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Research article

Sustainable space for a sustainable Earth? Circular economy insights from the space sector

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ABSTRACT

The drive toward an efficient use of finite resources and the emphasis on sustainability that characterises CE (Circular Economy) models is also shared by many space projects, as summarised decades ago with the catchphrase 'Spaceship Earth'. Carrying out a comparison of the applications of circular economy models and the space industry's best practice, the article argues that the space sector represents a sort of 'native environment' for circular economy and shows how to apply more efficiently those same CE principles down to Earth. Adopting a case-study approach and using evidence from a close-loop system originally conceived for life in a space environment (ESA-MELiSSA for water treatment), this study demonstrates how the space sector is not only fully 'CE compliant' but also provides a comprehensive framework to further extend the remit of the CE philosophy. If the world economy is indeed at the onset of a new industrial revolution (the so-called Industry 4.0), the space sector can offer insights on how to this revolution can be made both inclusive and sustainable.

1. Introduction and plan of the article

The concept of 'Spaceship Earth' –a shared environment, where available resources are finite and that are finite and fragile– is old, mentioned as it was by the economist Henry George back in 1879. It was adopted, over the decades, by others, especially in the political science discourse, George Orwell, the US Ambassador Adlai Stevenson, Barbara Ward, and Kenneth Boulding among them. A well-known definition is the one coming from Fuller's 'Operating Manual For Spaceship Earth':

> *"We can make all of humanity successful through science's world-engulfing industrial evolution provided that we are not so foolish as to continue to exhaust in a split second of astronomical history the orderly energy savings of billions of years' energy conservation aboard our Spaceship Earth. These energy savings have been put into our Spaceship's life-regeneration-guaranteeing bank account for use only in self-starter functions,"* (Fuller, 1963, online).

From the 1960s, the space sector has substantially changed. The last decade has witnessed a steady, rising contribution of the space industry to the overall economy, in sheer value first: in 2019, according to the Space Foundation's annual report, the sector reached a global US$ 423.8 billion (from US$ 323 billion in 2015; The Space Foundation, 2020), due to the growing involvement of the private sector in a previously government-dominated industry. The forecasts return an even stronger growth over the following years, up to US$ 720 billion by 2030 (according to the Space Foundation's estimates; Paladini, 2019). In the sector, the satellite segment represents the lion's share, accounting for about 75% of worldwide 2019 revenue (SIA, 2020).

According to a well-known OECD's definition, the space economy '*comprises a long value-added chain, starting with research and development actors and manufacturers of space hardware (e.g. launch vehicles, satellites, ground stations) and ending with the providers of space-enabled products [...] and services [...] to final users*" (OECD, 2007, online).

While still applicable to some extent, this definition looks both outdated and unable to capture the peculiarity of the sector, characterised by "high risk, high cost, and long payback periods" (Vedda, 2009: 99), where long-lead time and the medium-long terms of missions (Norberg, 2013; Neal et al., 2011), required a long-term financial support traditionally provided by the government. This has made the sector's depending on politically motived choices and geopolitical-oriented decisions (Paladini, 2019). Only recently the commercial satellite companies have started moving beyond from this approach (Fenema, 1999; Gurtuna 2013).

Its impressive growth and evolution notwithstanding, the century-old 'Spaceship Earth' still remains as a core concept in the space sector's philosophy. The thinking of a closed, finite system where nothing new

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is created but all has to be reused and transformed goes to the very roots of it. Which, on the other hand, explains well what is happening today, with the colliding paths of the space sector and the world industry's expanding adoption of circular economy models, in what looks more like a systemic interconnection than a series of coincidences.

Compared to 'Spaceship Earth', the circular economy (CE) is a more recent concept, at least as it stands today, but one rapidly gaining traction. Interestingly for this article's purposes, Boulding's definition of Earth as a closed economy (Boulding, 1966) is cited as one of the first working definitions of CE (Allwood, 2014), even though the expression 'circular economy' was not used by Boulding himself. According to the Ellen MacArthur Foundation (2014) "*circular economy aims to redefine growth, focusing on positive society-wide benefits (…) by gradually decoupling economic activity from the consumption of finite resources, and designing waste out of the system,*" (Ellen McArthur Foundation, 2014, online).

Circular Economy matters. The World Economic Forum (2014) outlined its economic gains in between US$ 340 to 380 billion of annual material cost savings during the transition phase in which economies move from the current linear to the circular model. The EU alone could save in between US$ 520 to 630 billion per year in material costs (Ellen McArthur Foundation, 2013). Automotive, communication, industrial machinery, furniture, and health-care equipment would be the biggest beneficiary, while fast-moving consumer goods (FCMG) producers could reduce material input cost by 20% –a yearly US$ 700 billion cost reduction– controlling both price volatility and supply risk (EC, 2019). Through CE, advanced economies can achieve resilient growth by reducing dependency on resource markets and exposure to resource price volatility. CE-informed business models would also bring significant benefits to entrepreneurship and job creation. Since its formulation, the CE has seen its applications progressively widening from waste management and engineering processes to a variety of fields. Its economic impact is huge and constantly growing, and so is its influence.

Nothing makes these 'colliding paths' of the CE and space sector more likely to happen than the transformations brought over by the so-called Industry 4.0, both at a conceptual level (Sun et al., 2012; Baldwin, 2019; Schwab, 2015; Kagerman et al., 2011; Lasi et al., 2014; Mangla et al., 2020) and in its widespread application (Fettermann et al., 2018), with its 'nine pillars' (Cristians and Methven, 2017; Vaidya et al., 2018; Forcina and Falcone, 2021) characterised by artificial intelligence, big data, IoT, smart manufacturing, and innovation technology on a planetary scale. In both cases, policy-makers have already made the connection, including on one side CE as one of cornerstones in their forward-looking, resource-efficient industrial policy (EC, 2014; 2015; 2019) and, on the other hand, with a brand-new formulation of space in a I4.0 perspective, in the ESA-led strategy known as *Space 4.0* (ESA/EC, 2016) in the more general EU planning for space (EC, 2013; 2016).

The overall aim, and the original contribution, of this article is to explore the modalities, and the far-reaching implications, of the CE and space sector's trajectories, both *per se* and under the Industry 4.0 overarching umbrella, together with highlighting the potential of the space sector as a 'beacon' of CE philosophy and offering insights for its more widespread application to a variety of fields.

