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3D Printing Recyclable Spacewear on Mars: Equivalent System Mass tradeoff with traditional techniques

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Abstract

Spacewear is a crucial factor in human space exploration and strongly impacts present capabilities and future perspectives. Special attention will have to be addressed to these aspects when considering future human permanent settlements on other celestial bodies.

Present day manned programs, like the International Space Station (ISS), mainly rely on expendable clothes, heavily contributing to mass and volume budgets of the mission. Conventional washing can largely extend clothes life at the cost of high water consumption. Alternative sanitation techniques currently under investigation, on the other side, are showing higher level of complexity and clothing wearout.

In the present paper the possibility of 3D-printing recyclable spacewear on Mars surface to support crew life and activities is assessed.

Using 3D-printing unlocks new capabilities that are not provided by traditional technologies: to adapt garments to crew size and needs, to tune physical properties and to unlock unprecedented design opportunities. On top of this, the utilisation of recyclable materials extends clothes lifespan and introduces further advantages, like the opportunity to repair clothes or to transform useless garments into more needed ones. Such a system can also reveal highly compatible with future EVA suits design and manufacturing.

A preliminary tradeoff for a ten years mission between disposable clothing, traditional washing and drying and a 3D printing system is presented, based on the Equivalent System Mass concept. The model includes a recycling unit integrated to the 3D printer. Latest advancement in clothes 3D printing on Earth and on ISS were used as a reference. Results obtained show how 3D printing can reach a break-even point against disposable clothes 50% earlier than washing machines, even with higher materials degradation. This is mainly due to net mass and water savings, along with increased flexibility, autonomy and optimization of clothing management strategies. These findings demonstrate how 3D printing of recyclable spacewear can reveal a promising technique in enabling human Mars exploration and in advancing life support technology.

1. Introduction

Clothes are a fundamental piece of equipment in life support systems of space exploration human missions. Their functions range from simply ensuring a comfortable stay inside the habitable elements to helping astronauts in keeping tools and objects at hand when performing delicate tasks in microgravity conditions, either inside or outside the spacecrafts. Spacewear shall therefore be regarded as one of the multiple systems that enable human presence in space, and can thus be the objective of gradual improvements, especially in view of future, long duration crewed missions in distant locations of the Solar System, Moon and Mars being the most awaited ones. This first implies that clothing life cycle shall be designed to be compatible with the new circumstances. The current way of managing astronauts garments on the International Space Station (ISS) consists in shipping expendable clothes to the crew along with cargo resupplies. After utilisation, clothes are disposed and incinerated with garbage upon atmosphere re-entry. Although garments can be utilised for longer time on the ISS than on Earth due to the controlled environmental conditions, this translates in an annual waste of over 400 kg of dirty laundry for a crew of six [1]. Providing supplies to a crew on the Moon or even on Mars would surely be more difficult than it is now on the ISS. Extending clothes lifespan would therefore reveal extremely beneficial in reducing the mass to be shipped from Earth, as well as the amount of waste to be disposed. The present study provides a rapid overview of present-day solutions, highlighting potential advantages and open points, and subsequently introduces a new concept based on the 3D-Printing of clothes made of recyclable materials. This would allow to process these items at their end of life in order to recover the original constituting material, that in turn could be re-printed into a new generation of items, either identical to the old ones or different, restoring or changing their functionalities. This solution is then compared to those employing expendable clothes and washing machines on an equivalent system mass basis [2]. The idea of closed-loop 3D-printing (CL3DP) is already gaining increasing attention and is under study by several companies with proven expertise in the field [3, 4]. Implementing this capability would indeed, for instance, reduce the intrinsic risk in spares handling thanks to the general possibility that would be unlocked of producing what is needed when is needed, being able at the same time to modify its design easily. This, in turn, translates into mass and volume savings and increased safety, reliability and design possibilities. Such a promising technology, combined with the emerging advancements in 3D-printed clothes [5], gives birth to what is hereby presented.

2. Overview of current washing and sanitation processes

Washing and sanitation techniques of clothes in space have been extensively studied and several challenges and opportunities have been identified.

Currently by using disposable clothing, the Equivalent System Mass of clothing is 11% of the ESM of all life support for a Lunar manned mission of ten years [6]. In the next future various techniques will allow the astronauts to extend the usage of the garments, and so to reduce the mass penalty for long-duration missions. NASA has already developed antimicrobial clothes, which can be worn up to 14 days. Considering that the current change rate of underwear is 3-4 days, this solution should be selected for a medium-short duration mission as ISS ones. However, in the case of long-duration missions, antimicrobial clothes seem to be inadequate due to their low mass saving.

