels reused as Furniture

1.1 Initial Idea & Concept trade-offs

Within the first demonstration project, an overall system analysis and open concept brainstorming was conducted. Main paradigm for this initial task was to elaborate which kind of furniture elements can be built out of payload rack blind panels in order to fulfil basic living needs of astronauts inside a future habitat. A starting point for the initial investigation were examples for achievable geometric forms, as can be seen in Figure 1. Baseline for the panel connection were dedicated 3-D printed connectors that connect either two or three panels with each other.

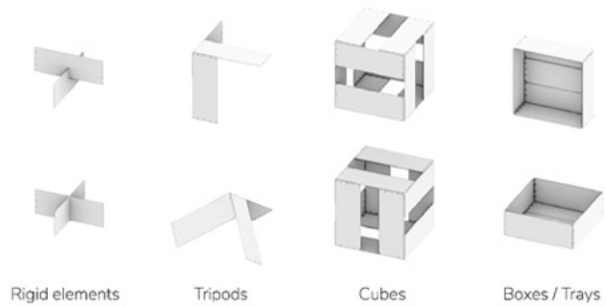


Fig. 1. Examples for some achievable geometric forms, created with close-out panels. [Source: LSG]

From here, different activities and functional areas within a future habitat were analysed, and preliminary furniture concepts were created, such as tables, chairs, bunk beds, divider walls, blinds, adjustable ladders, and various shelving systems. Figures 2-4 present examples of this initial concept analysis.

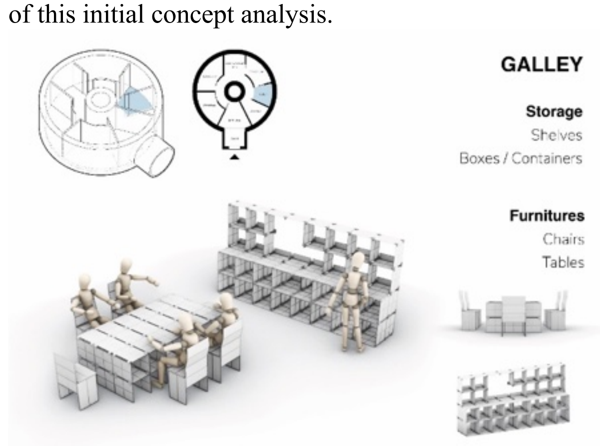


Fig. 2. Concept for the galley/social area incl. chair/ table combination and storage capability. [Source: LSG]

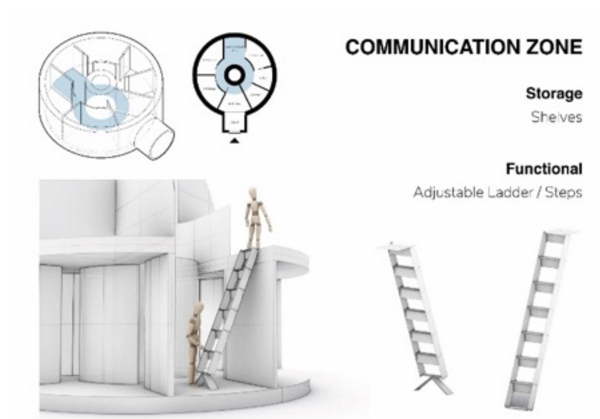


Fig. 3. Concept for a ladder system. [Source: LSG]

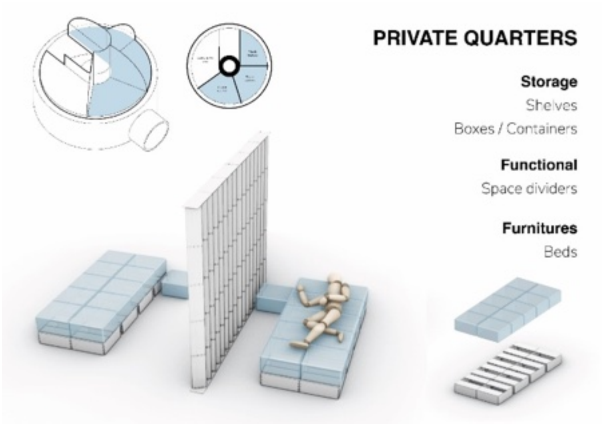


Fig. 4. Concept for a space divider in combination of a bed system. [Source: LSG]

The LIQUIFER team decided to further investigate the design of an archetypical chair as an example demonstrator. Generally, a chair represents a common and often used furniture element. Further, the chair design enables the demonstration of multiple aspects of the envisioned recycling approach (connector design, achievable stiffness, general utility). Last but not least, the chair design allowed the team to perform a solid testing and validation phase more easily. Further the chair appears to be the most generic object of application that could possibly be needed in each of the notional functional areas of a future planetary human outpost. It is a simple, but challenging example for an improvised structure under both static and dynamic stresses.

1.2 Used material – Recycling Concept

For the creation of the demonstrator (here: chair design no. 1) three main components were selected:

- Different dimensional variants of close-out panels,
- cargo transfer bag dividers, and
- 3D-printed connectors.

The different close-out panels (See Figure 5) used for the demonstrator are made of aluminium and include a set of pre-drilled holes, originally used to install the panel in the experiment rack, in order to secure the experiment facility during the launch phase. The close-out panels represent the main component element for the structural integrity of the chair. Main paradigm was to limit the adjustment procedures to the panels (e.g., drilling of additional holes, or other fixation adjustments such as nuts).

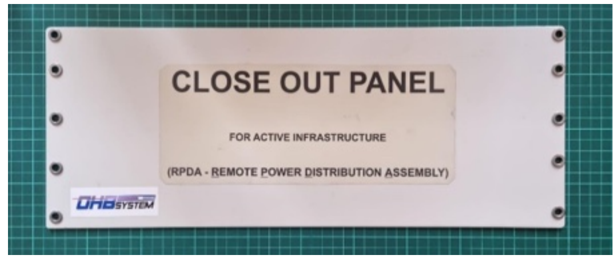


Fig. 5. Example of a typical close-out panel [Source: OHB]

In addition to the close-out panels, a combination of several different types of cargo transfer bag dividers (see Figure 6) were used for the upholstery of the demonstrator seating area, and the backrest area. The attachment of the dividers to the close-out panels was performed by attaching individual self-adhesive hook and loop strips, which will later interlock with the already existing Velcro strips of the cargo transfer bags dividers. Optionally, a second layer of cargo transfer bags dividers was considered initially but postpone for the actual testing phase.


Fig. 6. Example of cargo transfer bags dividers. [Source: OHB]

For connecting the close-out panels dedicated connectors are needed. These connectors shall make use of the already existing drill holes of the close-out panels.

Initial material assessment concluded that the use of a dedicated aluminium-based casting process would be too complex and would not provide sufficient accuracy for the subsequent assembly of the geometric demonstrator form. Therefore, the use of 3D-printed plastic connectors was used as first choice of manufacturing (Figure 7). Further, the main design logic followed the approach to limit the necessary material consumption and at the same time to provide enough structural integrity and stiffness to the chair demonstrator.