Until recently, the two paths have been running parallel but seldom met. The above-mentioned applications of CE in the space sector have taken place more due to the unique technological challenges of the medium than for the conscious adoption of conceptual CE models, even though this has just begun to change. But additional debate is certainly needed to make the whole process more systemic and effective. What matters, and should drive the conceptual effort, is that best practice developed in space initiatives in terms of circularity and sustainability are particularly valuable on the ground, especially given the emphasis Industry 4.0 puts on the responsible use of finite resources and sustainable processes. In its effort to foster the conceptual debate, this article, building on the existing literature and examining ongoing projects, will first show (1) what the space sector can offer as best practice to the overall industry in terms of CE approach; (2) why it is the space sector so uniquely suited for it; (3) how these insights can be usefully adopted by different industries on the ground under the overarching umbrella of Industry 4.0 revolution.

With these guiding research questions, the article will be structured as follows.

Section 2 *Material and Methods. Circular Economy meets the Space Sector*—is divided in three subsections. The first carries out a brief review of how CE principles, from their original conception, have been translated and adapted to the various manufacturing sectors. The second illustrates instead how space is a sector with specific rules that makes it especially suitable for CE applications both in principle and in practice. The last subsection, 3.3, deals instead with the adoption of a case-study approach as the methodology of choice for addressing RQ 1 and 2. It discusses an example of the way the space sector has adopted CE solutions *ante-litteram*, so to speak, developing a system of perfect circularity to solve the problem of water purification: the decade-long initiative MELiSSA, led by ESA (European Space Agency).

Section 3 *Results*– goes into details, with a conceptual discussion of the philosophy behind MELiSSA. It breaks down MELiSSA's close-loop functioning by using TRIZ-problem solving approach as an interpretative tool, showing how its cyclic system developed in a mechanistic way is perfectly 'CE compliant'.

Section 4 *Discussions*—takes the analysis back to a higher-level view and discusses the element offered for consideration. The first subsection 4.1, illustrates the practical uses that MELiSSA, from its original conception for in-space use (ISS at present, the Moon and Mars missions in future), have already been employed for on Earth in a few sectors, especially the ones, like NGOs, education, and SMEs, who more than others face constraints to embed CE in their operations. ESA's declared and unwavering commitment to SDGs reinforces the support to a wide MELiSSA adoption in a clearly acknowledged CE approach. Subsection 4.2 intends to offer insights on how to bridge the two parallel paths of space sector and CE under the Industry 4.0 framework. The space sector's evolution (now in its Cycle 5) takes it even closer to CE, in what looks now a two-way exchange, with reusability and addictive manufacturing increasingly embedded in the design phase.

Section 5 *Conclusions*– summarises the main findings and offering recommendations and directions for future research.

2. Material and methods. Circular economy meets the space sector

2.1. Circular economy

Considering the current hype, it might sound surprising how recent the CE's present formulation can be. While its origins can be tracked back to the 1970s and to Braungart's (McDonough and Braungart, 2002) 'Cradle to Cradle' formulation (Ellen McArthur Foundation, 2020), the concept has gained traction only recently in its paradigm-shift relevance, with most of the research and modelling on CE undertaken after 2010 (Geissdoerfer et al., 2017; Hopkinson et al., 2018).

The mentioned Ellen McArthur Foundation's definition is comparatively recent (2014). Kirchherr et al. (2017) demonstrated that, on sample gathered in an extensive systematic review, 73% of the definitions were from the past five years (therefore 2012). On the other hand, the 4 R formulations –REDUCE-REUSE-RECYCLE-RECOVER– proved to be consistently present all along, albeit in different combinations (Allwood et al., 2011; Gladek, 2017), being also embedded in the official EU definition (EC, 2019). Others have adopted instead a 5 R (Pan et al., 2015) and 6 R approach (Jawahir and Bradley, 2016) –REDESIGN-REDUCE-REUSE, RECYCLE-[REMANUFACTURE]-REPAIR. Unsurprisingly, industrial processes and waste management are the fields where CE principles were first defined; yet, there is already abundant literature about the application of CE principles beyond them (Urbinati et al., 2017; Yin et al., 2020; Kama, 2015; Gregson and Crang, 2015), drawing from existing case studies and doctrinal elaborations (Murray et al., 2017; Chertow and Ehrenfeld, 2012; Mattila et al., 2012).

A cursory review from various industries demonstrates that numerous efforts were made to reduce, recycle, and reuse materials (particularly critical materials), even before the conscious application of the CE principles. The new philosophy has, however, turned them into more coordinated and consistent measures. The CE research proposed additive manufacturing for sustainability (Muthu and Savalani, 2016; Sanchez et al., 2020) in many sectors, together with solutions aimed at reducing material losses (*e.g.,* milling; Mani et al., 2014). Businesses generally rely on third-party waste management contractors to discard equipment; therefore, take-back systems for reuse and remanufacturing of components are often non-existent, extensive reclaiming and scrapping operations put in place in many industries nonetheless. The cost of repair and remanufacturing makes these economically unviable (Matsumoto et al., 2016). Milios et al. (2019) identified that labour tax reduction is required to suppress the repair and remanufacturing costs, whereas the willingness to repair increases with the advent of additive manufacturing (Despeisse et al., 2017).

The automotive industry was one of the pioneers in the application of CE practice (Saidani et al., 2018). Four critical and transformative issues determined the changed in industry's business model, *i.e*., (1) avoiding shortages and securing supply of raw materials (Sievers and Tercero, 2012); (2) the geopolitical issues around raw materials and resource efficiency (EC, 2015); (3) scaling up the self-driving artificially intelligent vehicles; and (4) the zero-emission target to reduce environmental impact. Reuse and recycling of automotive components proved economically and environmentally beneficial (Ellen Macarthur Foundation, 2014, 2020; Ghisellini et al., 2016). Saidani et al. (2018) predict that emerging business models will enable usage-based, CE-compliant revenue opportunities. In this sense, all economic efficiency increases are subject to the rebound effects' risk (Korhonen et al., 2018). Production costs decrease with production efficiency gains, resulting in lower prices and higher consumption and in-turn more environmental degradation. The "Jevon's paradox" (Alcott, 2005) and the "boomerang effect" (Mayer et al., 2005) weight these rebound effects against efficiency gains.

It is worth noting that, if a CE-informed, closed-loop system is already underway in industries with high-value assets and equipment, this is not necessarily the case for other actors, such as SMEs. One fitting example comes from the textile and clothing industry, whose challenges to become eco-friendly are linked, and limited, by their low bargain power (Hvass and Pedersen, 2019; Saha et al., 2020). Large businesses within these industries can, and often do, actively promote circular practice in their supply chain consisting of numerous SMEs. However, such promotion generally happens in private regulation or quality control measures that SMEs must adhere to supply to large business, which explains the large variety in its implementation.