Another possible solution is sanitisation, which allows extending the clothing wear time without adding high mass, volume and power to the system. This technique is commonly used on Earth to clean sports gear, hospital and hotel facilities and, in details, it seeks to de-odor and eliminate microbes from clothing without the need for water. Different techniques are available, such as ozone or steam cleaning, which permit to clean and reuse the clothes for several days, but not for dozens or hundreds of times [6]. Ozonation, in particular, is one method of odor removal and sanitisation already in use on Earth. It is often used by nurseries for sanitation purposes and by dry cleaners for clothing which is too delicate for the chemicals used in traditional dry cleaning. For space applications, an ultraviolet (UV) generation is already studied to generate ozone thanks to its high affordability, safety and simplicity. In details, UV lamps convert the oxygen molecules into ozone, which decays into oxygen with a relatively short half-life, so as managing to remove the odor [7].

Another solution is steam sanitisation, which has low nominal temperature and process duration in comparison to the other techniques. It is non-toxic and penetrated easily fabrics, making it a good candidate for clothing sanitation. Finally, vacuum sanitisation, which is based on the fact that microbes cannot survive in vacuum, could be selected because of its simplicity and low power requirement [6].

Clothes can be cleaned and reused by using the washing machine, which allows the astronauts to wear the same garments hundreds of times. Compared to all the other techniques, the washing machine has the greatest Technology Readiness Level (TRL) even though it has not yet been developed for space applications. Moreover, the effectiveness of water washing is considered greater compared to sanitisation methods.

Despite the aforementioned advantages, the use of the washing machine is limited by water consumption. In fact, considering that clothing requirements drive requirements for other systems, including water, waste, habitation and air systems, laundry wastewater is a significant portion of the total wastewater loads. Whether the laundry is integrated into a single water recovery system or it features its recycling system, it will impact the waste system [8].

The following section will better describe how clothes 3D-Printing and recycling can be achieved.

3. Clothes 3D-printing

3D-printing has been widely leveraged by the contemporary fashion industry for its novelty and the design spaces it unveils. Today, it is an established technology regularly employed by industry leaders like Adidas and Northface.

The 3D manufacturing of entire garments is therefore emerging as the next evolution of this trend and the increasing interest it is currently attracting is sustained by rapid improvements in materials and processes. First pioneered by visionary artists and designers [5], the use of these techniques diffused widely recently, and various works and textile patterns have been realised and are already available [9]. Due to the different processes and materials involved, 3D-printed clothes usually are characterised by textile structures different than the traditional ones, in an effort to reproduce the same features of common textiles. As fashion firms and clothing manufacturers commit to a reduction of their environmental impact, the idea of closed-loop printing has been introduced into the next plans for a more sustainable future [10].

As for many innovations, numerous challenges still need to be overcome to unlock the full potential of this technology. The following section will briefly discuss the state of the art in the three main areas involved in this concept: materials, 3D-printing techniques and recycling processes.

3.1 Materials

Materials selection is the largest barrier to the development of such technology. Polymers shall be identified that are simultaneously suitable as clothing materials, workable into textiles through 3D-printing and recyclable with very few deterioration. The domain of candidate materials may change of course according to the available manufacturing and recycling processes.

Polyamides such as Nylon, as well as polyurethanes, polyolefins and polyesters are commonly used synthetic fibers. These polymers show different grades of printability and recyclability. Polyesters will be here regarded as a first choice for CL3DP for their large heritage in clothes manufacturing, optimal recyclability and good printability. Polyethylene terephthalate (PET), in particular, is commonly used in clothing manufacturing as Dacron and is already used to make fully recycled filaments for 3D printers [11].

Monomers design is however a developing frontier and has already yielded significant improvements in materials properties, including recyclability. Molecular engineering shall therefore be regarded as a strategic research area in enabling CL3DP.

3.2 Processes

Two 3D-printing processes have been mainly used up to now to print textiles: Selective Laser Sintering (SLS) and Fused Deposition Modelling (FDM). Melinkova et al. investigated several types of textile structures printed by FDM [12], demonstrating how this technique can produce flexible lace patterns and multilayered structures, also employing multiple materials using soft polylactic acid (PLA). Flexible structures have been produced also bu Grain et al [10] using recycled PET (rPET). Some of the problems related to FDM are the final surface roughness and the need for support structures. On the flipside, SLS may achieve higher detail and intricacy and produce higher quality, more textile-like structures, and has therefore represented the final choice for many high-end designers. Moreover, this technology is faster, more suitable for very frequent of continuous production, and requires less post-processing.