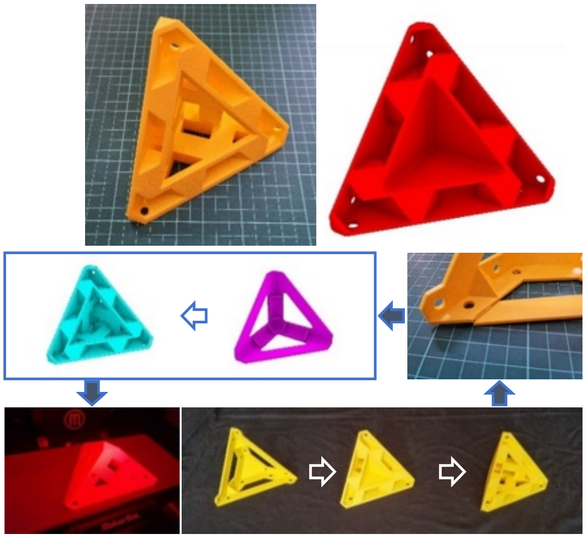


Fig. 7. Different design iterations of the 3-D printed connectors. [Source: LSG]

While the material for the later space-born system shall be a result of internal in-situ recycled plastic, the actual foreseen demonstrator of this project will rely on 3D-printed PLA components. Various design iterations were performed in order to find the best suitable layout for connecting the close-out panels.

1.3 Demonstrator Design "Chair One"

From the different demonstrator candidates, a chair was initially chosen. Figure 8 shows the final test design of the demonstrator. The manufacturing process of the chair demonstrator was conducted by printing the connectors and assembly of the different components.

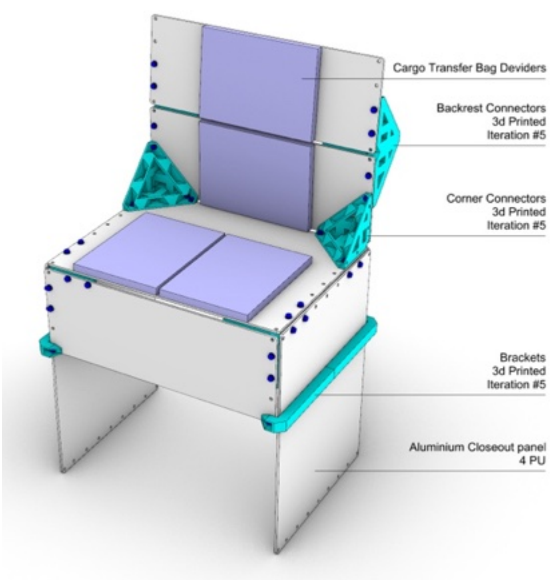


Fig. 8. CAD drawing of developed chair (type: one). [Source: LSG]

Following parameters were noted for the production of the demonstrator:

- Printing Time: Total: 94 hours
- Filament material: PLA (needed mass: 1,25kg)
- Tool: Creality Ender-3 v2 (Total peak power: 350 W)
- Screws (type: M6/20mm Stainless Steel Hex Socket screw, number: 48)
- Nuts (type: M6 Stainless Steel Hex nut, number: 48)
- Velcro band (Type: 20mm black hook end loop; total needed lengths: 120 cm)
- CTB Divers: (Type: Half Size, needed number: 2; Type: Full Size, needed number: 1)
- Close-Out Panel 1: (Type: 4U, number: 4, single mass: 1,1 kg)
- Close-Out Panel 2: (Type: 8U, number: 3, single mass: 2,2 kg)

The final demonstrator (See Figure 9) results in a total mass of 13,3 kg, including all 3D-printed connectors, screws & nuts, and upholstery elements. Sitting height is 50,3 cm, the back rest assembly adds an additional 34,9 cm so that the total height of the chair is 85,2 cm. The width of the chair is 52,9 cm. The chair provides a seat area of 1828 cm².

1.4 Test phase of the demonstrator

The full test campaign consisted of several phases that tested various aspects of the demonstrator. Investigation factors such as external environmental factors (e.g. radiation, vacuum, micro debris/ meteoroids) were considered negligible, as the architectural elements and furniture will only be used inside the habitat infrastructure.

Fig. 9. Final manufactured and assembled chair (type one), including addition stabilization struts on the side of the chair. [Source: LSG]

1.4.1 Static Strength Testing

The prototype demonstrator was tested to load the chair with weights (10 kg steps) until 100 kg was reached (see Figure 10).

Fig. 10. Static load test of the demonstrator; [Source: LSG]

The static strength testing showed that the chair could easily withstand the load of the weights applied, and therefore could support 100 kg.

1.4.2 Usability, Ergonomics, and Handling Testing

The test personnel had to use the chair for 60 min during normal office work. After the test phase a dedicated questionnaire was completed. Three different persons (main human distinguishing element: height and weight) sat on the prototype, performing nominal work procedures (e.g. writing/ office work, performing light work). Test duration: 60 min. (Figure 11).

General usability, stiffness, and comfort of sitting received high and medium ratings, resulting into an overall positive evaluation within these categories. However, the criterium movability received low ratings (with one medium rating), resulting into a less positive overall evaluation.

For this test, a total of four tasks had to be performed in order to test the general handling capability of the demonstrator such as lifting up, moving it from location 1 to location 2, maneuvering the prototype through a door (hatch), and carrying it upstairs (about 25 steps). All four tasks were performed without major difficulties. Lastly, the soft padding subsequently added to the chair proved to be crucial in masking the coldness of the metal surface and providing warmth, and the Velcro fitting was strong enough to prevent the padding from detaching when the person stood-up.

Fig. 11. Different positions for the usage of the demonstrator; Holding procedure of the demonstrator (Transportability & Handling) [Source: LSG]

1.4.3 Assembly and Disassembly Testing

The demonstrator was assembled without major challenges. Overall assembly time for the demonstrator took approximately 1.5h. This assembly time excluded production of the needed 3D-printed connectors. The disassembly time was much less and required only 30 min for the demonstrator. Both times include the time required for tooling and preparation (Figure 12).

Fig. 12. Different pictures of the assembly procedure. Overall assembly time was 1.5h; Disassembly time was 0,5h. [Source: LSG]

1.4.4 Overall Test Evaluation

In conclusion, the campaign has shown general positive overall results of the demonstrator capabilities and the test campaign was performed without major challenges. The overall test results verified most of the before stated system requirements. However, after several hours of intensive use of the chair, signs of material fatigue within the 3D printed connectors were visible in some places. These cracks did not lead to immediate failure of the overall construction, but allowed continued use.

The default structure of an FLD printed connector is a composition of a form defining shell of several layers filled with a volumetric geometry of adjustable density. An iterative process has shown that type and strength of stresses within one part can vary dramatically. This can be countered by varying shell thickness and infill density, in order to reach solid areas where needed.