One of the common themes that emerged from the review carried out so far across all industries is the attempt at embedding circularity in the design phase (Lieder and Rashid, 2016). Circular design strategies improve the availability of critical materials inputs (Peck et al., 2015; Korhonen et al., 2018) and reduce waste (Bakker et al., 2014). Allwood et al. (2011) recommended design strategies with lower processing, longer-lasting products, modularisation and remanufacturing, component reuse, and designing products with less material.

2.1. A sector in transformation: the space industry

As mentioned in Section 1, the traditional approach to space industry wants the sectors divided into two segments: one upstream, which includes launch systems, ground operations and satellite manufacturers and the other downstream, related to all providers of satellite communication services to the consumers (OECD, 2007). This distinction, which came into existence in the 1990s during the marked increase in the commercialisation of satellite services around the world, is still popular, irrespective of the fact that the sector itself has moved on, both for turnover and as a paradigm jump. The space industry went through a cycle development, each of which presenting widely different characters and actors (OECD, 2016, 2019).(see Table 1)

Cycle 4 –characterised by both the popularisation and the globalisation of space and that has seen the emergence of a different kind of downstream activities, mainly handled by private companies and supported by the ongoing digital revolution—has just been completed. The new Cycle 5 will be determined by an ever-increasing availability of data, and, among other things, by the widespread adoption of CE principles as presented above. This is where the peculiarity of the sector comes into play.

A starting point for analysis comes from the comparison with aviation, probably the closest sector to the space industry by nature and complexity. A series of efforts have been recently done to 'decarbonise' the sector (Sharmina et al., 2020; Bows-Larkin, 2015) to enhance its drive toward sustainability. More challenges loom ahead: the aircraft's service-life decreased to about 15 years from the typical 20–30 years due to newer efficient and safer models being introduced at regular intervals, and the world now faces the end-of-life management of approximately 8500–12,500 planes within the next 20 years. Regulatory issues, the volume of treated materials, and rising complexity in the fleet recycling process add to these hurdles (Jensen and Remmen, 2017).

Airbus and Boeing adopted the 'Process for Advanced Management of End-of-Life of Aircraft (PAMELA) (Towle et al., 2004) and Aircraft Fleet Recycling Association as end-of-life strategies. PAMELA demonstrated that it was possible to recycle up to 85% of an aircraft's components and set the industry standards. The initiative showed that mapping in the design phase would facilitate high-value recycling while complexity in material composition and assembly reduces recycling rates. Boing-led AFRA developed a series of guidelines on best management practices (BMP) and recently began to take on board CE models (AFRA, 2020).

Still, what makes the space sector somehow unique is its approach (*i.e*., the 'Spaceship Earth' philosophy), different from the industrial "make-use-dispose" and modelled instead like CES –Closed Ecological Systems (Tamponnet and Savage, 1994), which recover-recycle-reuse all components. As such, it offers plenty of examples of applications of CE models before those models were defined and applied to industry. As the environment –outer space—is unsuitable to life, every activity happens by default in a closed system, where everything has to be recycled, reused, transformed in a way or another.

3.3. A case study

To illustrate the concept of space as a sort of native environment for CE and explore the wide range of possible applications, this article made use of a case-study approach (Ridder, 2017; Seawright and Gerring, 2014; Yin, 2013). The case selected here is ESA-MELiSSA, probably one of the most popular projects, which, incidentally, is also one where the application *ante litteram* of CE principles is particularly evident.

The MELiSSA acronym stands for Micro-Ecological Life Support System Alternative, and it is an ESA (European Space Agency)-led, project of regenerative, advanced life support (ALS). Originally the brainchild of a French engineer, Claude Chipaux from Matra Space Branch (then Airbus) in the late-1980s, and building on NASA –Controlled Ecological Life Support System (CELLS)—and Soviet –the experimental facility Bios3—research in the field (Walker and Granjou, 2017), it soon became one of ESA's flagship initiatives, still ongoing after three decades.

After the 1993 original MELiSSA's Memorandum of Understanding, things rapidly evolved, up to today's 14 core partners and about 40 supporting parties under ESA coordination (ESA, 2020a; Lasseur et al., 2000). Since 2009, the core of its experimental activity has been tested at the MELiSSA Pilot Plant in Spain first and then applied elsewhere in the world. A private body, called The MELiSSA Foundationn and created by the MELiSSA consortium, provides funding to MELiSSA PhD students and organises communication and support events.

The idea behind MELISSA is deceptively simple: scaling down the Earth's ecosystem into sizeable dimensions for space travel, using a closed life-support system which recycles every waste product into water and goods and addressing almost intractable logistical problems for future living environment in outer space (Wheeler et al., 1992). The inspiration for MELiSSA ecosystem habitat is a terrestrial lake, where the metabolism process of plants and algae (biological photosynthesis) transforms wastage into food, air revitalisation, and water purification through a set of different processes (filtration, wet oxidation, mechanical grinding, bioreactors, etc.) with 100% conversion rate. In short, the perfect self-sustained ecosystem without any external resupply.

While the ultimate aim –long-term space manned missions—looks still far away, MELiSSA has already delivered, both in space and on the Earth. In 2009, when the first fully functional MELiSSA Pilot Plant (MPP; Godia et al., 2004) was inaugurated at the Departament d'Enginyeria Química at the Universitat Autònoma de Barcelona, the project had already produced 220 major scientific publications and various technological applications. Some of them were meant for space use, as the follow-up of ESA's ATV –Automated Transfer Vehicle–bio contamination monitoring for the ISS (Eurekaalert, 2009). Others were terrestrial applications, which have kept exponentially growing in importance and relevance over the decades, demonstrating how CE principles are naturally embedded in the space sector and proving accessible to both small and large organisations.

Table 1
Cycles of space development.

CYCLES	DATES	Description
Pre-space age –1	1926·1942	First rockets
Pre-space age 0	1943–1957	Military race for ICBMs; first satellites (Sputnik)
Cycle 1	1958–1972	Space race (from Sputnik to the end of the Apollo era); spy satellites; first humans in space
Cycle 2	1973–1986	First spacestations (Skyl ab, Salyut); shuttles; GPS; new space (private) actors
Cycle 3	1987–2002	Second generation of space stations (Mir, ISS); satellites; space technology transfers
Cycle 4	2003–2018	Popularisation of space application; cubes sat; globalisation of space activities (GVCs)
Cycle 5	2018–2033	Growing uses of satellite infrastructure outputs; inmass-market products; global monitoring; new space activities; robotics missions

(Source: Adapted from OECD, 2016).