Finally, while FDM starts from a filament, SLS is a powder bed technology. This would therefore impact the design of the recycling unit the martian habitat shall be equipped with, as different outputs shall be produced according to the printing process.

Innovative processes like tomographic reconstruction [13] might as well reveal an enabling technology for this application thanks to its speed and quality levels, but still requires further advancements.

3.3 Recycling

Two recycling routes have been identified that could be suitable for this application: mechanical recycling and chemical recycling. In the first case, garments would be shredded into small flakes and than fed into an extruder where flakes would undergo melting, mixing and shaping in form of fibers. Recycled fibers would therefore be used by the 3D-printer to produce the second generation of clothes. The melting step would necessitate temperatures between 280-300°C in order for the PET to reach the desired viscosity for extrusion. This temperature is also far above the recommended temperatures for sterilisation, which would play a significant role in the cleaning process.

While this option is relatively simple and effective, it has drawbacks: in the first place, polymers are usually more or less severely affected in their properties upon mechanical processing, due to the reduction in molecular weight brought by the shredding and cutting activity. Furthermore, chemical degradation may occur because of the relatively high temperatures. This could either drastically reduce the number of possible re-prints, or induce the addition of increasingly high amounts of virgin polymer to the mixture to preserve the original properties.

The second strategy implies a depolymerisation process were garments, perhaps after a pelletization process, undergo chemical treatment in a reagents solution where PET molecules are broken down into their monomeric constituents. These would then be re-polymerized to re-fabricate the initial material, whose fibers would finally be spun and printed. This principle is applied in well proven and very promising technologies on Earth, where more than 90% of the polymer can be recovered with virgin-grade quality and properties in few hours [14]. For CL3DP, this would ensure hugely larger numbers of re-prints with far lower resupply needs. Depolymerization could be achieved through different chemical reactions. In particular, hydrolysis and glycolysis can drive the highest yields of monomers. However, these processes would require a more complex apparatus to be developed to implement all the required reaction, purification and recovery steps. In some cases, moreover, water might be needed, which would be an extremely rare and precious resources for an early, long human mission on Mars. Despite this, recent research has shown how microwave based processes might actually be less reagents-reliant and more effective that traditional chemical routes [15]. Microwave recycling appears so promising and feasible that a european startup called gr3n [16] has recently attracted vast funding and support by the European Union and the Coca-Cola company.

The goal would therefore be designing a compact, efficient chemical recycling unit suitable for a Mars habitat, whose output product could be directly fed into the 3D-printer. It shall be pointed out that the above dissertation only concerns PET. Other, recent evidences show how different molecular formulations can easily achieve repeated polymerization and depolymerization cycles without undergoing relevant losses [17], also without catalysts [18]. If these new materials will be proven suitable for clothes manufacturing, that would enhance the application potential of CL3DP.

4. Concepts description

As previously mentioned, three different concepts have been selected for a comparison. This section will better describe how the alternative clothing care solutions have been conceived.

4.1 Disposable clothing

Disposable clothes are the current standard in clothing care for human missions. When assumed as an option for a very long duration mission, mass and volume budgets largely increase promptly, as will be detailed in the next sections. However, this constitutes the less time-consuming and the most easily handled solution for the crew. In a Mars mission scenario, things would not work differently compared to the current practice on the ISS, with clothes being stored in dedicated bags and containers after use. The largest concern in this case would be represented by the need to find a suitable site where to accumulate and dispose the rapidly increasing amount of wastes, as well as a way to handle that at the end of the mission: leaving clothes in a sealed container on the surface or below could be an option, but would not completely eliminate the risk of biological contamination. On the extreme opposite, returning wastes with crew would add large, useless mass to the trip. The most cautious options might therefore lie in the use of an incinerator, but it has not been included in the present study to obtain more conservative equivalent system mass estimates.

4.2 Washing and drying

As shown in Sec. 2, combining a washer and dryer machine represents the most robust solution for clothing care. The most critical aspect is here represented perhaps by both the copious water demand of a washing machine and by its recovery process. As already said, water would be an extremely limited resource on Mars and wastewater recovery might be daunting. Despite this, it has been assumed that up to 98% of the wastewater can be recovered. For the present scenario, a combination of a washing and a drying machine has been selected with the specification reported in Table 1.

The washer mass includes an auxiliary unit for wastewater processing having a mass equal to 3,67% of the washer mass [6].

The crew time allocated for handling this system is 0,18 hr-CM/day. An additional amount of mass equal to 5% of the system mass has been took as annual mass of spare parts to be substituted. It was also assumed that this strategy enables 100 re-uses of the treated items [6].