In addition, the present demonstrator deliberately refrained from drilling additional screw holes to optimize the connections between the elements, which led to some signs of material fatigue during the several hours of testing. However, it can be assumed that further improvements to the connecting elements and optimization of the screw hole positions can achieve greater and lasting stability.

Also, it should be noted that all tests were performed under a 1G-environment, which adds to the application loads of the chair. A moon gravitational environment will further ease the handling situation, and the structural stress of the overall chair assembly will be significantly less.

Summarizing, the test campaign proved the chair's high degree of utility and high potential for recycled furniture. The referenced demonstrator is, thus, a good starting point for creating architectural elements for a future lunar or Martian base.

1.5 Implication for Space Scenario

The demonstrator has shown that the reuse of aluminium parts (close-out panels) for assembly using 3D-printed connector elements can be used to produce statically stressed components (here: example demonstrator: Chair type one). The choice of the chair as a particularly demanding demonstration object has also shown that this construction method can even withstand dynamic loads to a certain degree.

In a reduced gravitational environment, the structural stability requirements for the connectors, and the overall geometric system, will be less severe. At 0.166g (Moon) and 0.38g (Mars) the 3D-printed connectors can potentially be built with less material, and still produce sufficient structural integrity and stiffness for an adequate usage inside the habitat.

Optimal connector design: dedicated 3D-printed connectors will play a major role for combining different elements together. These connectors can not only connect blind panels for creating furniture items or secondary structural elements (e.g. divider walls), but also connect and combine components and structural parts in order to create tools and consumable items. An optimal connector design is essential for a successful creation of an up-cycled new item. Therefore, dedicated individual design layouts need to be predeveloped upfront and later serve as a blueprint for the onsite 3D-printing process. Important here is that the necessary support structure is designed in a way to avoid unnecessary printing waste.

By selecting and arranging suitable panel sizes, the ergonomic requirements of the user can be adequately met and further improved by combining them with other elements such as CTB dividers, so that long-term use is feasible.

As the present chair design only functioned as a demonstrator for recycling blind panels in future habitats on the Moon and Mars, the possibility of creating other structural elements has immense potential. Additional items (see Figure 13) like honeycomb panels, broken fans, Carbon Fiber Reinforced Polymers (CFRP), Glass-Fiber Reinforced Plastics (GFRP), housing cases, aluminium rods, different textiles, and cables/wires could be used to create further architectural elements such as beds, room dividers, ladders, cupboards, and tables. Furthermore, tools such as buckets, EVA tools or intravehicular consumable items like plates, knifes or cups could be made partially from hand tool modified reused parts in combination with cast or 3d-printed elements produced on demand.

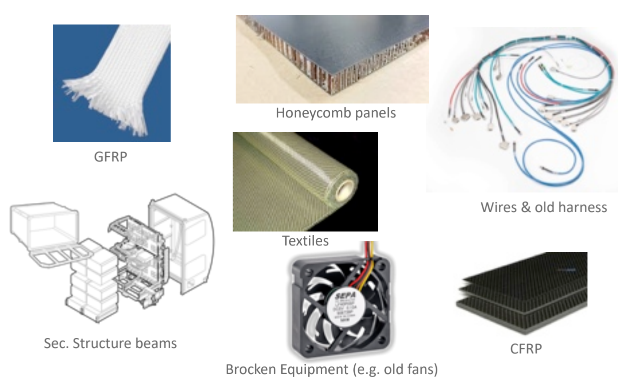


Fig. 13. Example set of possible addition source material for recycling and up-cycling activities within future Moon or Martian habitats.

Considering the overall system aspects, two major requirements and guidelines are essential for a successful recycling and up-cycling environment in future extra-terrestrial habitats.

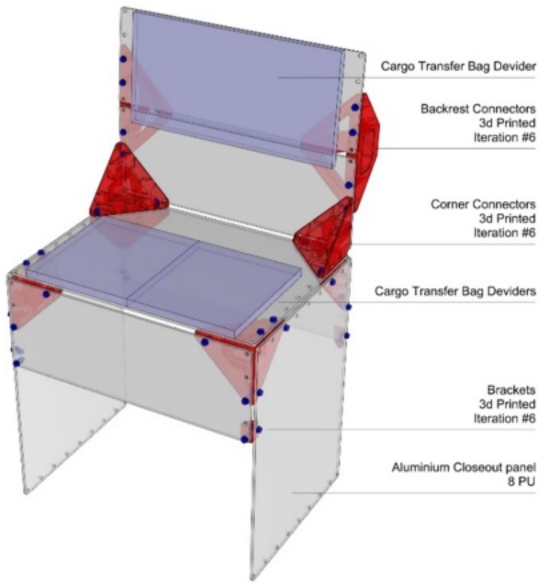


Fig. 14. Final design of the chair demonstrator. [Source: LSG]

Firstly, a recycling paradigm needs to be implemented at the beginning of design and development. Materials shall be selected, and components designed, as far as possible to be reusable in a second stage of their lifecycle. The items targeted for recycling could be further optimised by including future design features into the original design, such as mounting/assembly holes, dedicated openings or interlocking mechanisms, as well as detachable connecting elements, for easier separation. The challenge is to incorporate these design features while meeting the primary lifecycle requirements of each item, and not compromising its function.

Fig. 15. Final version of the chair demonstrator [Source: LSG]

Secondly, a local transformation infrastructure needs to be in place in order to allow the astronauts to assemble the new items. For assembling and reconfiguring the blind panels for the demonstrator (Chair One), no specific technologies need to be developed. Nevertheless, an adequate set of handheld tools (e.g. screwdrivers Allen keys, socket wrenches, drills, metal saws, files), work bench (incl. assembly area), and an intermediate storage location need to be foreseen.
Figures 14 and 15 display the final design of the demonstrator after the final iteration procedure. This final design improved the demonstrator by adding additional drill holes where needed in order to utilise the full potential of the connector elements. This decision was based on the considerations regarding reusability of items and the resulting conclusion that contingency drillholes in the original design of parts will facilitate their reconfiguration, and that a notional future lunar infrastructure shall include the needed tools and facilities as recommended, to allow the modification and storage of hardware parts for further assembly.

4. Food package recycling into filament demonstrator

4.1 Initial Idea & Concept trade-offs

The idea at the base of the demonstrator was to recycle the food packaging generated during a manned mission through a complete recycling process in order to obtain a low-density polyethylene (LDPE) 3D-printable filament. The plastics recycling for 3D-printing purposes in space defines a well-known field of interest (the Refabricator on board the ISS is a clear proof of that), both with refer to basic materials as PLA, ABS, etc... and with refer to some high-performances thermoplastic such as PEEK and PEKK [1]. The LDPE recycling is, however, a practice much less investigated and tested in the literature and, therefore, represents an as challenging as newsworthy world premiere in view of a sustainable and Earth-independent human presence in extraterrestrial habitats.