While the follow-up on MELiSSA's project has made explicit references to CE principles –as shown in the next section– the original, decade-old conception did not take its lead from that. MELiSSA started with a closed-loop, 5-compartment design (C1–C5), which evolved across iterations and proofs of concepts (Mergeay et al., 1988; Lasseur and Schmitt, 2000). It took several individual studies and projects over years before reaching an individual level of maturity to be able to cointegrate all of the subsystems into the MMP of Barcelona. "*MPP integration was modelled via a mechanistic approach, meaning that each simulation result may lead to improvements in the models and greater knowledge (technology and performances) of the system*," (Poughon et al., 2009: 1402). Otherwise said, it was an engineering problem first and foremost, not an economic, let alone a management one.

Which it does not mean that MELISSA philosophy cannot be studied and applied into a different setting, not for just it concerns practical applications of the single designs (Table 2 is not exhaustive, but represents good sample) but on a more general, philosophical approach. There are lessons that can be learnt from MELISSA's problem solving approach, which, while independent from CE principles, feed naturally and complement them.

Table 2
--MELiSSA'S terrestrial applications.

Project/Product	Sector	Details
Water treatment	environment	1.8 million cubic metres of water treated every day with MELiSSA based technology in Europe
Spin-off companies	various	IPStar, 2005, dealing with technology transfer of MELiSSA related terrestrial applications
BIOSTYR	environment	https://www.veoliawatertech.com/
VILLA TROGLODYTE	environment	https://jbpastoretfils.mc/?p = 28,912&lang = en
FAIRMONT MONTE CARLO	environment	https://www.firmus.net/en/fgwrs-process-demonstrator-fairmont-monte-carlo/
UNIVERSITY OF KENITRA	environment	http://youbenefit.spaceflight.esa.int/treatment-of-highly-polluted-ground-water-in-morocco/
CONCORDIA BASE	environment	https://www.firmus.net/en/grey-water-treatment/; https://www.melissafoundation.org/page/concordia-antarctica-station
THE UNIVERSITY OF MÁLAGA	environment	https://www.semillasanitationhubs.com/
SEMILLA SANITATION HUBS	environment	https://www.semilla.io/activities/semilla-ce-hub-malaga
FORT DU PETIT LANGOUSTIER	environment	https://www.melissafoundation.org/page/environment
FREIXENET/DAMN BIER	agrifood	https://www.melissafoundation.org/page/agrofood
INSPIRATION	agrifood	https://www.esa.int/ESA_Multimedia/Images/2016/09/Spirulina_in_Congo
Sparkling Wine	agrifood	MELiSSA related biomass sensor
LA TRAPPE ABBEY BREWERY	agrifood	https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Water_recycling_for_monks_and_astronauts_awarded_Dutch_innovation_prize
EZCOL -private company	life-science	https://www.ezcol.com/
ALGOSOLIS	life-science	http://algosolis.com/en/
BIOFACADES/PHOTOBIOREACTOR	life-science	https://www.melissafoundation.org/page/photobioreactor
PCU	life-science	https://www.melissafoundation.org/page/higher-plant-characterization

(source: Authors' elaboration on Melissa Foundation; various company sources, 2020).

The following section, which offers an interpretative framework of MELISSA approach from a systemic point of view, attempts to offer insights in this sense, and together take away points in a CE perspective.

3. Results. MELISSA as a theoretical model

In order to answer the question raised above, it is important to start from MELISSA's famous diagram (ESA's original design as reproduced from Poughon et al., 2009) and breaking it down into its theoretical components.

If this engineering problem is translated into systemic terms, it is more apparent that the initial problem for the ecosystem MELISSA scientist had to address was the gradual loss of O2, H2O, and foods through several consumption cycles due to inherent system efficiencies, as well as the generation of waste that needed to be disposed of. The outcome of this consumption was a net loss of resources. The system needed to increase the benefits necessary for consumption whilst minimising the harmful effects associated with human waste. The ideal system would gradually separate and extract elements from food and fluid consumption waste that could be transformed into resources thanks to specialised bacteria cultured in an environment accelerating their biochemical cycles (Hendrickx et al., 2006), using for example, heat, light, CO2 or H2O.

To show how MELiSSA is fully '5 R compliant' in a CE perspective, it is necessary to break it down in stages. And, to this purpose, the closed-loop, five-compartment design MELISSA pioneered in its MMP is more clearly analysed and translated into systemic terms by adopting a TRIZ-led approach. TRIZ acronym stands in Russian for the Theory of Inventive Problem Solving (Teoriya Resheniya Izobretatelskikh Zadatch) and, as such, it was developed by Genrich Altschuller and his colleagues in 1946 (Altshuller, 1999). Working for the Inventions Inspection department, Altschuller identified that inventions and patents, when considered from a higher perspective, had in common certain innovation patterns. TRIZ came to a wider attention at the end of the Soviet era and was popularised in the UK by Karen Gadd (2011). TRIZ has been used by many blue chip organisations such as the Rolls-Royce Group or BAE systems to enhance engineers' creativity and problem-solving skills. TRIZ advocates that each problem can be abstracted into a higher-level conceptual problem. Once the meta-problem is solved, the solution can then be applied back to the specific problem.

Before looking at MELISSA under TRIZ's framework, it is the case to note that the technical solution brought forward by MELISSA doesn't seem to have been generated by a TRIZ approach, even though, when examining the relationship resources/constraints/solutions devised, it is difficult not to notice TRIZ's principles at work. A possible explanation may come from the fact that, during the three decades of MELiSSA project, two of them saw the involvement of two Russian institutes –IBP Krasnoyarsk and IBMP, Moscow (Lasseur and Vyacheslav, 2018); it is not farfetched to imagine that the conceptual design had been influenced by the Russian approach. What has instead directly been applied it is a modelling tool called PhiSystem, an original simulation modelling programme based on open source, standard MBSE descriptive language SysML (Systems Modeling Language). PhiSystem was devised by team MELISSA and the French Sherpa Engineering, one of MELiSSA partners, and it achieved the remarkable result of modelling an extreme complex closed-loop system in its different iterations, each one learning from its predecessors (Sherpa, 2020) (see Fig. 1).

As the aim of this study is to go at the core of MELISSA philosophy, shedding as much as possible its mechanistic complexity, a choice has been made in this article to describe the system adopting an original, mixed TRIZ-CE perspective instead of the far more articulated and engineered-minded PhySystem. The following diagrams attempt therefore to illustrate how a near perfect circular system was invented by ESA to minimise the harmful effects of waste in the space station whilst maximising the benefits of transforming it into a resource. That is, transitioning from what was designed to be a cyclic process to a circular system, which can be transposed and adopted in different settings. The matrix in Chart 2 illustrates how the ideal outcome is delivered by the ideal solution.