4.3 Printing and recycling

In the last scenario, a special 3D printer is part of the habitat equipment. The machine would be able to print textiles and garments using special synthetic polymers suitable for clothes manufacturing. The design of each garment could be easily changed during the mission to adapt crew physical and functional needs. Moreover, damaged or torn items could be repaired or modified. What is very interesting is also the possibility of printing or fixing EVA suits parts [19]. At the end of usage, clothes would undergo the recycling process in a special recycling unit. It has been assumed that each recycling step causes a 5% loss in the processed mass. Due to the longer processing times for both printing and recycling, a higher crew time than in 4.2 has been accounted, equal to 0.4 hr-CM/day. It is now considered that maximum 15 re-prints are allowed before the deterioration of the materials becomes too severe to fabricate clothes. The specification of the system, modeled on a downscaled, commercially available industrial SLS printer [20], are reported in Table 1. Power consumption in 3D printers is actually much lower than washing machines, but the values have been assumed equal to conservatively compensate for the potential consumption of the recycling unit.

Table 1: Systems Specifications

	Washer/ Drier	**3D Printer/ Recycling**
Mass [kg]	81,87	200
Spare parts [kg/day]	0,0112	0,00822
Volume [m^3]	0,18	1
Power [kW]	1	1
Cooling [kW]	1	1
Capacity [kg/load]	5,3	0
Water use [kg/load]	51	0

As for the previous case, 5% of the system mass is considered to calculate the amount of additional spare parts to be supplied.

5. Methods

5.1 Equivalent System Mass

The Equivalent System Mass (ESM) concept has been used to perform a trade-off among the three concepts described above. This model allows to convert system or mission related parameters - such as power consumption and crew time, into mass values, in accordance to special conversion coefficients, also called *mass equivalency factors* [2]. Table 2 reports the coefficients applied for the present cases.

Table 2: Infrastructure cost factors

VolumeEq [kg/m3]	67
CoolingEq [kg/kW]	136
PowerEq [kg/kW]	65
CrewTime [kg/CM-hr]	0,6
Wastewater Processing Penalty [kg/(kg/d)]	12,9

This method allowed to model the evolution in time of the masses involved in each scenario, thus quantifying the impact each solution might have on the mission under this key aspect. A solution that is heavier in the first place, for instance, might reveal lighter than an alternative whose equivalent mass increases more rapidly over time.

5.2 Reference mission scenario

The human Mars mission here envisioned is a long duration mission for a crew of four members. The exact duration of the mission has not been fixed to assess the relationship between mission length and system performances and impact. A set of clothing items has been selected to form a baseline wardrobe. Each item is identified by its mass, volume and usage rate, i.e. the number of days the item can be worn before undergoing washing or recycling. This in turn defines a consumption rate for the clothes, which is a direct measure of the clothing mass demand of the crew. Table 3 collects these parameters for the selected wardrobe.

Table 3: Garments usage, mass and volume rates

Item	Usage rate [days]	Laundry load [kg/d]	Laundry volume [cm3/d]
Headband	30	0,0033	5
Wristband	30	0,0007	2
Running shorts	7	0,0157	75
Handkerchief	7	0,0014	17
Short shirt	15	0,0300	64
Long shirt	15	0,0367	123
Trousers	30	0,0200	39
Pants	30	0,0217	55
Polo Shirt	10	0,042	109
Boxer	2	0,0353	92
Towels	0,71	0,245	150
Socks	14	0,0057	18
TOTAL	**178**	**1,83***	**0,003***

*Results are multiplied by the number of crew members. The value for volume is expressed in m^3.

6. Results

The chart in Figure 1 shows the evolution in time of ESM for the three concepts. As can be noted, using disposable clothes is convenient for a short duration mission, but the related equivalent mass rapidly increases due to the absence of material recovery strategies. It takes around one year, indeed, for a system employing a washer and a dryer to become more convenient under these terms, while around 288 days are taken before the CL3DP alternative reaches a break even point (BEP).

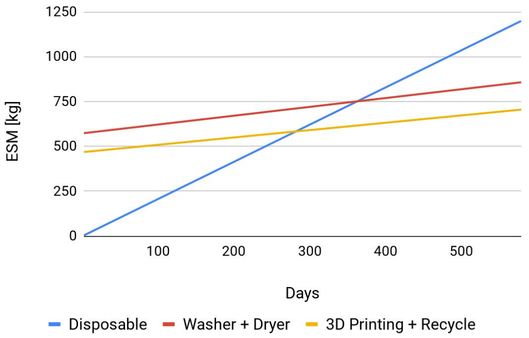

Figure 1: Equivalent System Mass versus Time for the three concepts.