4.2 Used material – Recycling Concept

Commercial low-density polyethylene Ziplock® bags of various size (see Figure 16) have been selected and procured by the Consortium as suitable representatives of the food packaging materials commonly used in a number of Space applications.
The LDPE Ziplock® bags that have to be recycled were firstly collected and cleaned, then they underwent a shredding process in order to be reduced in fine granulates. After this, the powder/granulates was dried in

order to eliminate all the moisture and dust that could have had a negative influence on the mechanical quality of the final product, and finally the recycled raw material was used as feedstock for the filament extruder, which turned it into a neat and tight filament ready to be 3D-printed.

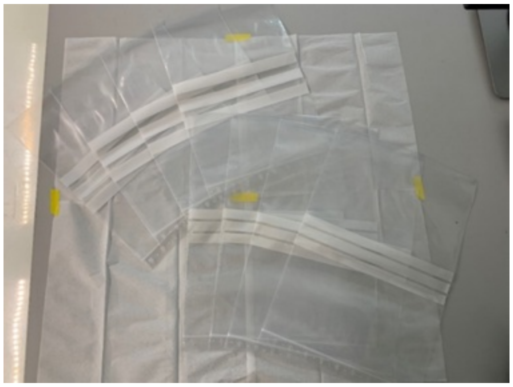


Figure 16: Commercial Ziplock® bags.

4.3 Demonstrator recycling process

To perform the entire recycling process, the 3devo recycling machines SHR3D IT Shredder, AIRID Dryer and Precision450 filament maker [2] have been used.

The recycling process started with the cleaning of the Ziplock® bags. This cleaning process was performed by washing the Ziplock® bags under rinsing water and using 2% Mucasol® solution. Before the real shredding process, a manual cutting step was performed (see Figure 17 a) given the specific geometry and shape of the Ziplock® bags and in order to simplify the following steps. Then, the clean bags, manually-chopped into smaller pieces, underwent a double-stage shredding process by means of the shredder (see Figure 17 b). In the frame of ESA research, three different mechanical shredding machines were evaluated and the SHR3D IT Shredder was the preferred choice over the others due to its good dimensional results, little contamination, and convenience of usage.

After the shredding, the drying process took place using the AIRID Polymer Dryer under a properly set fume hood (see Figure 17 c), so that undesired gas emission could have been controlled. The AIRID Polymer Dryer was used to eliminate any moisture complication that may occur within a polymeric material. Moreover, the machine is equipped with a stirring rotator which guarantees evenly dried materials across all surface areas. On the basis of the LDPE peculiar characteristics, the drying temperature, the duration, and the input material morphology (i.e. granules or flakes) and quantity were selected to correctly start and perform the drying process. According to literature, in the case of polyethylene-based feedstock it was not mandatory to perform a drying process, being this material not so prone to absorb moisture and humidity [2]. However, this step was performed in order to give the re-LDPE the proper consistency for extrusion. The overall drying process lasted two hours and the set temperature was 65 °C.

Finally, the obtained dried material was used as feeding material for the PRECISION 450 Filament Maker for the filament extrusion process (see Figure 17 d). This machine, also able to process PLA, PEEK, PETG, PEKK, can manage temperatures up to 450°C. It is equipped with the 3devo's Precision Screw, which offers faster extrusion speeds and steady filament flow, and as a result more precise filament diameter [2]. On top of this, an automatic neat spooling system is also embedded in the machine, which, together with the *DevoVision App*, which allows for a live data acquisition and monitoring, increase the efficiency of the overall process. During the filament extrusion process, the software receives real-time data of constant measurements displaying filament thickness, extruder RPM, puller speed, current filament length and mass, and other settings/information, allowing for a user-friendly fine-tuning of the process.

Via its unique vertical extrusion set-up, automated fan cooling, sophisticated optical sensor and a dynamic puller wheels system, the filament maker is able to provide precise roundness, accurately guide the filament towards the spooling process and achieve a diameter precision tolerance of ± 0.20 mm.

Essentially, three parameters were adjusted in order to reach the desired filament outcome:

- screw RPM;
- fan cooling speed and orientation;
- heaters temperature profile.

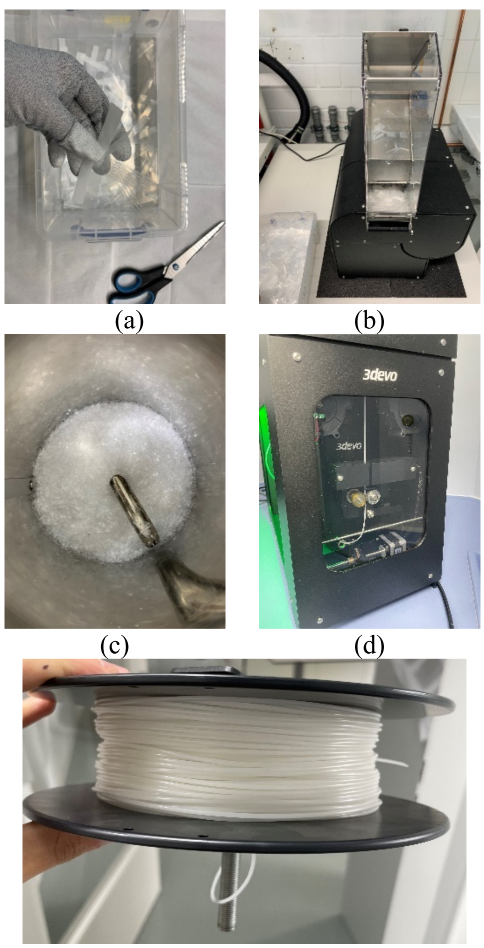
Depending on the extruding conditions, the screw RPM and the fan cooling speed/orientation can play a more or less significant role, while the most important factor for a good quality filament extrusion is the heating system temperature profile. The temperature profile, indeed, consists of three different zones: *feeding*, *transitioning* and *metering* zones; where the material is respectively fed into the extruder, melted down, and finally where the obtained viscous fluid is pressurized and pushed out. Within these three zones, there are four heaters which together control the temperature profile.

The final extrusion setting for the re-LDPE was the one reported in Table 1.

Table 1: LDPE extrusion baseline setting.

re-LDPE Extrusion Setting					
Heaters Temperature Profile				RPM	Fan Cooling
H n°4	H n°3	H n°2	H n°1	5.5-6.2	20-30%
185 °C	185 °C	185 °C	190 °C		

Important to be mentioned is that at the end of every recycling test, a deep purging procedure of the filament maker must be performed. Cleaning the filament maker consists in extruding special cleaning materials such as HDPE and DevoClean Mid Temp EZ [2].
As previously mentioned, the process parameters were live-monitored during the extrusion by means of the *DevoVision App*. In particular, the filament thickness was monitored with refer to the pre-set upper and lower limits (1.60 mm ± 0.20 mm, 1.75 mm ± 0.20 mm and 2.85 mm ± 0.20 mm). Then, when the desired thickness had been achieved, thanks to the combined action of the optical sensor and of the puller wheels, it was tightly spooled (see Figure 17 e) taking advantage of the spooling wizard program embedded in the filament maker. This was very important since a poor spooling would have meant the impossibility to 3D-print the filament spoiling the overall recycling process.