The system is the assembly of sub-systems delivering higher-level benefits. Before any changes are made to the system, the harmful effects of the system are illustrated in red. The ideal system then addresses

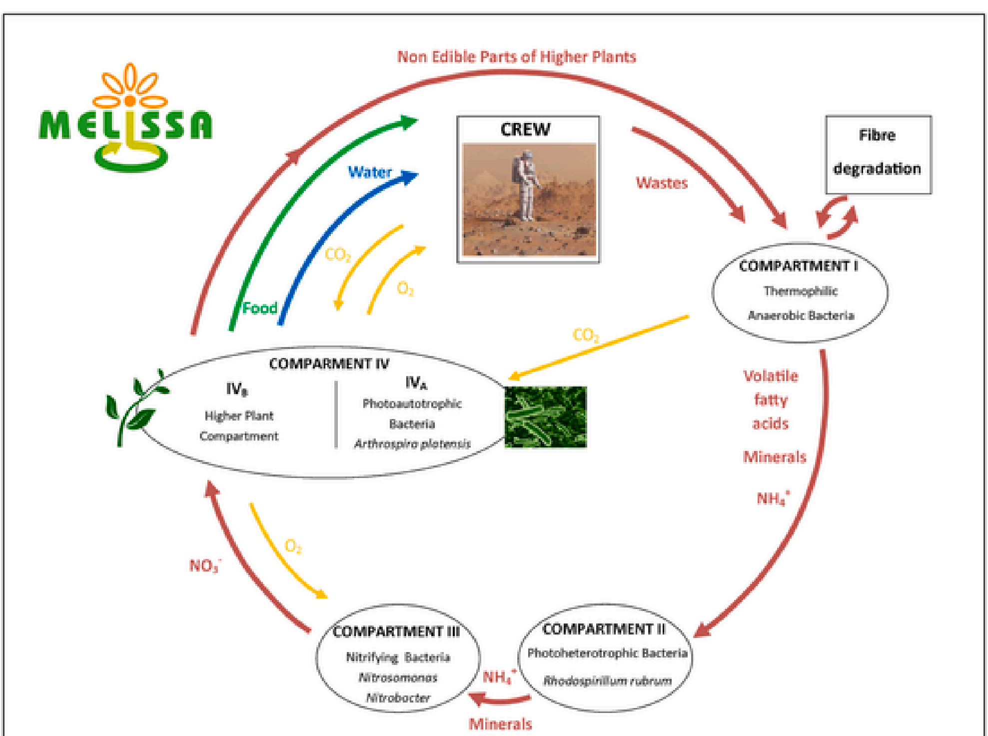

Chart 1. MELiSSA's closed-loop concept. *(Source: ESA, from* Poughon *et al.,* 2009*).*

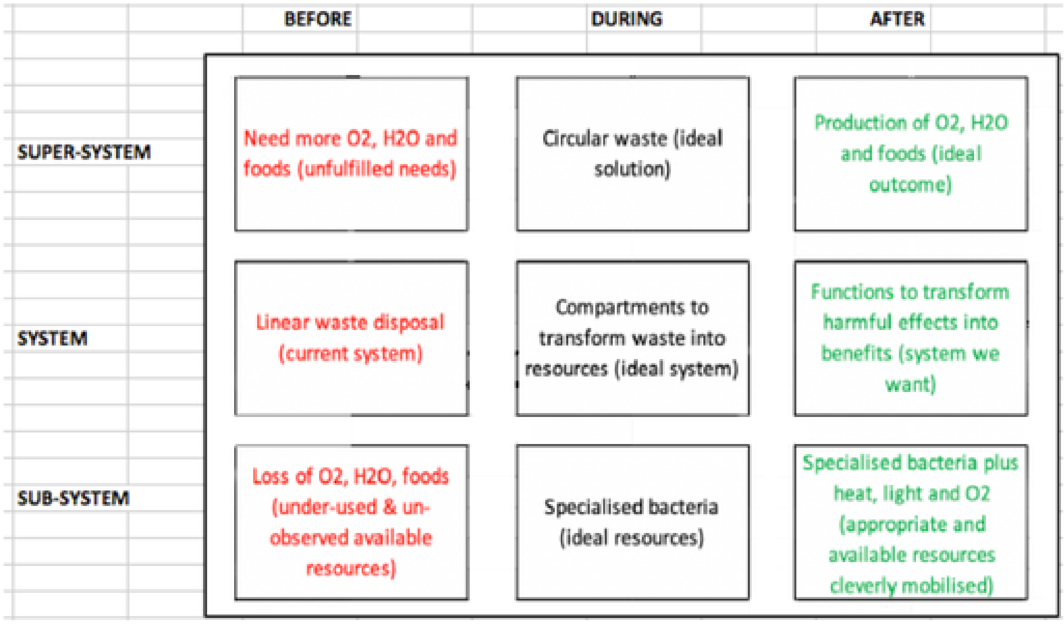

Chart 2. Harmful effects transformation into benefits at super-system level. (*Source: Authors' original elaboration on MELiSSA's closed-loop concept).*

theoretically the harmful effects (red) whilst aiming at delivering the intended benefits. After the system is completed, the ideal outcome (green) is achieved by the mobilisation of resources, assigned to specific functions.

Chart 3 connects the resources needed to support system functions delivering an ideal outcome, waste becomes a resource, in what proves to be a CE, '5 R compliant' [REUSE-REDESIGN-RECYCLE-RECOVER-REDUCE] system (Chen et al., 2020). It shows how the super-system delivers an ideal outcome where beneficial effects are maximised and harmful effects minimised by the utilisation of dedicated resources, designed to deliver benefits. Once these benefits are aggregated into a functional system, the ideal outcome is achieved.

Wastes from plants and ISS members are recycled into consumable resources such as O2, H2O and nitrates to support plants' fertilisation. Liquid and solid wastes are recovered and liquefied using specific bacteria flourishing in a heated environment. This heterogeneous liquid waste can then be transferred into other compartments where elements are extracted from this liquid resource using other bacteria and algae. The functions of the system liquefy waste, remove fatty acids and accelerates nitrification useful for plants growth, while the compartmentalisation allows for optimising the outcomes for each function (Tamponnet and Savage, 1994) and improving reuse rates. Thanks to this super system, solid and liquid wastes effectively become a resource for plants and humans. It is the [REDESIGN] redesigning of a marine ecosystem, aimed at [REDUCE] reducing wastes harmful effects by [REUSE] reusing human and plant by-products, [RECYCLE] recycled into resources to [RECOVER] recover vital substrates, in a textbook application of a CE-informed, WTE –waste-to-energy—system (Pan et al., 2015; Chen et al., 2020).