What is interesting is that the two curves of the clothing care solutions are slightly diverging, suggesting that the printing option could be always more convenient. It must be noted that the slopes of the curves are determined by the time-dependent factors, which are: the daily mass and volumetric consumption rate of the garments - which are in turn determined by the amount of re-uses enabled by the selected technology -, crew time, wastewater recovery percentage, printing material losses and spare part supplies. This means that a change, or a combination of changes in these parameters due to technological breakthroughs or inaccuracies in the present assumptions could completely change the results. The most critical factors identified - i.e.

those aspects that would require more experimentation before providing a confidence level on the assumptions similar to that of the other parameters - are three: the material losses of the CL3DP process, which are dependent both on the printing and on the recycling step; the amount of viable recyclings, which are heavily influenced by the material design and by the recycling route; and the wastewater recovery capabilities, which are currently extremely poor in terrestrial applications.

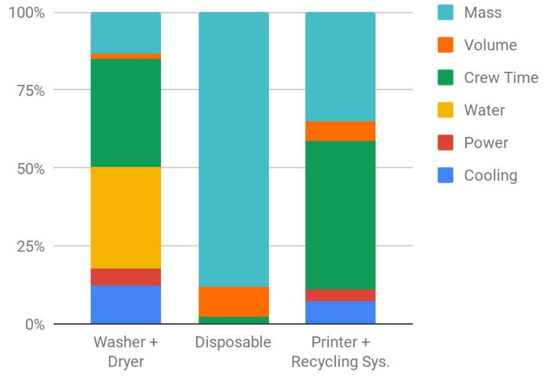

Figure 2: Contribution to the total ESM of each system parameter in each concept.

This factor, in particular, is also the most influential on the slope. The very optimistic assumption on the 98% recovery has been therefore made to counterbalance the error deriving from the other two hypotheses. Regarding the achievable amount of recylings, it can however be observed that the influence of this parameter on the performance of the CL3DP solution in terms of ESM after 10 years is not too heavy: Figure 3 shows how the decrease in total ESM for this option when a higher number of recyclings are allowed becomes less and less relevant as this number increase, slowly approaching an asymptote. This, in turn, indicate that satisfactory results can be obtained even with not too high materials recyclability.

Finally, Figure 2 displays how the ESM is distributed across the various contributing factors for the three case. As expected, mass is the largest penalty of a disposable clothing option, while water and crew time are the pain points in using a washing machine or a 3D printer, respectively.

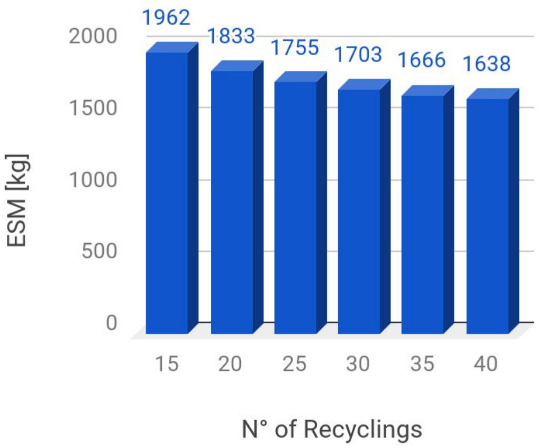

Figure 3: Evolution of total ESM for CL3DP with increase in materials recyclability.

7. Future work

With respect to the model here presented, future work includes a deeper survey of other polymers for such applications, a more detailed description of human operations during printing and recycling, and the comparison with other innovative clothes caring systems such as 3D print-knit machines [21]. But in order to fully understand the effective potential of CL3DP for clothes caring, extensive experimental studies need to be carried to systematically investigate PET recyclability and printed garments properties.

8. Conclusions

Future Mars crewed missions will require special clothes caring systems capable of ensuring crew comfort in the hostile conditions on the planet during the early months of human presence.

A trade-off analysis has been here presented, comparing three different clothes caring solutions: disposable clothes, washable clothes and recyclable printed clothes, suggesting how the latter might reveal competitive with the robust and traditional approach of washing and drying clothes. On the basis of these early conceptual findings, further insights on this topic shall therefore be pursued. Adopting CL3DP might unlock other beneficial capabilities such as repairability, transformability and tunability of garments, potentially extending to EVA suits in-situ manufacturing or supporting the fabrication of other spare parts.

Finally, fostering the development of clothes CL3DP not only aligns with the growth of a modern frontier in fashion industry, but more importantly tackles the larger and way more concerning problem of plastic pollution and life-cycle. Ultimately, this would lead to a greener planet, while we are exploring the red one.

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