(a) (b) (c) (d) (e)

Figure 17: recycling of LDPE: (a) manual cutting phase, (b) shredding phase, (c) drying phase, (d) extrusion phase, (e) re-LDPE spool.

4.4 Demonstrator Testing Phase
A total of 23 functional requirements were verified via review of design, analysis, inspection and testing. The quality inspection campaign confirmed that all the recycled spools showed a neat and tight filament with not such entanglement to prevent 3D-printing. Furthermore, the roundness consistency of the diameter along the filament spooled length was in the prescribed range of tolerance and it also confirmed the weight consistency which can be derived by the overall roundness consistency and absence of degradation of the filament (i.e., absence of changes in the material properties). Multiple filaments having a diameter of 1.60 mm ± 0.20 mm, 1.75 mm ± 0.2 mm and 2.85 mm ± 0.2 mm along their overall length have been extruded. The filaments thickness has been recorded live using the *DevoVision App* and then transported into *Excel* for data post-processing as showed in Figure 18.

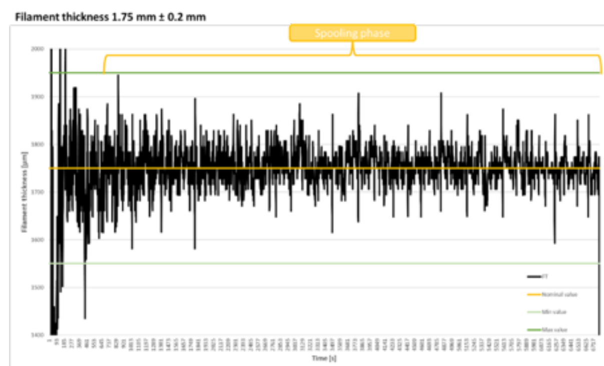
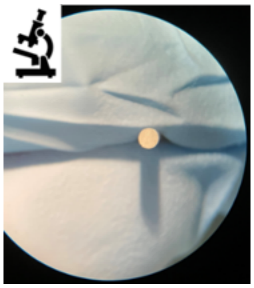


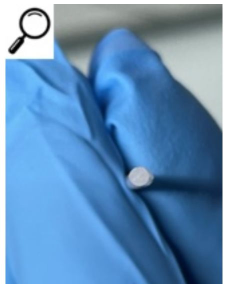
Figure 18: Filament thickness variation along its spooled length: case 1.75 mm ± 0.2 mm.

After a visual inspection (see Figure 19), the extruded re-PE filaments appeared homogenous in properties without any visible sign of granules of different densities. No burnt particles were detectable as well. The use of a common lab microscope with a magnification factor of 10 also allowed to inspect the filaments more in detail in search of encapsulated air bubbles, discoloration and contamination (dust and/or dirt). The device-aided examination did not highlight any signs of material degradation if not a slightly rough filament surface which is explainable with being the extrusion process very complex and challenging and being the material recycled from recycled hardware. Moreover, being the optical sensor embedded in the filament extruder machine only mono-dimensional, potential ovalization cannot be detected by the *DevoVision App*, therefore a dedicated test has been set-up to address this topic. By cutting the filaments in several randomic locations and observing at the microscope the cross section, no ovalization has been observed and the filament looked always very rounded.

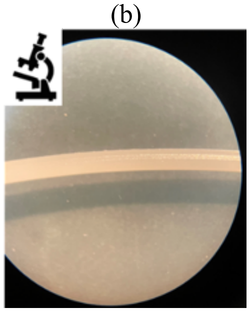
(a)



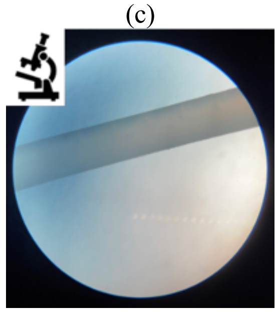
(b)



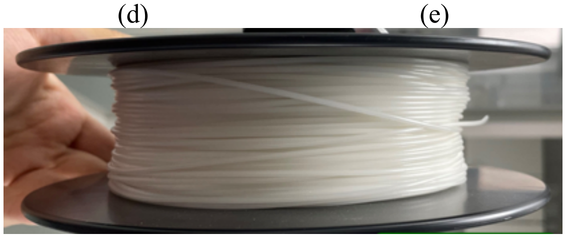
(c)



(d)



(e)



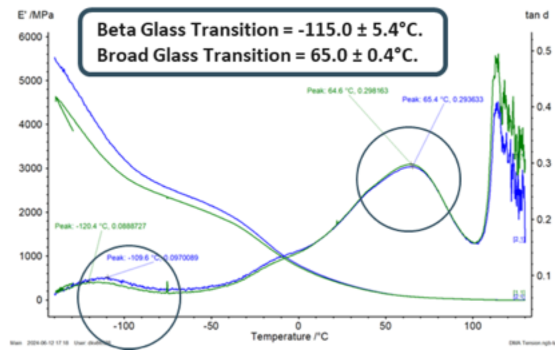
(f)

Figure 19: Recycled polyethylene filament inspection: (a) no burnt particles detected, (b) & (c) no ovalization spotted, (d) & (e) no air bubbles encapsuled, discoloration, contamination or degradation observed, (f) neat and tight filament spooled.

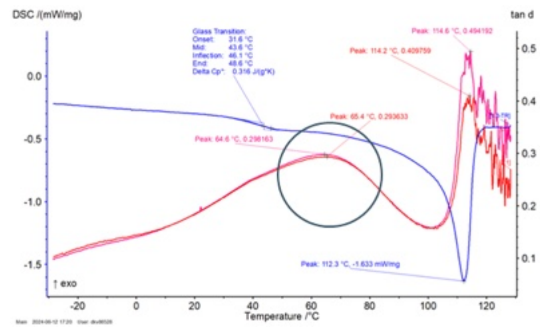
The various re-PE filaments were shipped to ESA laboratory at Harwell and tested with respect to:

- Glass transition temperature via dynamic mechanical analysis (DMA) and differential scanning calorimetry (DSC).;
- Degradation onset temperature via thermogravimetric analysis (TGA);
- Oxidation induction time via DSC.

Concerning the glass transition temperature, two DMA tests were run (see Figure 20 a) to confirm literature reference trends [3], [4] and [5]. These showed that if it is true that there is a small peak at -115.0°C which implies a β-transition, it is also visible a very broad peak which correlates with a transition shown in the DSC data (Figure 20 b). Broadness of the peak could be due to a large range of chain lengths in the sample, each becoming more mobile due to the increased free volume approaching the melt. It was therefore concluded that β-glass transition (T_β) occurred at -115.0°C, while a broad glass transition (T_g) happened at 65.0°C.