Chart 4 breaks down MELiSSA system by illustrating the function fulfilled by each compartment.

This iterative process is necessary as each steps of the process delivers a specific function, exactly in the logic of any typology of mechanistic modelling approach (Noorman, 1991) at an engineering level.

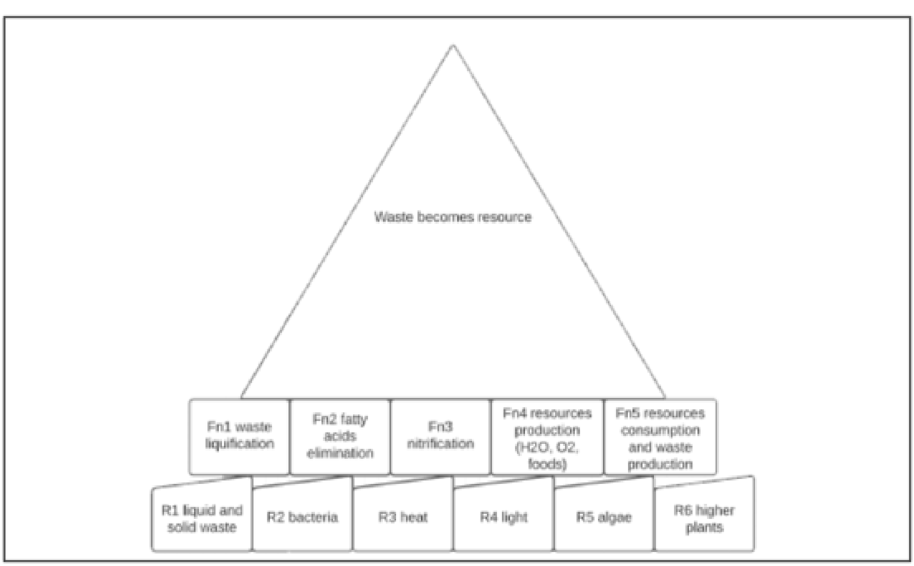

Chart 3. Ultimate goal supported by system benefits and resources (adapted from Gadd, 2011). (Source: Authors' original elaboration on MELiSSA's closed-loop concept).

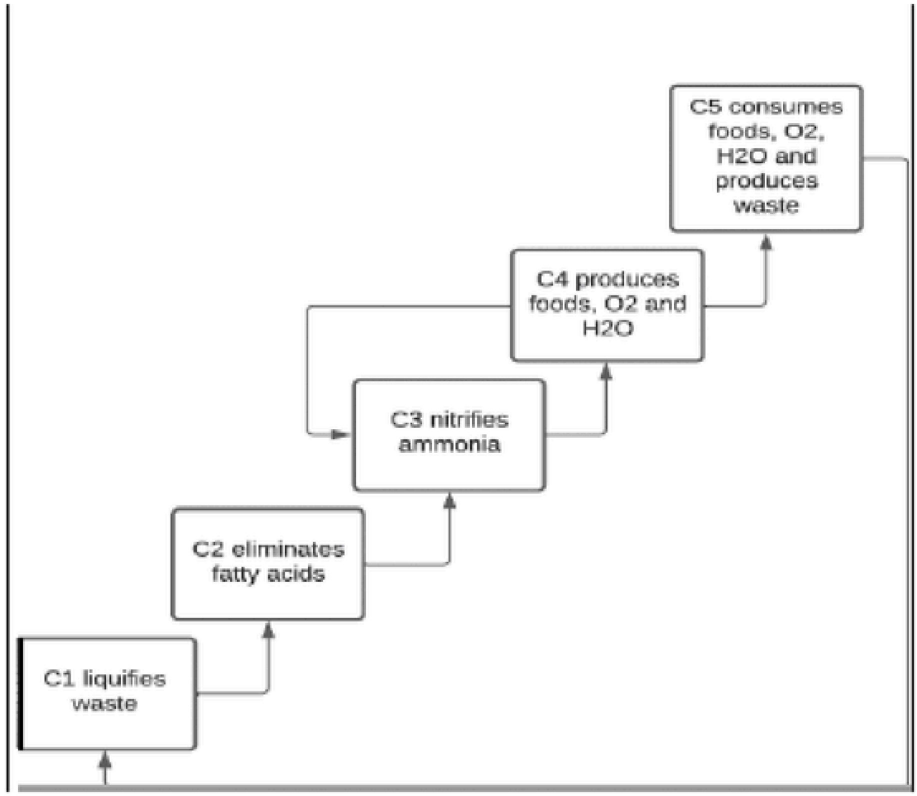

Chart 4. MELiSSA compartments delivering specific benefits. **(***Source: Authors' original elaboration on MELiSSA's closed-loop concept).*

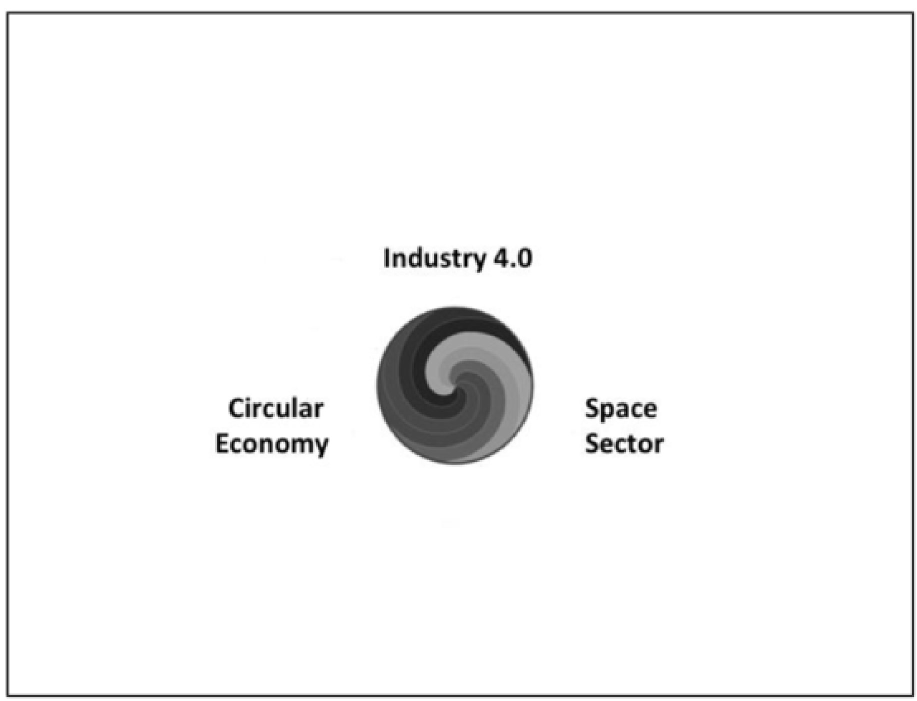

Chart 5. The integrated framework. (Source: Authors' elaboration).

The first compartment with the support of thermophile anaerobic bacteria liquefies waste. The second compartment removes fatty acids that are harmful. The third compartment oxidise ammonia to transform into nitrate, which are then fed to plants. These plants such as rice or maize generated foods, as well as O2 and H2O, used by humans afterwards. Humans are integral part of the system as they generate waste and consume some of the benefits produced by MELiSSA.

Built as a closed-loop system, MELiSSA embodies all the challenges, and the virtues, of the CE philosophy, where waste and by-products are integral part of the super-system and unidentified or neglected resources are transformed and reused as future inputs to different parts of the system. The solution is thus embedded into the problem formulation itself, and this is why methodology like TRIZ, or PhySystem, applied afterwards to sectors as different as automotive, smart buildings, and education (MELiSSA Foundation 2020a; Solize, 2020; Sherpa 2020), can successfully deliver when designing circular systems wherever they take place, being in outer space, Lower Orbit (like in the of the ISS) or down to Earth.

4. Discussion. Space and CE in industry 4.0 framework

4.1. MELiSSA for the world. From space to Earth

As a regenerative model founded on the principle of living within the limits of available renewable resources, CE has the net effect to stop environmental degradation (Lieder and Rashid, 2016), which explains why it has especially gained traction in the last decade when sustainability and climate changes have got on the radar of the world's policy imperatives. ESA MELiSSA is a good example of the role the space sector as a whole can play for both advanced and developing countries in general (Moriconi-Ebrard et al., 2016) and for sustainability in particular.

The interpretative key to its significance is in ESA's words themselves: "*Understanding and recreating an ecosystem in which humans can survive could benefit people who live in less affluent places where water or even clean air is sparse – regardless of whether these people are colonising a distant planet or living in a desert on Earth,*" (ESA, 2021, online).

While this is not the place to discuss in details the overall sustainability gains from MELiSSA, it is worth highlighting the impact of MELiSSA philosophy, which, from the original conception of 100% reuse of materials in outer space settings, has found its ways into Earth-based applications, some of which with huge potential in terms of meeting SDGs and assisting both commercial and non-commercial actors in their transition to a more sustainable world. This is especially true for NGOs, the third sector, HEIs and education in general, and SMEs, whose constraints in terms of resources and costs are higher than in the case of big public organisations and TNCs. The fact that ESA is fully committed to foster the widest application possible to the SDGs –the majority of the ESA missions are designed with targeting one or more SDGs specifically in mind (ESA, 2020d), has helped in this sense.

An example here is the use of the technology for environmental use (Table 2), in the self-sustaining water filtration system developed at the University of Kenitra in Morocco, which provides drinkable water to the village of Sidi Taïbi near Kenitra 30 km from Morocco's capital Rabat. Building directly on MELiSSA -based organic membranes, a joint-venture from the French Firmus and German Belectric set up in 2014 a self-sustaining unit powered by solar panels and wind energy (ESA, 2020b) The organic and ceramic filtering membranes in Kenitra are of the same kind of the ones already used in Antarctica, Concordia Based), since 2005 and that recycle so called "grey water" from household appliances –like showers, washing machines and dishwashers—into clean water. However, while Concordia's plant serves only 16, Kenitra goes up to 1200 users.

Far more cases could be offered for analysis, and they are going to become only more widespread in the future. If anything, a proof that the sector is becoming increasingly conscious of the wide implications in terms of CE is given by ESA-MELiSSA itself. The MELiSSA Foundation, created after the successful implementation of the modules, adopted as its logline "*creating a circular future*" (MELiSSA Foundation, 2020b, online). Semilla Sanitation Hub, a startup offspring from MELiSSA and whose clients span real estate owners to aid agencies and event organisers, went so far to use a 3 R acronym –REUSE-REDUCE-RECOVER—on their homepage (Semilla Sanitation Hubs, 2020). The space sector can usefully show what are the enabling conditions for such a regenerative system that can be replicated across other industries' supply chain. A closed-loop system is already underway in industries with high-value assets and equipment (Saidani et al., 2018). Allwood et al. (2011) identified that reuse, repair, and remanufacturing of products are material efficient activities, while recycling is for energy-efficiency and GHG reduction. But things can be taken further than that, with benefits both in the space sector and industry as a whole. This is where Industry 4.0 as an essential nexus between CE and space comes into play.

4.2. An integrated framework. CE, space 4.0, and industry 4.0

One of the cornerstones of Industry 4.0 conceptualisation mandates that, while its nine innovation-enabler fundamental pillars (*i.e.*, Big Data &AI, Horizontal &Vertical Integration, Cloud Computing, AR, IoT, Additive Manufacturing &3D Printing, Autonomous Robot, Simulation, Cyber-Security; Russmann et al., 2015) make smart systems possible, it is only when they are all used together that Industry 4.0 unleashes all its potential (Sap, 2020; Haskel and Westlake, 2018).

The same can be said for CE and the space sector, once they have been fully embedded in the Industry 4.0 framework in a way that put them into the same ecosystem and allows for a easier exchanges of concepts, insights and best practice.(see Fig. 5)

The space sector looks uniquely positioned to play a fundamental role in Industry 4.0, both for its characteristics and the institutional support already granted (EC, 2016), and the new Cycle 5, as illustrated in Section 2.3 (OECD, 2016, 2019), looks particularly promising in this sense. Cycle 5, started in 2018 and expected to last until 2033, has already brought a series of new actors on the world scene and a different set of procedures at all levels, taking the sector away from the traditional upstream and downstream divide and steering it toward a different configuration, in an increasingly overlapping series of value chains whose potential for spillovers to other sectors are far higher. The adoption of incremental technologies, including data analytics, additive manufacturing, and robotics, had the net effect of reducing those material costs and production times, which, as previously discussed had always been the bane of the sector, changing dramatically the way both private and public operators plan their missions.