(a)



(b)

Figure 20: Recycled LDPE glass transition temperature via dynamic mechanical analysis (a) and differential scanning calorimetry (b).

Regarding the degradation onset temperature, this was evaluated via TGA taking the intersection between the tangent lines of maximum and minimum gradient in a specified range. The minimum of this range was found out to be 338.8°C, therefore this value has been taken as the start of the degradation (see Figure 21).

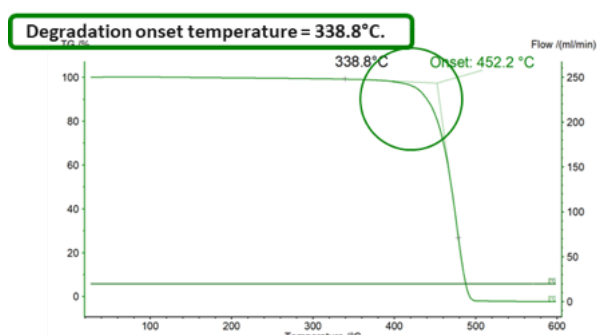
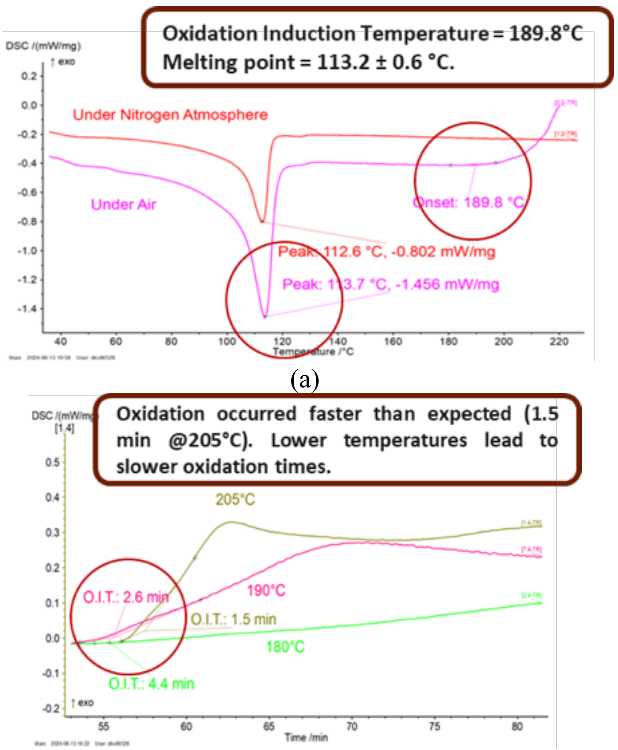


Figure 21: Recycled LDPE degradation onset temperature.

The oxidation induction time study was conducted, via DSC, firstly at 205°C since this was the temperature value at which the reference literature value was taken [7]. However, the oxidation turned to be almost instantaneous, so the oxidation induction temperature and melting temperature were evaluated. Melting temperature was found to be 113.7°C, while oxidation induction temperature was found to be 189.8°C (see Figure 22 a). The oxidation induction time test was therefore repeated at 180°C and 190°C such as to still comply with ISO 11357-6. First tests showed oxidation induction temperature as onset of exothermic peak whilst under air, while under nitrogen no peak was observed. Consequently, the oxidation induction time at 205°C was measured as 1.5 min, while at 180°C as 4.4 min, resulting in both cases in a largely lower value than expected from literature (see Figure 22 b). One reason could be the lack of antioxidants usually observed in recycled material.



(a)

(b)

Figure 22: Recycled LDPE oxidation induction temperature (a) and time (b).

The conclusions that can be drawn after the thermal test campaign at ESA Harwell lab were 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 met the success criteria with respect to the mean value;
- The evaluated degradation onset temperature was in line with the reference value [6] and respecting the prescribed success criteria. Therefore, this test was considered passed;
- The measured 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 recycled 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 perhaps appropriate to benchmark and judge the obtained results.

A recap of the results of the tests performed to thermally characterize the re-LDPE extruded filament, the selected literature reference values and the prescribed success criteria have been reported in Table 2.

Test	Reference Value	Success Criteria	Result	Pass/Fail
Glass transition temperature	From -130°C to -100°C According to [3], [4], [5].	±5%*	-115°C	Pass
Degradation onset temperature	325°C According to [6].	±5%*	338.8°C	Pass
Oxidation induction time	17.19 min @ 205°C According to [7].	±5%*	1.5 min	Fail

Table 2: Results of the re-PE filament thermal testing performed at ESA Harwell lab.

4.5 Implications for Space Scenario

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.

In the case of the recycling of LDPE, 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 will not be 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 having given prescribed mass and volume constraints.
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 disruptions 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 also be implemented.
Nonetheless, not only the design of the printer will be affected by the extraterrestrial environments, but also the feedstock and the operations. 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.

5. Metal Tool Casting *Demonstrator*

5.1 Initial Idea & Concept trade-offs

The idea for the final demonstrator is aluminium parts recycling. The material is available from hardware (defunct spacecraft, landers or rovers) remaining after various missions on Mars and, in particular, on the Moon. The potential to recycle aluminum parts shows a large variety of resulting hardware. Such options as habitat structures, full-sized demonstrator of rover spare parts was considered, as well as a casted multi-tool to assist astronauts in construction and repairs. The demonstrator selected for this particular activity and based on the available resources, is a downscaled prototype of a multi-tool that could be potentially used for the construction of the habitat, fastening or screwing bolts and nuts etc. as shown on the figure below.

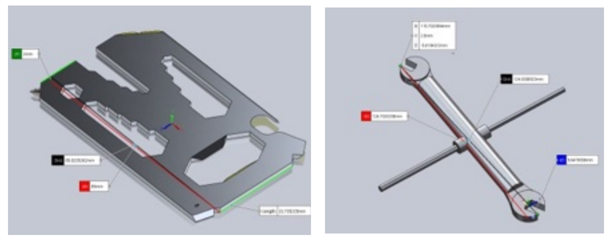


Figure 23: Considered prototypes for the multi-tool

5.2 Used material – Recycling Concept

Aluminum was selected as a primary material for recycling due to such reasons as: high availability on space vehicles (especially on the Moon), machinability, nominal compatibility with load bearing applications, relatively low melting point compared to steel or titanium and high recyclability rates (up to 90% in terrestrial applications).
Additionally, recycling of aluminum via casting is well known and established on Earth, which means that adoption of such method, is more feasible for extraterrestrial applications. Finally, since the aluminum is 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 that melted mass.
Based on the extensive research of past missions, it was decided the casted tool demonstrator to be produced out of recycled aluminum rods composed of alloy 7075.