Its potential for sustainability goes beyond ESA-MELiSSA, and spans to key areas such as energy production, essential for reducing the planet's carbon footprint. Initiatives like clean energy production of green hydrogen from water electrolysis for the European Spaceport in French Guyana (ESA, 2020c) are clear examples, but, again, more that can be usefully brought for analysis. The EO (Earth Observation) capabilities developed by the space agencies have already proved essential in managing enhanced environment risks provoked by the climate change, together with being open to everybody and free to use (NASA, 2018). Moreover, in one of the trends that is certainly going to keep growing is the way private process innovators are changing the sector, followed by the incumbents, especially in addictive manufacturing (Russell, 2017; EOS, 2016) already identified above as one of the cardinal points of CE applications to industry. Space X's reusable rockets and adaptation of experiences and data from high-volume industries (Space X, 2021; OECD, 2019), such as the automotive industry, are just the beginning.

Other innovations that have already made their appearance in space manufacturing, and that will only scale up in time, include extensive 3D printing (*e.g.*, Space X rockets and RocketLab engines), the growing reliance on off-the-shelf components in the supply chain and the Cubesat revolution of low-cost, low-impact satellites, which have become the tool of choice of small organisations and educational institutions.

It is true that Industry 4.0 revolution is at its very beginning, and we are only glimpsing at its 'enormous potentials' (Hofmann and Rusch, 2017). Still, once the integration in Industry 4.0 framework progresses over the next decade, the sector will see a more coherent acknowledgement of how much of the space industry function with inherent CE processes and principles, which will lead to their spillovers to a variety of terrestrial uses, as shown by MELiSSA, and to a more programmatic integration of their lessons from other sector. But it will work in the other way as well, with the space sector learning as well from other industries how to make the most of the innovation technology and CE gains realised elsewhere. There are good hints this is happening already.

In the case of CE, the integration in Industry 4.0 will yield different but equally fundamental gains, thanks to the ongoing regulatory efforts and, a fortiori, the institutional support aimed not only at strengthening CE practice but also embed them into the sectors' industrial DNA under the Industry 4.0 framework. While the research and the debate that explore linkages between Industry 4.0, sustainability, and circular economy is in its infancy (Stock and Seliger, 2016; Stock et al., 2018; Jabbour et al., 2018; Dev et al., 2020) and still lying down the foundations for a roadmap forward, the so-called "CE-I4.0 nexus" (Dantas et al., 2021) is the way to go to address the evident challenges a widespread application of CE in the Industry 4.0 framework entails. The automotive sector already proved that the technical breakthrough in integrating connected devices (the so-called IoT, Internet of Things) with electrical components of vehicles (Yi and Park, 2015) along with lighter and new materials (lithium-ion batteries) to reduce vehicle weight and emission create new challenges to end-of-life recycling (Diener and Tillman, 2016; Simic, 2015).

If there is one aspect of the CE literature has consistently shown as crucial is addressing the existing barriers of various kinds to the adoption of CE models to shape extremely complex sectors (Kumar et al., 2019; Masi et al., 2018; Matsumoto et al., 2016) and the overall impact on sustainability. Early research has already highlighted correlation between CE and social sustainability (Turkeli et al., 2018), and outlined circular business model integrating waste, natural resources, environmental and economic aspects (Rosa et al., 2019).

The EU and governments worldwide have been consistently trying to remove regulatory obstacles in adopting and implementing CE-compliant business models (MacArthur et al., 2015; Kirchherr et al., 2017), even before the EU Green Deal launch (EC, 2019), so far with mixed results, especially when it comes down to the single countries (Domenech and Bahn-Walkowiak, 2019). More comprehensive approaches to sustainability have also been actively supported by MNCs' industrial policies for a while now (Bair, 2017). Such policy intervention and voluntary practices have the scope to reduce the up-front investment costs and other market barriers for a circular business model (Dey et al., 2020), increasing CE adoption in manufacturing (Lieder and Rashid, 2016), construction (Benachio et al., 2020), and the maritime sector (Milios et al., 2019). More needs to be done (Leitão et al., 2016; Elkhodr et al., 2016; Schumacher et al., 2016) to make it works, and this is where the insight gained from the space sector can help the most, if the lessons learnt in projects like MELiSSA are disseminated and applied as shown in the previous section. And if the last five years are any guidance for the future, the efforts made at the EU and ESA level in both senses are signals encouraging enough.

5. Conclusions

There are few doubts that, in 21st century as never before, the world is threatened by global challenges, be them natural disasters, pandemics, or climate change consequences, which all require global actions. And, as never before, space can become an enabler, and it "*can play a pivotal role in meeting those challenges*," (Lehnert et al., 2017).

The space industry underlying philosophy is of a regenerative system that renews and regenerates the sources of energy and materials that have been consumed. The applications of MELiSSA technology have shown so far a wide range of scope and depth, in field as different as life science with the development microalgae for human use, O2 and food; for the environment with water treatment; or for the agrifood industry to improve dietary requirements.

More importantly, MELiSSA's decade-long initiative showed how the space sector constitutes a sort of native environment for the application of CE approach. In the 1990s MELiSSA closed-loop system there is all the CE principles in action, before even getting a working definition in this sense. This is why the space sector represents such an opportunity now that concepts like sustainability and circular economy are becoming more and more widespread and central in today's industrial and economic global environment. With the transformative environment brought in by Industry 4.0 framework, there is scope for making it happen sooner than later, and in a more effective way. This study has suggested a few modalities this may happen, shown the logic behind the process, and this intended to be its original contribution to the debate.

Of course, this is just a preliminary analysis: more studies are needed for this debate to continue and progress, and the way forward is to systematically analyse all instances where those components highlighted in the previous section combine and interact in the overall framework.

Even at this initial stage, however, some firm points can be offered for reflection.

On one hand, the space sector has become more self-conscious of its peculiarities and its potential as an enabler of CE procedures. The spillovers from MELiSSA have shown how the willingness of both parts to share and incorporate on the other, circularity economy and sustainability best practice from the space sector into the manufacturing as a whole.

There is, however, a different, more subtle dynamic at work, and it is in the sense of making the sector more integrated into the overall economy from a different direction, taking on board gains from innovation technology, addictive manufacturing, and big data in Industry 4.0 logic that applies to both CE and the space sector itself. If anything, the policymakers seem to be, for once, in advance, already bridging the regulatory gaps and paving the way forward.

In both cases, the overall aim is the same: a closer integration of the space sector in the general economy, in a more environmental-friendly, CE-informed approach. 'Spaceship Earth' has the potential to be no longer just a logline, but a fast-approaching, all-encompassing reality.

Credit author statement

This journal article is the product of the joint work of the three authors. More specifically, Stefania Paladini was the lead author and responsible for the overall outline, the sections' content, and critical analysis. Krish Saha contributed to Section 2, Research and Methods, while Xavier Pierron gave his contribution to Section 3, Results. The three authors all agree to the article submission and publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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