5.3 Demonstrator Design

The finalised design is shown in 24 below.
The 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 to prevent accidental release.
The tool's design is envisioned with handles offering a secure grip, as well as a balanced mass distribution, which reduces the risk of strain or injury. Furthermore, the design aims for a compact footprint to be easily carried and stored within the limited space of the habitat.

In addition, the tool is designed with a focus on sustainability and product circularity, allowing re-recycling of the part once the fatigue limit has been reached.

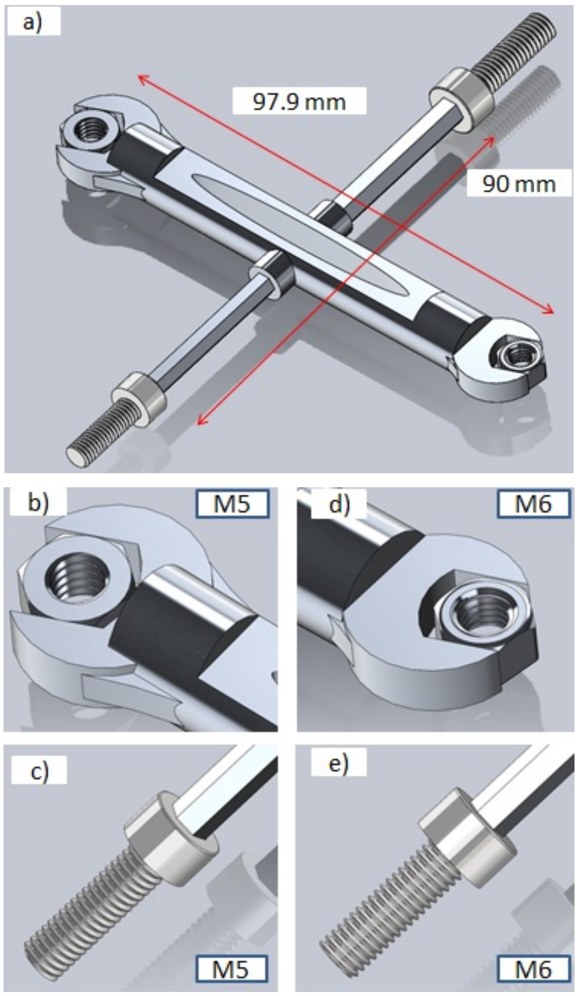


Figure 24: Multi-tool finalised design (a-e) to be casted with recycled aluminium

5.4 Recycling process

The multi-tool demonstrator is manufactured via sand casting method. Firstly, a pattern is created via 3D printing in the shape of the desired tool and then pressed within the sand. The pattern is then removed from the sand, leaving behind a cavity. These preparation steps are shown in Figure 25.

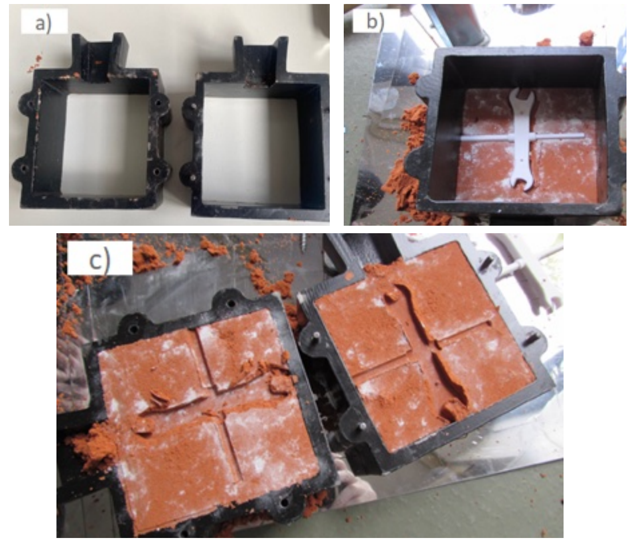


Figure 25: Preparation of the casting container (a-c)

The cavity is then filled with molten aluminium. Once the aluminium cools down and solidifies, the sand is removed to reveal the finished tool (see Figure 26).

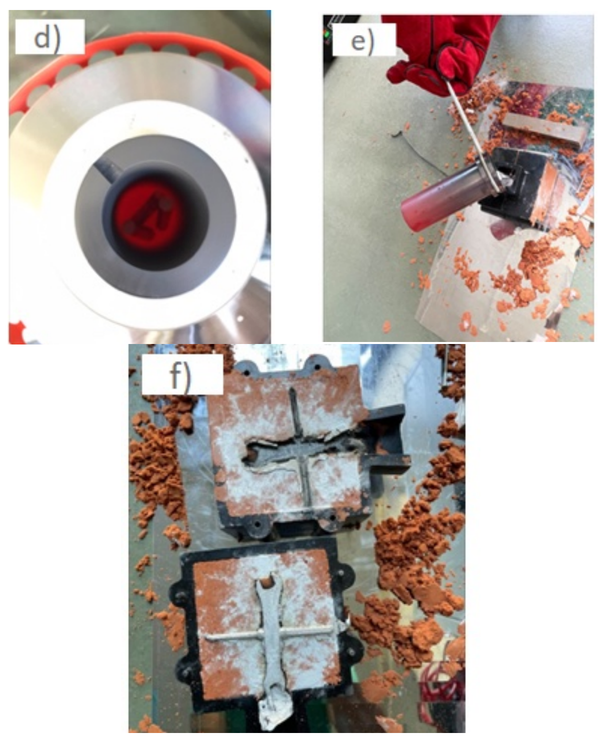


Figure 26: Melting of aluminium, pouring and extraction of the casted tool (d-f)

Throughout the casting process such parameters as the pouring temperature, pouring speed, moisture level in the sand, quality of the 3D printed insert, purity of the feedstock material etc. were assessed and partially controlled when possible.

As a result of manufacturing trials, six distinct specimens were manufactured with different degree of success. Amongst all samples, two parts with the best quality achieved were selected for subsequent testing. These samples are shown in Figure 27.

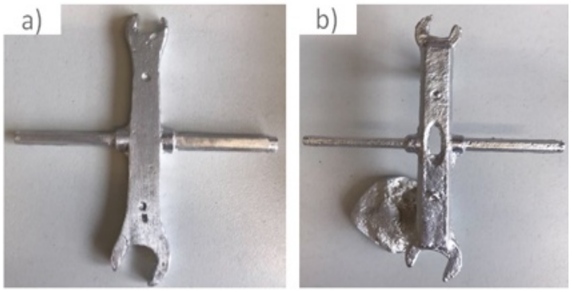


Figure 27: Manufactured specimen selected for testing: Trial 1 (a) and trial 2 (b)

One of the goals of this activity was to minimize post processing of the tools in order to avoid release of particles/dust that inevitably results from machining or other types of post processing. This goal was partially achieved with Trial 2 that required minimal post-processing relative to Trial 1. Namely, only residual melt left after the addition of extra air release openings had to be removed before the fit check for all the tools could be successfully performed with the corresponding fasteners.

5.5 *Demonstrator Testing Phase*

Following the manufacturing trials, casted specimens were inspected with respect to dimensional accuracy, surface roughness, functionality and other aspects. In total, two selected multi-tools were studied by various methods against 22 functional requirements.

Amongst different tests, the most interesting and insightful of the tools functionality is the cycling test where fasteners, depending on the tool, are repeatedly tightened and loosened to the specified torque.

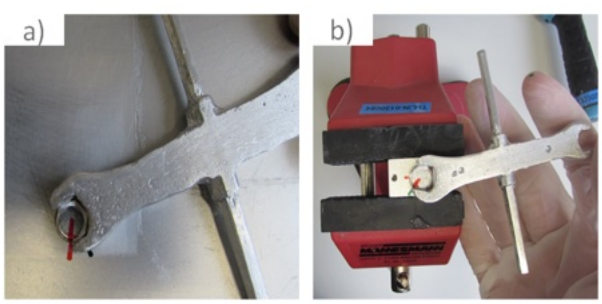


Figure 28: Cycling test of M5 wrench (Trial 1) 1 (a-b)

The cycling test was setup in a way displayed in Figure 28 above and executed repeatedly until the particular tool failed and the test could no longer be continued.

During this particular test, different tools showed distinct failure modes. As Figures 29 and 30 illustrate, the Allen keys of the component obtained during Trial 1 and 2 were stripped after a few cycles and could not be used anymore. Meanwhile, M6 wrench cracked at the base of one of the jaws as can be seen below. This happened due to a combination of increased tolerances and high torque values. M5 wrench in Trial 2 could not be used at all, as the gap between the wrench and the corresponding fastener was oversized.

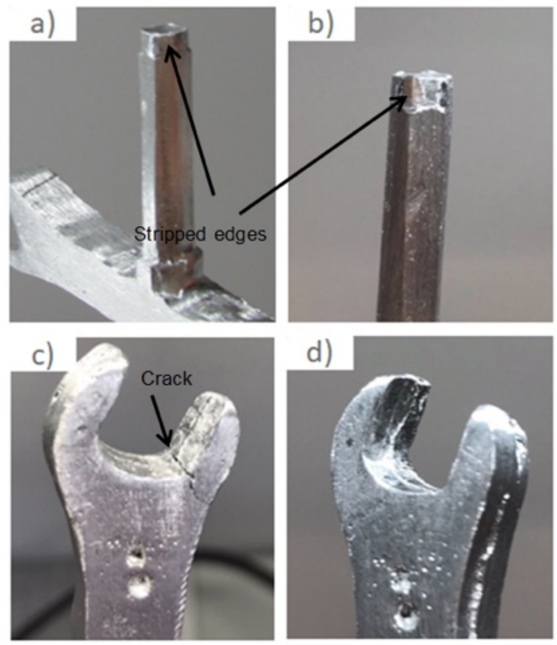


Figure 29: Damage on the Trial 1 specimen (a-d)

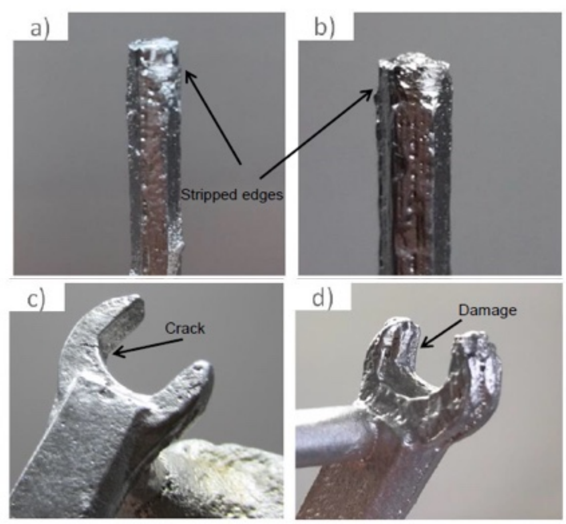


Figure 30: Damage on the Trial 2 specimen (a-d)

There is a number of factors that lead to premature failure of the tools. Firstly, the mechanical properties of aluminium 7075 are decreased significantly during recycling. Although this effect can be mitigated with

suitable pre and post-processing such as by using grain refiner, heat treatment and other techniques, these activities were beyond the scope of the present project.
Another outcome of the testing campaign is the identified density of the components that amounted to approximately 88% which is much lower than expected. Decreased density is expected given a basic sand-casting setup and limited resourced that did not allow a precise control over multiple variables that influence the quality of the manufactured components. Additionally, significant variations of porosity with respect to manufacturing parameters were also observed.

5.5 Implications for Space Scenario

Adoption of the manufacturing workflow described in the previous sections for use in extra-terrestrial environment presents a number of challenges.

Firstly, the hardware and consumables needed to cast the tool have to be brought, initially, from Earth, which will require a comprehensive mass and power budget development.

Secondly, environmental factors are one of the most critical considerations when designing a multi-tool for Moon and Mars scenarios is the environmental conditions. Both Moon and Mars have harsh environments that can affect the performance and functionality of the tool. Extreme temperatures, dust, and low gravity are the important factors that shall be taken into account. On the other hand, vacuum casting (on the Moon) is likely to prove beneficial for the casting quality as this environment allows avoiding oxidation, reducing the number of contaminants and yields a better final quality of the manufactured parts.

The outcomes of the testing campaign suggest that the use of casted components with the simplified manufacturing process shall be limited to non-load bearing applications for reasons beyond higher-than-expected porosity.

Indeed, aluminium 7075 is an inherently suboptimal alloy choice for casting as it is prone to embrittlement, cracking and requires post processing such as heat treatment in combination with aging. At the same time, utilization of the grain refiner is crucial for strength and hardness control of this material.

This approach shall be considered to improve mechanical properties of the casted parts, though this is only possible to a certain extent. Post-processing, though beneficial for mechanical properties of the manufactured component, comes at a cost of time and additional complexity which is an important consideration for extra-terrestrial applications. Finally, such an important aspect as the presence of contaminants on the feedstock coming from actual hardware is to be considered. Indeed, certain components made out of aluminium for example honeycomb panels often include epoxy resin. Similarly, structural components are usually coated and therefore these inclusions might complicate pre-processing of the material prior to manufacturing.

The outcome derived from this HARMONISE demonstrator study is the possibility of re-casting failed attempts, as well as re-casting a damage tool due to wear and fatigue failures. This ability to re-cast indicates the possibility of a fully circular process, relevant mainly for non-load bearing components, which is crucial for sustainable operations in space. The lessons learned from this demonstrator highlight the feasibility of creating a self-sustaining manufacturing cycle, reducing dependency on Earth-supplied materials over time, and enhancing the viability of long-term sustainable extra-terrestrial habitats.

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